FOUR ESSAYS IN NATURAL RESOURCE ECONOMICS: DYNAMIC MODELING OF RENEWABLE AND NONRENEWABLE MARINE RESOURCES

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Contents

Introduction

Natural, human, and human-made capital enable the privileged lives that many of us live today – lives that entail much more than the basic cycle of human survival and reproduction.

Figure 1 below depicts a perspective on the interplay between natural capital, human existence, human capital, human-made capital, human production of goods and services, and human welfare. This perspective represents a general motivation for the work presented in this thesis.

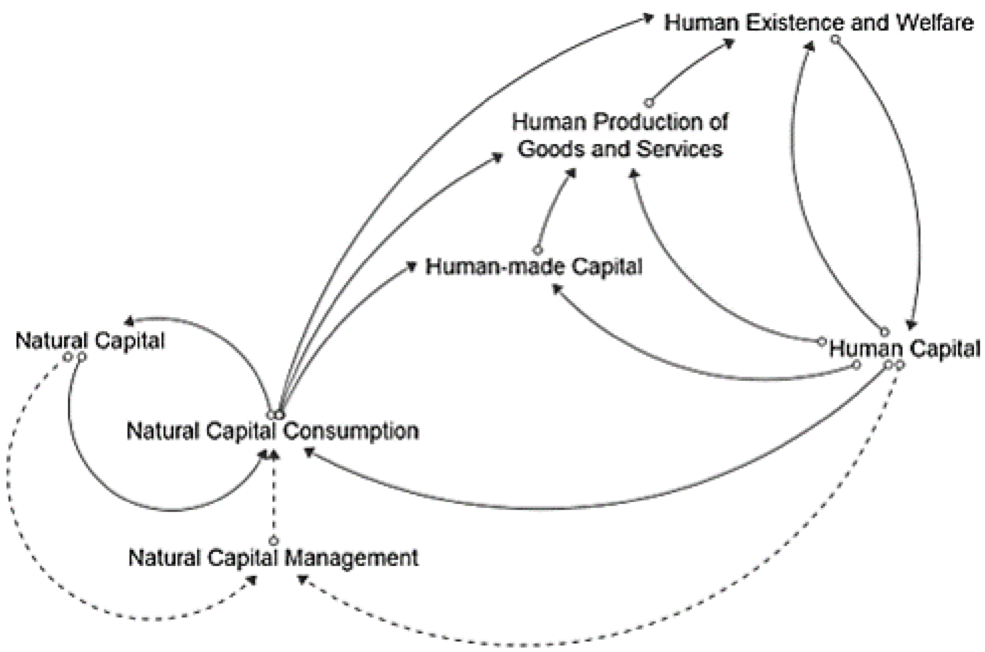

Figure 1: A perspective on the interplay between natural capital, human existence, human capital, human-made capital, human production of goods and services, and human welfare

Natural capital is a prerequisite for our existence. As such, it can be considered the basis for everything human – not only our lives but also the modern economy and today's privileged ways of living.

Natural capital in terms of breathable air, drinkable water, food, and shelter enable human survival and reproduction. Human survival and reproduction, in turn, allow the development of human and human-made capital, enabling more sophisticated use of natural capital and further development of human capital and human-made capital. Advanced use of natural capital, human capital, and human-made capital allow advanced and efficient production of goods and services, which enable high levels of human welfare.

Although advanced use of natural, human, and human-made capital is primarily good for our welfare, it can also challenge responsible use of natural capital and the foundation of our welfare. This is because much of the natural capital is limited and/or exhaustible. An increasing human population, advances in human and human-made capital, and growing living standards can put pressure on this natural capital. This, in turn increases the threat of kicking the legs out from under our high standards of living, potentially leading humanity back to more primitive standards of living – or even extinction. Luckily, part of modern human capital is the ability to acknowledge this threat and consider it before making decisions regarding the use of natural capital. This sophistication in human capital may enable sustainable high standards of living.

This thesis aims to contribute to the literature on management and use of marine natural resources. The ocean covers 70.8% of the Earth's surface. Besides representing natural capital on its own, it also holds many natural resources – including commercial resources such as fish, crude oil, natural gas, and minerals. Overall, the ocean and its contents make out a significant proportion of the world's natural capital and are arguably crucial to human existence and welfare. Therefore, it is essential to manage the ocean and its resources responsibly and efficiently.

The thesis is split into two parts. The first part includes two pieces that deal with renewable marine resources. More specifically, it deals with fish, a key food source for humans. The second part of the thesis comprises two pieces that deal with nonrenewable marine resources. Specifically, the second part deals with marine metallic minerals, which contain metals that are vital inputs to human-made capital, enabling advanced production of goods and services, including production, storage, and consumption of renewable energy.

In the first paper, in part I, we present an age-structured fishery model with endogenous natural mortality and weight. Using the model, we show that assumptions of exogenous natural mortality and weight, which are common in the bioeconomic literature, can lead to significant overestimation of biological and economic potential of long-lived cannibalistic fish such as the North-East Arctic (NEA) cod. Moreover, we confirm that the NEA cod fishery can achieve both higher sustainable yield and net present value (NPV) by changing the fleet-composition and biological target reference points.

In the second paper, in part I, we present an age-structured predator-prey fishery model inspired by NEA cod and capelin. Using this model, we show that preferred selectivity and optimal harvesting change with the levels of predation and predation-weight conversion rates. Among other things, we show that positive scaling of age-specific predation coefficients can shift the preferred selectivity towards smaller predator individuals and increase the optimal fishing pressure on the predator stock. This finding is important because it brings awareness to why managers should think twice before changing gear restrictions in direction of targeting bigger fish on basis of single-species analyses, in which selectivity studies are common.

In the third paper, in part II, we explore four conceptual optimization problems to investigate the role of reserve-dependent capital efficiency, cross-sector competition, and mineral security in mineral industry transition. Analyses of the solutions show that these factors can, in different ways, drive a transition to deep-sea mining. This study covers a gap in the mineral economics literature and sheds light on how some increasingly important current factors can affect a mineral industry transition.

In the fourth and final paper, in part II, we present a stochastic dynamic simulation model for exploration and extraction of seafloor massive sulfide deposits on the Norwegian continental shelf - a topic which is underresearched. The model is developed based on information elicited from literature and database reviews, a participatory systems mapping session with 82 offshore professionals, and in-depth interviews with 20 professionals from industry, academia, and public policy. The model maps the processes of exploration and extraction. Further, it is used to simulate the expected resource and economic potential of the emerging industry.

Although each part of this thesis deals with specific marine resources, the content is also relevant for other renewable and nonrenewable resources, as many of the principles that apply to the management of fish and minerals are transferable to management of other resources, such as seaweed, crude oil, natural gas, etc.

Endogenous versus Exogenous Natural Mortality and Weight in Bioeconomic Models

Rasmus Noss Bang and Stein Ivar Steinshamn, *Norwegian School of Economics*

ABSTRACT

We present an age-structured multi-fleet model with cannibalism mortality and endogenous weight at age. Using the model and three simplified versions, we show that assumptions of exogenous natural mortality and weight can lead to significant underestimation of optimal fishing mortality in both maximum sustainable yield (MSY) and maximum economic yield (MEY) scenarios for long-lived cannibalistic fish such as the Northeast Arctic cod. In addition, we show that the harvest, spawning stock biomass (SSB), and net present value (NPV) levels associated with optimal exploitation rates increase significantly with assumptions of exogenous natural mortality and weight. The underestimation of optimal fishing mortality, and the corresponding overestimation of SSB and NPV, is more significant in MSY than MEY scenarios. Meanwhile, the overestimation of harvest is more significant in MEY than MSY scenarios. The study also confirms that the Northeast Arctic cod fishery can achieve higher sustainable yield and NPV by changing the fleet composition and target reference points.

Key words: Age-structured model, cannibalism mortality, endogenous weight, fleet composition, Northeast Arctic cod.
JEL codes: Q2, Q22.

INTRODUCTION

Age-structured analysis, pioneered by Hannesson (1975) and Reed (1980), has dominated the bioeconomic literature in recent years (Tahvonen 2008, 2009; Steinshamn 2011; Skonhoft, Vestergaard, and Quaas 2012; Diekert 2013; Diekert et al. 2010a, 2010b; and Helgesen, Skonhoft, and Eide 2018, to mention a few), and to a large extent replaced lumped-parameter models, for example, Clark and Munro (1975). Yet age-structured *bioeconomic* models are rarely considered in practical stock management, whereas age-structured *biological* models are widely used in such context. However, there is increasing interest in incorporating economic considerations in stock management (ICES 2021). As such, there is demand for further development of age-structured bioeconomic models and practically oriented bioeconomic studies.

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Our aim here is primarily to investigate the effects of endogenous (stock-dependent) natural mortality and individual weight in a single-species context, which we think is largely neglected in the bioeconomic literature. Because of data availability, we use Northeast Arctic (NEA) cod as a case, but many of the results should be transferable to other long-lived, cannibalistic, demersal species around the world.

Biological studies show that cannibalism mortality may be significant for NEA cod up to the age of 5 years (Yaragina, Bogstad, and Kovalev 2009; Kovalev 2004; Kovalev and Bogstad 2005; Bogstad, Yaragina, and General 2021; Hannesson 2018). Moreover, Kovalev (2004) shows that cannibalism mortality for cod of age 3 and 4 are strongly correlated with spawning stock biomass (SSB). Further, state-of-the-art *biological modeling* for the NEA cod fishery considers weight endogenously. For example, Kovalev and Bogstad (2005) model weight as decreasing functions of total stock biomass (TSB). Even so, single-species, age-structured, *bioeconomic* models typically do not consider natural mortality and weight endogenously. As such, two potentially significant balancing feedback effects are ignored, namely that higher SSB and TSB are associated with higher natural mortality among younger individuals and lower weights at age, which in turn have negative effects on SSB and TSB. The lack of considerations of endogenous natural mortality and weight may significantly weaken the validity of single-species, age-structured, bioeconomic results, which may represent a problem in a range of settings.

To fulfill our primary aim, we present an age-structured, bioeconomic model with endogenous natural mortality and weight for the NEA cod fishery. Using the model, and three simplified versions, we quantify the effects on maximum sustainable yield (MSY) and maximum economic yield (MEY) of treating these parameters endogenously versus exogenously. Our results indicate that assumptions of exogenous natural mortality and weight significantly decrease optimal fishing mortality and significantly increase associated harvest, SSB, and net present value (NPV) in MSY and MEY scenarios for long-lived cannibalistic fish such as the Northeast Arctic cod.

A secondary aim of this study is to contribute with a *practically oriented* and *detailed* investigation of the possibilities of improvements in sustainable and economic yield in the NEA cod fishery through changes in the fleet composition and fishing pressure. Several studies have investigated similar questions in the case of the NEA cod fishery (e.g., Diekert et al. 2010b and Sumaila 1997). As such, this aspect is not novel per se. However, existing applied bioeconomic studies do not consider endogenous natural mortality and weight. Moreover, they typically focus on what is optimal in unconstrained management scenarios. What is optimal in unconstrained management scenarios may not be relevant in practice, partly because the overall optimal strategy may be impossible to implement, and partly because the results do not necessarily give a good indication of what direction to move in when prevented from applying said strategy. Our applied contribution lies in the inclusion of endogenous natural mortality and weight, yielding more conservative estimates on biological and economic potential, and the study of a wide range of scenarios, some of which may be of more practical interest than unconstrained management scenarios.

In the following, we provide the necessary background on the NEA cod fishery and age-structured models. Next, we present our model versions and motivate the chosen optimization scenarios. Following this, we present our results. Then, we test the sensitivity of the results in the model version with endogenous natural mortality and weight. Finally, we summarize our findings.

NORTHEAST ARCTIC COD FISHERY

NEA cod forms the world's largest cod stock with an estimated spawning stock biomass of about 1.4 million tons in 2020 (ICES 2020). The mature part of the stock migrates between the feeding grounds in the Barents Sea and the spawning grounds off the Lofoten Islands. It accumulates in the spawning grounds in the period that stretches from January to April every year, and the eggs are spawned during March and April. The eggs and fish larvae are transported to the Barents Sea by ocean currents. The immature part of the population grazes in the Barents Sea until it matures and starts participating in the annual migration between the spawning and feeding grounds.

The fish stock is managed jointly by Norway and Russia through a bilateral fisheries commission (NFD 2018). A total allowable catch (TAC) is agreed upon every year based on the management objectives, a harvest control rule, and negotiation. The harvest control rule is designed to maximize sustainable yield, with precaution for recruitment-overfishing (Gullestad et al. 2018, 12–37; Eikeset et al. 2013).

The TAC is distributed between vessels that, for practical purposes, can be categorized into three broad groups: Norwegian conventional vessels, Norwegian trawlers, and Russian and third countries' trawlers. The non-Norwegian fleets are pooled together in one group because of the structure of the data that we use to parameterize certain parts of the model (see data received from the Institute of Marine Research in online appendix table A1). We will refer to this group as the "Other countries' (OC) trawler fleet" throughout the remaining parts of the paper.

Historically, 10–15% of the TAC has been allocated to third countries. The remaining share of the TAC has then been split equally between Norway and Russia. Hence, the OC trawlers typically get 55–57.5% of the TAC, while the Norwegian part of the fishery gets the remaining share (JNRFC, n.d.). A distribution key determines the distribution of the Norwegian share of the TAC as a function of its size (NOU 2016). The trawl share is rising from 27% when the quota is low to 33% when the quota is high. This is the so-called trawl ladder.

The fleet composition is important in the context of management because the fleets are heterogeneous in terms of selection pattern and economic details. The fleets operate with different gears and in various geographical areas. As a result, they target different age groups in the stock. Most vessels in the Norwegian conventional fleet operate on the spawning grounds off the Lofoten Islands during the spawning season. Hence, they naturally target the mature part of the stock. OC trawlers operate in the Barents Sea. The same goes for Norwegian trawlers. However, the Norwegian trawlers operate farther west than most vessels in the OC trawler fleet (see, e.g., attachments 13a and 13b to JNRFC 2018). Norwegian trawlers may also operate relatively close to the spawning grounds during the spawning season. Since both trawler fleets operate in the Barents Sea, where the immature population grazes, they target a younger part of the population than the Norwegian conventional fleet. Because the Norwegian trawlers operate farther west and closer to the main spawning grounds than the OC trawler fleet, they naturally target older individuals than the OC trawler fleet (Ottersen, Michalsen, and Nakken 1998). Although we do not present an explicit spatial model, the spatial characteristics are of high relevance and indirectly reflected in the harvest functions through the selection patterns of the fleets.

To further motivate our detailed study of the NEA cod fishery, there is currently an ongoing Norwegian public debate concerning whether the trawl ladder should be maintained. As the Norwegian conventional fleet is known to deliver higher-quality raw material and create more jobs in coastal communities than the Norwegian trawler fleet, many argue that the conventional fleet should get more of the Norwegian share of the TAC (see, e.g., Fylkesnes 2019). Others argue that the trawl ladder should be maintained because the Norwegian trawler fleet plays an essential role in the year-round supply of raw material and provides year-round employment (see, e.g., Martinsen and Lysvold 2016). Others seem to believe it is better to utilize the Norwegian trawler fleet to a greater extent at the expense of the Norwegian conventional fleet because it performs better in terms of first-hand profitability (see, e.g., Jensen 2019); however, it appears that many of those with this opinion only consider snapshots of current performance, and fail to consider how changes in the fleet composition may affect the future potential of the fishery.

Although the trawl ladder debate is more complex than outlined above, it is explained sufficiently to understand that the distribution of the Norwegian share of the TAC is a hot topic. Further, one can imagine a scenario in which the international distribution of the TAC is rigid, while the distribution of the Norwegian share of the TAC is flexible. This reality calls for study of scenarios with constraints on the international distribution of the TAC.

LITERATURE

In age-structured models, where the objective is to maximize sustainable yield, a general finding is that it is optimal to spare small fish for future harvest as this results in better utilization of the growth potential of the stock (Beverton and Holt 1957; Reed 1980; Helgesen, Skonhoft, and Eide 2018; Diekert et al. 2010b; Skonhoft, Vestergaard, and Quaas 2012; Kvamme and Bogstad 2007; Kovalev and Bogstad 2005). This may not be the case when the objective is to maximize economic yield. For example, if costs associated with harvesting large fish are higher than those associated with harvesting small fish, it may prove economically optimal to target small fish (Helgesen, Skonhoft, and Eide 2018; Skonhoft, Vestergaard, and Quaas 2012; Diekert et al. 2010b). On the other hand, size-dependent pricing of fish, and considerations regarding future recruitment, may work in the opposite direction, namely, to target large fish (Zimmermann, Heino, and Steinshamn 2011; Sumaila 1997). When the selectivity of the available harvest technology is suboptimal and possibilities for alterations are limited, periodic pulse fishing often proves optimal (Hannesson 1975; Tahvonen 2009). However, downward-sloping price functions and positive discount rates may dampen or eliminate pulses (Golubtsov and Steinshamn 2019). Although pulse fishing may prove optimal in a model, it may be associated with high costs not accounted for and thereby prove suboptimal in the real world (Helgesen, Skonhoft, and Eide 2018).

Hannesson (2018) presents an interesting biological study of density-dependent growth and cannibalism and discusses its implications for fishing strategies in the NEA cod fishery. The study finds that cannibalism mortality implies higher fishing mortality for older and more cannibalistic fish. Our analyses confirm this result—not only for MSY scenarios but also for MEY scenarios. Moreover, Hannesson (2018) indicates that density-dependent growth increases optimal fishing mortality, for any given selection pattern, to improve growth. This result is also confirmed by our analyses—again, not only for MSY scenarios but also for MEY scenarios. Kovalev and Bogstad (2005) also present a relevant study. Using a biological age-structured model, they evaluate the maximum long-term yield for NEA cod. They model weight at age using a linear relationship between weight and the total stock biomass in the previous year. Cannibalism mortality is not part of their baseline model. However, they also present model versions with cannibalism mortality for age groups 3 and 4. The results presented by Kovalev and Bogstad (2005) illustrate how MSY estimates are affected by cannibalism mortality. In addition, they show that it is possible to increase the sustainable yield by altering the selection pattern such that relatively more large fish are targeted.

Diekert et al. (2010b) present an age-structured model for the NEA fishery, *assuming exogenous natural mortality and weight at age*. Using the model, they estimate that the fishery could more than double its NPV by targeting older and larger fish by increasing mesh size and reducing the overall effort without changing the fleet composition significantly. Although Diekert et al. (2010b) deal with the fleet composition, their emphasis is on the value of changing mesh sizes.

Sumaila (1997) also presents an exciting and relevant study. Using a game theoretic framework combined with an age-structured model, he investigates the economic benefits that can be realized from the NEA cod stock, and the effect of exploitation on stock sustainability under cooperation and noncooperation between trawlers and conventional vessels. Given the available data, he shows that the optimum optimorum (the optimum of the optima, often called supremum) is obtained under cooperation between the fleets. It involves side payments and no predetermined harvest shares, in which case the conventional fleet buys out the trawler fleet and becomes the producer of the optimum optimorum.

MODEL

The model applied here is a deterministic, single-species, age-structured, multi-fleet optimization model. The model scope does not explicitly entail multispecies or ecosystem considerations, as in Goto et al. (2021), for example. The same goes for intrayearly seasonality. The biological part of the model describes mortality, growth, maturation, and recruitment, while the economic part describes costs, revenues, and profits.

The model considers three fleets: the Norwegian conventional fleet, the Norwegian trawler fleet, and the OC trawler fleet. The fleets' harvest functions, which include the control variables of the model, bridge the biological and economic dimensions. Although harvest functions are modeled for all three fleets, the model and analysis take a Norwegian perspective; no economic details are included for the OC trawler fleet because of a lack of data. In other words, the OC trawler fleet generates no costs or revenue in the model. We shall return to highlight this in the results section.

We will use four versions of the model to investigate the ceteris paribus effects of endogenizing natural mortality for young age groups and weight at age for several age groups across a wide range of optimization scenarios. In the primary version, "Endogenous M and W," illustrated in figure 1, we consider natural mortality and weight endogenously through linear functions of mature individuals with coefficients estimated by ICES (2018) data. In the second version, "Exogenous M," natural mortality is kept constant at average levels calculated from the same ICES

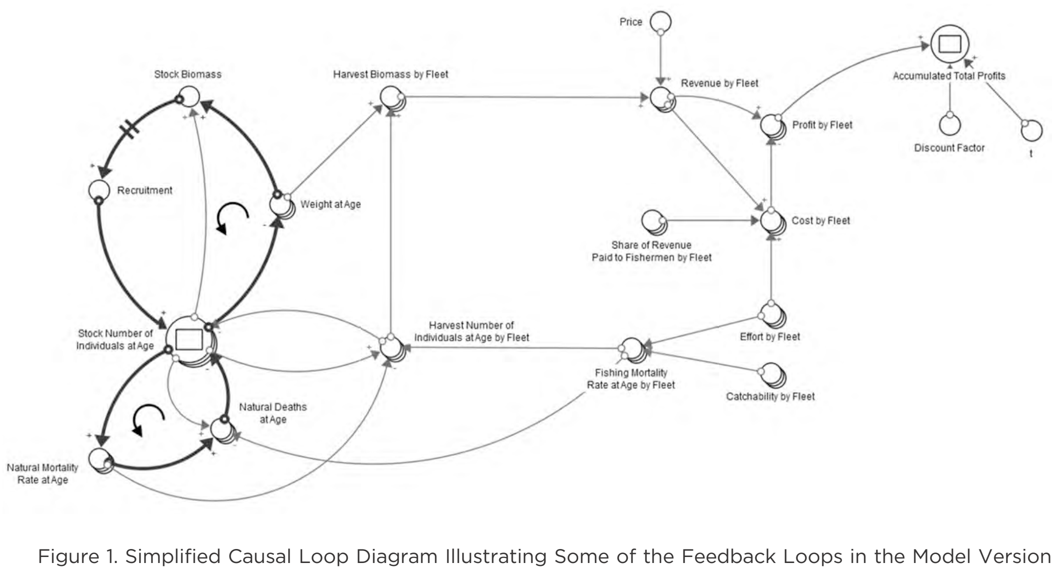

Figure 1. Simplified Causal Loop Diagram Illustrating Some of the Feedback Loops in the Model Version with Endogenous Natural Mortality and Weight. Key loops, including natural mortality and weight, are highlighted by bold arrows.

data. In the third version, "Exogenous W," weight at age is kept constant at average levels calculated from the same ICES data. Finally, in the fourth version, "Exogenous M and W," both weights and natural mortality are kept constant at the levels above. In the following, we present the primary model, which is the most complex of the four.

AGE STRUCTURE AND DYNAMICS

NEA cod may reach an age of 24 years (Diekert et al. 2010b). However, few fish survive beyond 12 years because of natural mortality and high fishing pressure (ICES 2018). With lighter fishing pressure, that may change. Therefore, the age structure in the model is defined from age class 3 to age class 13+. This means that recruitment to the stock happens when the fish becomes 3 years old. Age class 13+ includes all individuals that are 13 years and older.

In accordance with traditional Beverton-Holt modeling (see, e.g., Beverton and Holt 1957), the number of individuals in age group $a + 1$ in period $t + 1$ ($N_{a+1,t+1}$) is modeled as a function of the number of individuals in age group a in period t ($N_{a,t}$), the natural mortality for age group a in period t ($M_{a,t}$), and the total fishing mortality for age group a in period t ($F_{a,t}$):

$$N_{a+1,t+1} = N_{a,t}e^{-(M_{a,t}+F_{a,t})}, (3 \le a \le 12), \tag{1}$$

$$N_{13,t+1} = N_{13,t}e^{-(M_{13}+F_{13,t})} + N_{12,t}e^{-(M_{12}+F_{12,t})}. \tag{2}$$

The recruitment determines the number of individuals in age group 3 in period t (R_t). The recruitment process is described in the next subsection.

RECRUITMENT

The recruitment to the stock is modeled by a Beverton-Holt recruitment function. Since recruitment happens when the fish reaches the age of 3, the recruitment in period t (R_t) is modeled as a function of the size of the spawning stock biomass in period $t - 3$ (SSB_{t-3}):

$$R_t = \frac{\alpha_{SSB} SSB_{t-3}}{\beta_{SSB} + SSB_{t-3}}, \tag{3}$$

where α_{SSB} and β_{SSB} are coefficients estimated using a least squares method on ICES (2018) data with recruitment measured in thousands and SSB measured in tons. α_{SSB} is estimated to 725,526, and β_{SSB} is estimated to 128,392. The corresponding R^2 is calculated to 0.44.

The sum of mature individuals in each age group a in period t (K_t) is modeled as a function of the maturity parameters for the different age groups (k_a) and the number of individuals in each age group in period t ($N_{a,t}$):

$$K_t = \sum_{a=3}^{13+} N_{a,t}k_a, \; 0 \le k_a \le 1 \;\; \forall \; a \in (3, \ldots, 13+). \tag{4}$$

The numerical specification of the maturity parameters is based on data from ICES (2018). Average values for 2000–18 are calculated and applied to the model (see online appendix table A2).

The total spawning stock biomass in period t (SSB_t) is the sum of the number of mature individuals in each age group a in period t ($N_{a,t}k_a$) multiplied by the average weight of individuals in each age group a in period t ($W_{a,t}$):

$$SSB_t = \sum_{a=3}^{13+} N_{a,t} k_a W_{a,t}. \tag{5}$$

The details for weight at age are described in a later subsection.

NATURAL MORTALITY

Natural mortality accounts for all fish that die of natural causes, that is, everything except harvest. NEA cod is cannibalistic: older individuals are inclined to feed on younger individuals, especially when other food sources are scarce (Kovalev and Bogstad 2005; Yaragina, Bogstad, and Kovalev 2009; Kovalev 2004; Hannesson 2018). The natural mortality due to cannibalism may be significant for younger age groups and should thus be modeled. Therefore, the natural mortality for age group a in period t ($M_{a,t}$) for age groups 3 and 4 has been modeled as a function of the number of mature individuals in period t (K_t):

$$M_{a,t} = \alpha_a^M + \beta_a^M K_t, \ (3 \leq a \leq 4). \tag{6}$$

The estimators α_a^M and β_a^M in equation 6 are estimated by linear regression in STATA with data from ICES (2018; see figure 2 and online appendix table A3). Data for the period 1984–2017 have been used. The natural mortality ($M_{a,t}$) for age groups 5–13+ are assumed constant and specified in accordance with ICES (2018) data and convention.

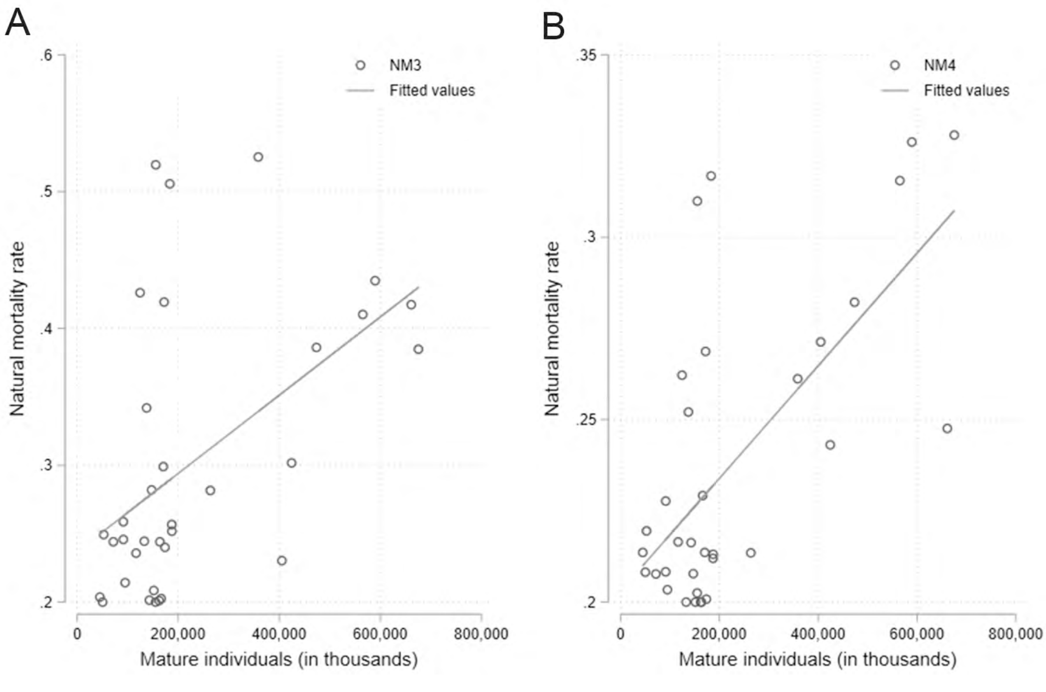

Figure 2. ICES Natural Mortality for Age Groups 3 and 4 Plotted against the Number of Mature Individuals (NM3 and NM4 in Panels A and B) versus Modeled Natural Mortality for Age Groups 3 and 4 (Fitted Values in Panels A and B)

FISHING MORTALITY

Fishing mortality represents fish that die from harvesting. It is induced by three fleets: the Norwegian trawler fleet (*Fleet 1*), the Norwegian conventional fleet (*Fleet 2*), and the OC trawler fleet (*Fleet 3*). The total fishing mortality for age group a in period t ($F_{a,t}$) depends on the effort applied by each fleet $i = 1, 2, 3$ in period t ($E_{1,t}$, $E_{2,t}$, $E_{3,t}$) and the fleets' catchability coefficients for age group a ($q_{1,a}$, $q_{2,a}$, $q_{3,a}$). The effort units are defined as operating days. The catchability coefficients measure the efficiency and gear selectivity of the different fleets, and the numerical specification of these will be accounted for later. The total fishing mortality for age group a in period t is modeled as follows:

$$F_{a,t} = \sum_{i=1}^{3} q_{i,a} E_{i,t}. \tag{7}$$

WEIGHT AT AGE

From a single-species perspective, it is reasonable that an increase in the number of mature individuals will lead to a reduction in the average weight for most age groups because of a rise in the pressure on the ecosystem and an increase in the competition for food, that is, reduced availability of food per individual. Kovalev and Bogstad (2005) suggest modeling weight as decreasing functions of total stock biomass. Therefore, considering ICES (2018) data, and a desire to avoid circular references in the model, the average weight for individuals in age group a in period t ($W_{a,t}$) has been made endogenous for age groups 5–11 and modeled as a function of the number of mature individuals in period t (K_t):

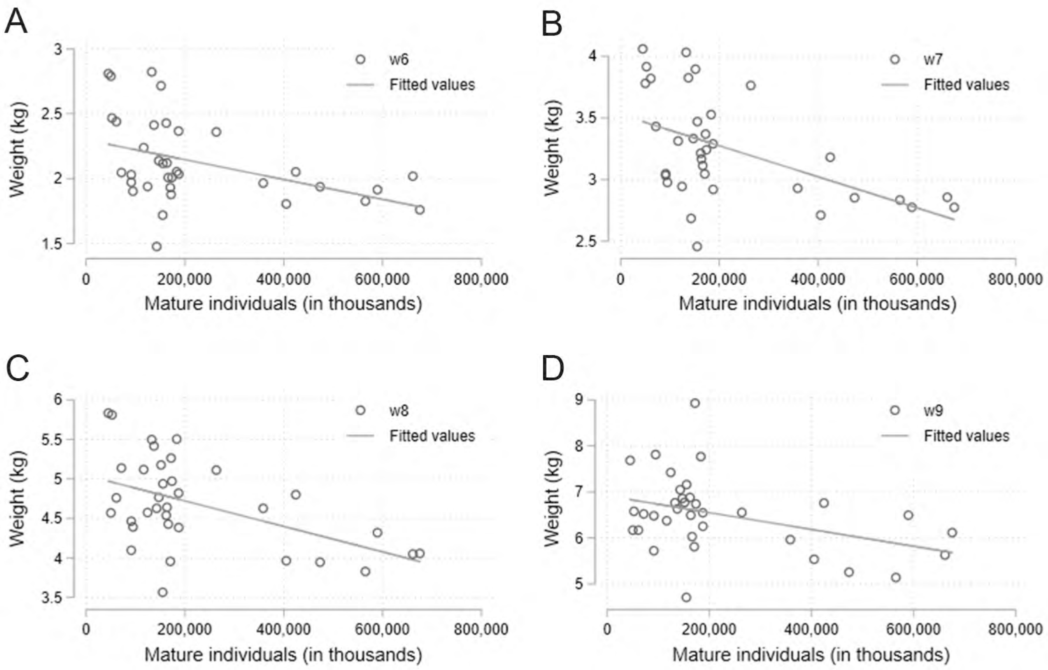

Figure 3. ICES Weight at Age for Age Groups 6, 7, 8, and 9 Plotted against the Number of Mature Individuals (w6, w7, w8, w9 in Panels A, B, C, and D) versus Modeled Weight at Age for Age Groups 6, 7, 8, and 9 (Fitted Values in Panels A, B, C, and D)

$$W_{a,t} = \alpha_a^W + \beta_a^W K_t, \ (5 \leq a \leq 11). \tag{8}$$

The estimators α_a^W and β_a^W are estimated by linear regression in STATA with data from ICES (2018; see figure 3 and online appendix table A4). Weight is measured in kilograms (kg), and the number of mature individuals is measured in thousands.

The average weights for the age groups 3, 4, 12, and 13+ are assumed to be constant and set to 0.27 kg, 0.66 kg, 12.7 kg, and 14.3 kg, respectively. The values for age groups 3 and 4 are assumed to be constant because their contribution to the total stock biomass and harvest is limited. The weights for age groups 12 and 13+ are assumed to be constant in line with ICES (2018) data.

HARVEST

The fleets' harvest measured in number of individuals by age group in period t ($y_{i,a,t}$) is determined by the fleets' harvest functions. Fleet i's harvest from age group a depends on the effort applied by all fleets in period t ($E_{1,t}$, $E_{2,t}$, $E_{3,t}$), the fleets' catchability coefficients for age group a ($q_{1,a}$, $q_{2,a}$, $q_{3,a}$), the natural mortality for age group a in period t ($M_{a,t}$), and the number of individuals in age group a in period t ($N_{a,t}$). A Baranov type of harvest function has been used (see, e.g., Baranov 1918), and it is assumed that harvest is linearly dependent on the density of the stock and that all three fleets have simultaneous and complete access to all stocks. The harvest function for fleet i for age class a is formulated as follows:

$$y_{i,a,t} = \frac{q_{i,a} E_{i,t}}{F_{a,t} + M_{a,t}} N_{a,t} \left(1 - e^{-(F_{a,t} + M_{a,t})}\right). \tag{9}$$

The catchability coefficients ($q_{i,a}$) applied to the model are estimated using an optimization model developed for this project, and data from the Norwegian Directorate of Fisheries (2011–15), data received from the Institute of Marine Research (online appendix table A1), and data from ICES (2018) have been used. The optimization model used to estimate the catchability coefficients is formulated as follows:

$$\begin{aligned}
&\min \sum_{t=init}^{T} \left(\sum_{i=1}^{3} \left(Y_{i,a,t}^{D} - Y_{i,a,t}^{E} \right)^2 \right) \text{ wrt. } q_{1,a}, q_{2,a}, q_{3,a},\\
&\text{s.t.} \quad Y_{1,a,t}^{E} = \frac{q_{1,a} E_{i,t}^{D}}{\sum_{i=1}^{N} q_{i,a} E_{i,t}^{D} + M_{a,t}^{D}} N_{a,t}^{D} \left(1 - e^{-\left(\sum_{i=1}^{N} q_{i,a} E_{i,t}^{D} + M_{a,t}^{D} \right)} \right),\\
&\qquad Y_{2,a,t}^{E} = \frac{q_{2,a} E_{i,t}^{D}}{\sum_{i=1}^{N} q_{i,a} E_{i,t}^{D} + M_{a,t}^{D}} N_{a,t}^{D} \left(1 - e^{-\left(\sum_{i=1}^{N} q_{i,a} E_{i,t}^{D} + M_{a,t}^{D} \right)} \right),\\
&\qquad Y_{3,a,t}^{E} = \frac{q_{3,a} E_{i,t}^{D}}{\sum_{i=1}^{N} q_{i,a} E_{i,t}^{D} + M_{a,t}^{D}} N_{a,t}^{D} \left(1 - e^{-\left(\sum_{i=1}^{N} q_{i,a} E_{i,t}^{D} + M_{a,t}^{D} \right)} \right),\\
&\qquad a = 3, 4, \ldots, 13; \; i = 1, 2, 3; \text{ and } t = init, \ldots, T,
\end{aligned} \tag{10}$$

where the superscript D is used to signify that the variables/parameters are treated as data input.

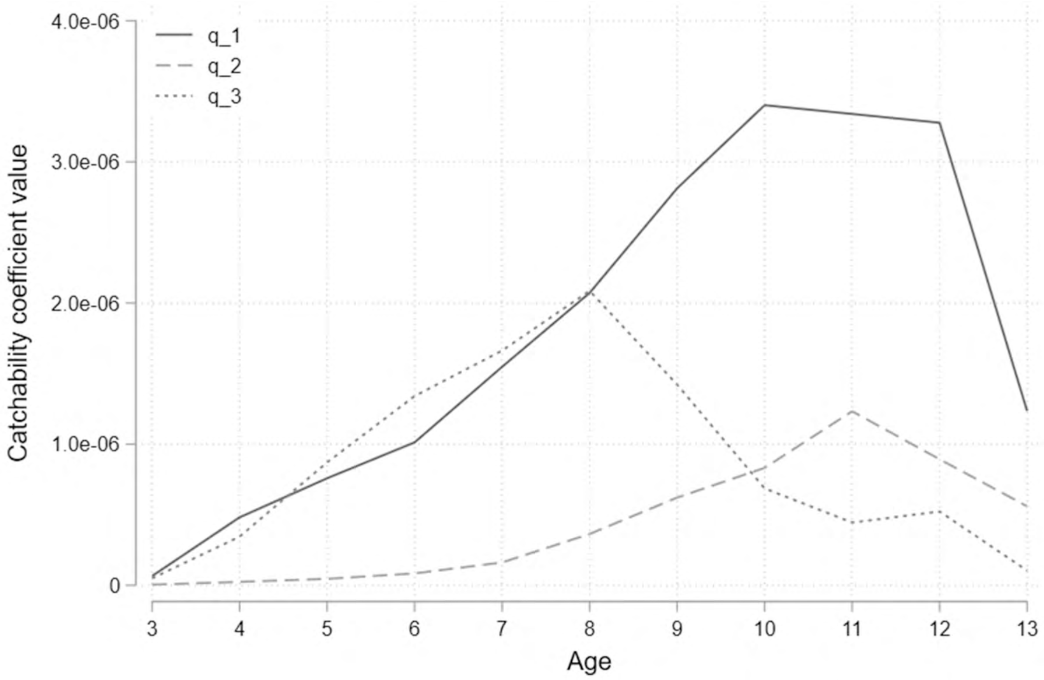

Figure 4. Estimated Catchability Coefficients for Norwegian Trawlers (q_1), Norwegian Conventional Vessels (q_2), and OC Trawlers (q_3)

Solving the model in equation 10 can be considered a best attempt to solve a system of three equations with three unknowns for each age group. The three equations are the fleets' harvest functions for each age group, and the unknowns are the fleets' catchability coefficients for each age group.

Data on effort for the Norwegian coastal fleet have been used to represent the effort for the Norwegian conventional fleet, while data on effort for the Norwegian oceangoing fleet have been used to describe the effort for the Norwegian trawler fleet. This approach involves some inaccuracy because the Norwegian oceangoing fleet includes conventional oceangoing vessels, which is part of the Norwegian conventional fleet in the model. However, considering that the conventional oceangoing vessels make out a small proportion of the Norwegian fleet, it should not affect the results too much, and the approach should thus be appropriate.

Because of the lack of data, the effort levels for OC have been estimated based on the assumption that the effort applied by OC is proportional to the effort applied by Norwegian trawl relative to harvest measured in biomass. This rough estimation approach could result in some bias. However, considering that the main model does not include any economic details for the OC trawler fleet, it is not important for the results. The selectivity and fishing pressure of the OC trawler fleet is more important in that respect, and that is appropriately represented by the product of the catchability coefficients and effort levels.

The estimates obtained from solving the optimization problem in equation 10 are shown in figure 4.[1] An overview is also provided in table format in online appendix table A5. The latter also

1. The Norwegian trawlers' catchability coefficient for age group 11 has been calibrated because of an extreme outlier in the data (see online appendix table A1 and figure A13). Therefore, that catchability coefficient is calculated by taking the average of the estimates for the Norwegian trawler fleets' catchability coefficients for age groups 10 and 12.

includes corresponding R^2 values. Figure 5 shows the observed versus estimated catch per unit effort (CPUE) by fleet for age group 7, which is among the age groups that are most heavily targeted by the fishery. Figure 5 is included to further illustrate the nature of the estimation results obtained from the optimization model mentioned above. Equivalent figures for the remaining age groups can be found in online appendix figures A6–A15.

We note that the catchability coefficients are estimated based on few data points. Ideally, more data should have been included in the estimation, but our access has been limited to data in the interval 2011–15. Although the data points are mostly spread over wide harvest- and stock-size intervals, and although the overall results are in line with what should be expected based on the descriptions of the NEA cod migration pattern and operational areas of the fleets in the section "Northeast Arctic Cod Fishery," we cannot exclude risk of random error. Thus, these estimates should be considered uncertain.

We also note that there is a potential overestimation of the efficiency of the conventional fleet and a potential underestimation of the efficiency of the trawler fleets because we assume all fleets have simultaneous access to the stock. In the actual fishery, the Norwegian conventional fleet has exclusive access to the mature part of the stock during the first part of the year, while the trawler fleets gain access to the remaining part of the mature part of the stock once it migrates back to the Barents Sea. Thus, the trawler fleets get access to a smaller mature stock than the Norwegian conventional fleet. In other words, the trawler fleets may be somewhat more efficient than our model and estimation procedure suggests.

Moving on, fleet i's total harvest measured in biomass in period t ($y^B_{i,t}$) is modeled as the sum of fleet i's harvest measured in number of individuals from each age group a in period t ($y_{i,a,t}$) multiplied by the average weight of individuals in each age group a in period t ($W_{a,t}$):

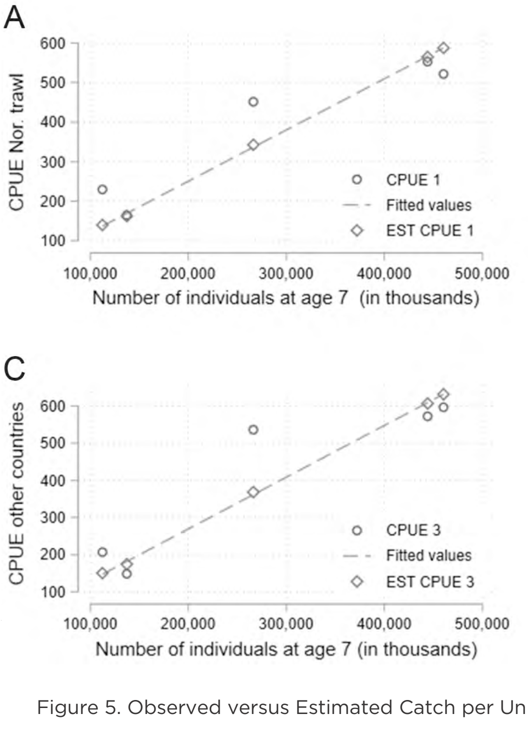

Figure 5. Observed versus Estimated Catch per Unit Effort by Fleet for Age Group 7

$$y^B_{i,t} = \sum_{a=3}^{13+} y_{i,a,t} W_{a,t}. \quad (11)$$

The total harvest measured in biomass for all fleets in period t (Y^B_t) is the sum of the total catch measured in biomass for each fleet in period t ($y^B_{i,t}$):

$$Y^B_t = \sum_{i=1}^{3} y^B_{i,t}. \quad (12)$$

REVENUE AND COSTS

The model has two revenue functions, one for the Norwegian conventional fleet and one for the Norwegian trawler fleet. The revenue for fleet i in period t ($I_{i,t}$) depends on how much fleet i harvests in period t ($y^B_{i,t}$) and the average price faced by the fleets in period t (P):

$$I_{i,t} = y^B_{i,t} P. \quad (13)$$

In many age-structured models, the prices are indexed by age because large fish tend to have a higher price per kilogram than small fish. Zimmermann, Heino, and Steinshamn (2011) show that positively size-dependent pricing shifts optimal harvesting strategies towards lower harvest rates and higher mean body size of caught fish. However, the reality of the prices and price dynamics in the NEA cod fishery is complex. Although the Norwegian trawler fleet harvests more small fish than large when compared with the Norwegian conventional fleet, the trawler fleet has experienced higher average prices per kilogram than the conventional fleet in several years (Norwegian Directorate of Fisheries 2009–18). This is likely explained by differences in the intrayearly seasonal fishing pattern, and the quality of the fish delivered and sold by the vessel groups. To keep focus on the effects of density-dependent natural mortality and weight, and avoid giving the Norwegian conventional fleet a potentially undue advantage, we assume both fleets face the same constant price $P = 14$ NOK/kg.

The model has two cost functions: one for Norwegian conventional vessels and one for Norwegian trawlers. The total costs for each fleet in period t ($TC_{i,t}$) depend on the number of vessels in operation in fleet i in period t, defined by the total number of operating days divided by the observed average number of operating days per vessel ($E_{i,t}$ / $E_{i,avg}$) and the average unit cost related to operating a vessel in fleet i (C^D_i). Further, it depends on the total effort applied by fleet i in period t in terms of operating days ($E_{i,t}$), the average unit cost tied to applying effort for fleet i (C^E_i), and the revenue for fleet i in period t ($I_{i,t}$), as well as the share of income that goes to paying the crew and fees (C^L_i):

$$TC_{i,t} = \frac{E_{i,t}}{E_{i,avg}} C^D_i + E_{i,t} C^E_i + I_{i,t} C^L_i. \quad (14)$$

The numerical specifications of the cost parameters in equation 14 are based on data from the Norwegian Directorate of Fisheries (2009–18) and the Norwegian Central Bank (to adjust for inflation). Data for the period 2009–16 have been used. Financial costs and regular taxes are excluded. Costs related to depreciation on vessels and permits are also excluded. The remaining costs, which include costs related to vessel and gear maintenance and regular operating expenses, are then adjusted for inflation and categorized according to the cost structure in the model. Since the fleets catch other species in conjunction with cod, all observed costs are multiplied by a factor equal to the fleets' observed share of revenue generated by the harvest of cod. These factors are calculated to an average of 0.322 for the Norwegian trawlers, and 0.677 for the Norwegian conventional vessels. In other words, we assume that about 32% of the observed trawler costs are tied to the harvest of cod. Similarly, we assume that about 68% of the observed conventional costs are tied to the harvest of cod. We make the reservation that this may be a source of inaccuracy, because it is possible that the fleets have some ability to change these proportions. However, we do not think the inaccuracy is very large. In addition, we consider changes in relative proportions to be more relevant in a multispecies setting than in a single-species setting.

C_i^D and C_i^E are estimated by taking the average of the costs occurring in each category mentioned above over the period 2009–16. C_i^L is specified as the average of the yearly percentage of total income used to pay crew and fees in fleet i. The parameter values applied are presented in online appendix table A16.

The profit for fleet i in period t ($\pi_{i,t}$) equals the revenue for fleet i in period t ($I_{i,t}$) less total costs ($TC_{i,t}$): $\pi_{i,t} = I_{i,t} - TC_{i,t}$. Total profit for the Norwegian part of the fishery in period t (π_t) is formulated as $\pi_t = \pi_{1,t} + \pi_{2,t}$. The NPV of the Norwegian part of the fishery is defined as the sum of discounted profits:

$$NPV = \sum_{t=0}^{T} \delta^t \pi_t. \tag{15}$$

The discount rate is set to 5%, which implies a discount factor (δ) of 0.9523, and the model is run for $T = 65$ years with a time step of 1 year.

SCENARIOS

We present a wide range of optimization scenarios to be solved in each of the four model versions: Endogenous M and W (baseline model version), Exogenous M, Exogenous W, and Exogenous M and W.

In all scenarios, we assume the existence of a managing authority that maximizes sustainable yield or the net present value of the Norwegian part of the fishery, with respect to effort of the participating fleets, subject to different constraints.

The control variables are restricted such that $E_{i,t} = E_{i,t+1}$ for all fleets $i = 1, 2, 3$ and all periods $t = 0, 1, \ldots, 65$ in all scenarios. These constraints enforce steady-state fishing schemes, which is what we will focus on. The constraints implied by the fish stock dynamics apply to all scenarios. Other constraints are scenario-specific and concern the distribution of the TAC in terms of shares. Since the model is deterministic and the managing authority determines the effort levels in the fishery, the managing authority indirectly decides the catch, which we will refer to as the TAC.

Table 1 gives an overview of the chosen optimization scenarios. Under scenarios 1–7, the objective is to maximize sustainable yield measured in biomass, and under scenarios 8–13, the objective is to maximize economic yield, or, in other words, net present value given the various constraints. "Optimal" means that the distribution of catch across fleets is not constrained, and "Today's" means that the actual rules and regulations in place today apply. "Forced alternative" means that an alternative distribution of the quota is forced. The specifications of the scenarios with forced alternative constraints will be presented in the results section.

Scenario 1 represents today's management. In this scenario, the objective is to maximize the sustainable yield with respect to effort. Meanwhile, the Norwegian share of the TAC is constrained to 45%, while the OC share is constrained to 55%. Finally, the Norwegian trawler fleet is constrained to receive 33.3% of the Norwegian share of the TAC, while the Norwegian conventional fleet is constrained to receive the remaining 66.6%. Overall, this implies that the OC trawler fleet gets 55% of the TAC, while the Norwegian trawler fleet and Norwegian conventional fleet get 15% and 30%, respectively.

Table 1. Overview of Maximum Sustainable Yield and Maximum Economic Yield Scenarios to Be Solved in Each of the Four Model Versions

			Constraints on the Distribution of the TAC	
Scenario	Objective	Control Variables	International TAC Distribution (Nor. share, OC share)	Norwegian TAC Distribution (Nor. trawl share, Nor. conventional share)
1	Max. sustainable yield	E_1, E_2, E_3	Today's (45%, 55%)	Today's (33.3%, 66.6%)
2				Optimal
3				Forced alternative
4			Optimal	Today's (33.3%, 66.6%)
5				Optimal
6				Forced alternative
7			Forced alternative	Forced alternative
8	Max. economic yield	E_1, E_2, E_3	Today's (45%, 55%)	Today's (33.3%, 66.6%)
9				Optimal
10				Forced alternative
11			Optimal	Today's (33.3%, 66.6%)
12				Optimal
13				Forced alternative

Scenario 2 is motivated by the ongoing Norwegian public debate regarding the trawl ladder, that is, the sharing rule in the Norwegian part of the fishery. In this scenario, the objective is to maximize the sustainable yield. As in scenario 1, the international distribution is constrained. However, now the managing authority is free to tweak the Norwegian distribution of the TAC. This optimization scenario may be of practical interest as the Norwegian authorities may be better positioned to tweak the trawl ladder in the Norwegian part of the fishery than the international distribution of the TAC.

We consider it interesting to identify whether the benefits of giving the Norwegian share of the TAC to one fleet instead of another is significant. This motivates scenario 3, which maximizes sustainable yield with a constraint that ensures the entire Norwegian share of the TAC is allocated to the least beneficial Norwegian fleet.

In scenarios 4–6, the managing authority maximizes sustainable yield without constraints on the international distribution of the TAC. However, in scenarios 4 and 6, the Norwegian distribution of the TAC is constrained in a similar manner to scenarios 1 and 3, respectively. In scenario 5, the managing authority maximizes sustainable yield without any constraints on the international and national distribution of the TAC. Scenario 7 forces allocation of the TAC to the least beneficial fleet. The motivation for these scenarios lies in our interest in comparing the fleets' selection patterns and their abilities to realize the growth and harvest potential of the fish stock.

In scenarios 8–13, the managing authority maximizes economic yield subject to similar constraints as in scenarios 1–6. The motivations for the various constrained scenarios are also similar to those regarding scenarios 1–6.

RESULTS

The model versions are set up in MS Excel. The Analytic Solver add-in (http://www.solver.com), created by Frontline Systems, developers of Solver in MS Excel, has been used to solve the optimization problems. This section presents the results from solving scenarios 1–13 in each of the four model versions: Endogenous M and W (baseline model version), Exogenous M, Exogenous W, and Exogenous M and W. First, we present a detailed overview of the results from the Endogenous M and W model version, scenario by scenario, with a particular focus on the possibilities of improvements in sustainable yield and economic yield in the NEA cod fishery through changes in the fleet composition and fishing pressure. Then, we provide an aggregated overview and comparison of the results from all model versions. Finally, we highlight key takeaways from detailed overviews of the results from the alternative model versions: Exogenous M, Exogenous W, and Exogenous M and W.

Before diving into the results, the reader should note that we make an essential distinction between “optimal” and “beneficial.” “Optimal” refers to the objective, while “beneficial” refers to whatever is specified, which could very well be the objective, but may also refer to what is beneficial in other terms given an overarching objective. The reason to make a clear distinction between “optimal” and “beneficial” is that the objective agreed upon internationally may differ from the objective of a nation. For example, it could be of international interest to design the target reference points and harvest control rule to maximize sustainable yield, while Norway as a nation could be interested in maximizing the NPV of the Norwegian part of the fishery subject to the international objective. As such, it is interesting to not only focus on what is optimal given an objective, but also add focus to what is beneficial given an overarching objective.

BASELINE MODEL VERSION

Table 2 gives a detailed overview of the results from the model with endogenous natural mortality and weight. The first things to note regarding the results include the following: (1) The model’s validity is confirmed, among other things, by noticing that the unconstrained scenarios 5 and 12 yield the highest annual catch and economic return, respectively. (2) The scenario that maximizes sustainable yield without constraints on the distribution of the TAC (scenario 5) also gives the highest annual profit among the MSY scenarios. (3) The scenario that gives the highest economic yield (scenario 12) is also the scenario that gives the highest yearly harvest among the MEY scenarios. (4) In every scenario where economic yield is maximized, the economic return is higher than in any scenario where sustainable yield is maximized. (5) All MEY scenarios involve higher spawning stock biomass than any MSY scenario.

Scenario 1 represents today’s management: the objective is set to maximize sustainable yield subject to today’s international and national distribution of the TAC, that is, settings that comply with today’s actual regulation. The model is then solved to find effort levels that generate the highest possible long-term sustainable yield. The estimated yearly harvest in steady state is in the range of MSY estimates provided by Kovalev and Bogstad (2005), and the fishery is profitable.

When the sustainable yield is maximized subject to today’s international distribution of the TAC, but without any constraints on the Norwegian distribution of the TAC (scenario 2), the model indicates that it is optimal to distribute the entire Norwegian share of the TAC to the Norwegian *conventional* fleet (*Fleet 2)*. Compared with today’s management (scenario 1), such a policy change increases the long-term sustainable yield by 16,000 tons per year—a significant increase considering that only 15% of the TAC is reallocated. However, the NPV is slightly reduced when compared with scenario 1, indicating that the Norwegian trawler fleet has a cost advantage that compensates for its more inefficient selection pattern relative to the Norwegian conventional fleet, at least to some extent.

Table 2. Maximum Sustainable Yield and Maximum Economic Yield Results (End. M and W)

		Constraints on the Distribution of the TAC		Economic Results	Biological Results					
Scenario	Objective	International TAC Distribution (Nor. share, OC share)	Norwegian TAC Distribution (Nor. trawl share, Nor. conv. share)	NPV (billion NOK)[a]	TAC (thousand tons)	SSB (thousand tons)	F_{SSB}	M_3	M_4	Weight Index[b]
1	Max. sustainable yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	19.7	680	1,532	0.44	0.332	0.254	0.97
2			Optimal (0%, 100%)	19.6	696	1,567	0.44	0.336	0.256	0.96
3			Nor. trawl (100%, 0%)	18.1	647	1,501	0.43	0.326	0.251	0.97
4		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	25.9*	757	2,087	0.36	0.367	0.273	0.93
5			Optimal (0%, 100%)	26*	781	2,209	0.35	0.376	0.278	0.92
6			Nor. trawl (100%, 0%)	24.2*	701	1,886	0.37	0.349	0.264	0.95
7		OC trawler fleet (0%, 100%)	–	–	590	1,283	0.46	0.310	0.243	0.99
8	Max. economic yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	30.2	618	2,782	0.22	0.375	0.277	0.92
9			Optimal (0%, 100%)	30.8	636	2,752	0.23	0.376	0.278	0.92
10			Nor. trawl (100%, 0%)	28.5	575	2,957	0.19	0.377	0.278	0.92
11		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	34.4*	699	3,305	0.21	0.407	0.295	0.89
12			Optimal (0%, 100%)	34.9*	724	3,401	0.21	0.415	0.299	0.88
13			Nor. trawl (100%, 0%)	32.4*	639	3,241	0.20	0.396	0.289	0.90

Note: [a] Results marked with an asterisk are calculated based on the assumption that Fleet 3 gets 55% of the yearly profits even when it does not participate (equivalent to the share of the TAC that it receives in today's management). This is enforced because the OC trawler fleet does not generate any revenue, costs, or profits within the model even when it participates (see description in the model section). Without the 55% assumption, the yearly profits and NPV would be much higher in cases where the OC trawler fleet does not participate compared with cases where it does participate, simply because the first involves allocating the entire TAC to one or two fleets that generate economic output in the model, while the second involves allocating a share of the TAC to a fleet that does not generate any economic output in the model. The 55% assumption makes all economic results directly comparable. [b] The weight index indicates the sum of weights at age for individuals of age 5–11 relative to the sum of observed average weights at age for individuals of age 5–11. An index value less than 1 indicates that steady-state weights at age are lower than the observed average weights, while an index value higher than 1 indicates that weights at age are higher than the observed average weights.

To highlight the ability of this fleet to realize the stock's growth and harvest potential when compared with the Norwegian conventional fleet, we maximize the sustainable yield subject to today's international distribution of the TAC and a constraint that requires the Norwegian share of the TAC to be distributed to the Norwegian trawler fleet (scenario 3). Comparison of the results from scenarios 2 and 3 clearly shows the Norwegian conventional fleet's advantage over the Norwegian trawler fleet in terms of a more efficient selection pattern. Allocating the entire Norwegian share of the TAC to the trawler fleet would result in 49,000 tons of lost harvest per year and a significant reduction in NPV when compared with the scenario where the whole Norwegian share of the TAC is given to the conventional fleet.

Comparison of NPV across scenarios 1–3 is interesting. Scenario 1 generates higher NPV than both scenarios 2 and 3. The comparison indicates that the Norwegian part of the fishery is well off in economic terms by using a mixed fleet composition, with a low trawl share and high conventional share, when the objective of the managing authority is to maximize sustainable yield and the international distribution of the TAC is rigid. In other words, today's Norwegian distribution of the TAC is economically rational when the target reference points and harvest control rule are designed to maximize sustainable yield, and the international distribution of the TAC is rigid.

When the sustainable yield is maximized without any constraints on the international distribution of the TAC, but with today's distribution of the Norwegian share of the TAC (scenario 4), the results show an increase in the yearly harvest of about 77,000 tons compared with today's management (scenario 1). The policy change is also associated with an increase in NPV of about NOK 6.2 billion. These results indicate that the use of the OC trawler fleet has significant negative bioeconomic impact on the Norwegian part of the fishery because of its inefficient selection pattern—it hurts not only the harvest of the fishery as a whole, but also the potential NPV of the Norwegian part of the fishery, at least under MSY regimes.

When the sustainable yield is maximized without any constraints on the distribution of the TAC, the results indicate that it is optimal to distribute the entire TAC to the Norwegian conventional fleet (scenario 5). The results suggest that such a policy change would increase yearly harvest by 101,000 tons compared with today's management (scenario 1). Moreover, the results indicate that the policy change would be associated with an increase in profits of about NOK 6.3 billion, slightly more than the increase seen in scenario 4 from scenario 1. The latter is interesting because it indicates that the Norwegian conventional fleet is in a better position to utilize its bioeconomic advantage in terms of a more efficient selection pattern when the OC trawler fleet does not participate. When the OC trawler fleet does not participate, harvest can be scaled up while sparing more young fish for future harvest, and this may explain why it is more economically beneficial to make use of the conventional fleet in scenario 5, as opposed to using a mixed fleet composition.

To further highlight the differences between the fleets' abilities to realize the growth and harvest potential of the stock, sustainable yield is maximized subject to constraints that require the entire TAC to be allocated to the Norwegian trawler fleet and the OC trawler fleet, respectively (scenarios 6 and 7). Comparison of the results from scenarios 4–7 further highlights that the Norwegian conventional fleet has the most efficient selection pattern. Moreover, they clearly show that the OC trawler fleet has a highly inefficient selection pattern compared with the other fleets.

When the objective is set to maximize economic yield subject to today's international and national distribution of the TAC, the model indicates that it is optimal to reduce the overall effort levels (scenario 8). This implies a reduction in the overall fishing pressure, resulting in higher stock numbers at age. The increase in stock numbers at age results in an increase in harvest per unit effort, which reduces costs per kilogram of harvest, and thus, profit per kilogram of harvest goes up. This positive effect on profits far outweighs the direct negative impact of reduced catch volume. Compared with scenario 1, the policy change gives rise to an increase in NPV of about NOK 10.5 billion.

When the economic yield is maximized subject to today's international distribution of the TAC, but without any constraints on the Norwegian distribution of the TAC, the results indicate that it is optimal to distribute the Norwegian share of the TAC to the Norwegian conventional fleet (*Fleet 2*) (scenario 9). To highlight the differences in economic yield when utilizing the Norwegian conventional fleet versus Norwegian trawler fleet (*Fleet 1*), economic yield is maximized subject to today's international distribution of the TAC, and a constraint that requires the Norwegian share of the TAC to be allocated to the Norwegian trawler fleet (*Fleet 1*) (scenario 10). Comparison of the results from scenarios 8–10 indicate that it is better to utilize the Norwegian conventional fleet compared with the trawler fleet when the objective is to maximize economic yield and the international distribution of the TAC is rigid.

When economic yield is maximized with no constraints on the international distribution of the TAC, but with today's distribution of the Norwegian share of the TAC (scenario 11), the results show an increase in NPV of about NOK 3.6 billion when compared with scenario 9. With no constraints on the distribution of the TAC, the results indicate that it is optimal to distribute the entire TAC to the Norwegian conventional fleet (scenario 12). The results suggest that the overall shadow cost of today's management (scenario 1) amounts to about NOK 15.2 billion. The unconstrained scenario 12 also yields 44,000 tons more harvest than today's management, and at the same time, the stock is maintained at a healthier level.

To investigate the differences between economic yield when utilizing the Norwegian conventional fleet and the Norwegian trawler fleet (*Fleet 2* vs. *Fleet 1*), economic yield is maximized subject to a constraint that requires the TAC to be allocated to the Norwegian trawler fleet (scenario 13). Comparison of scenarios 11–13 again highlights the positive bioeconomic advantage of the Norwegian conventional fleet in terms of a better selection pattern.

In summary, the baseline results confirm that the Northeast Arctic cod fishery can achieve a higher sustainable yield by altering today's fleet composition. Moreover, they indicate how the fishery can increase its net present value by simultaneously changing target reference points and altering the fleet composition.

ALTERNATIVE MODEL VERSIONS

Table 3 shows the average NPV, harvest, SSB, fishing mortality, natural mortality, and weight across all MSY and MEY scenarios in each of the four model versions: Endogenous M and W, Exogenous M, Exogenous W, and Exogenous M and W. The aggregated results clearly indicate that assumptions of exogenous natural mortality and weight can overestimate the biological and economic potential of the stock. Moreover, the results clearly show that optimal fishing mortality goes down when assuming exogenous natural mortality and weight, because without density-dependent natural mortality and weight, the benefits of fishing from a large stock, in terms of numbers, will be higher because of nonexistence of the negative effects associated with these key parameters.

When natural mortality rates of younger individuals are assumed constant (Exogenous M), an increase in the number of mature individuals will not affect the natural mortality rate of the younger individuals. In other words, one of the balancing feedback loops illustrated in figure 1 is

Table 3. Average SSB, Harvest, and NPV across All MSY and MEY Scenarios and All Four Model Versions

Weight			Natural Mortality: Endogenous	Natural Mortality: Exogenous [][a]
Weight	Endogenous	Average NPV (billion NOK)	27	34.4 [+27%]
		Average harvest (thousand tons)	672	730 [+8.5%]
		Average SSB (thousand tons)	2,346	3,162 [+35%]
		Average F_{SSB}	0.316	0.247 [–22%]
		Average natural mortality index[b]	1.179	1 [–15.2%]
		Average weight index[c]	0.932	0.91 [–2.1%]
	Exogenous [][a]	Average NPV (billion NOK)	33.2 [+23%]	41 [+51%]
		Average harvest (thousand tons)	718 [+6.7%]	805 [+20%]
		Average SSB (thousand tons)	2,658 [+13%]	3,410 [+45%]
		Average F_{SSB}	0.292 [–7.8%]	0.243 [–23%]
		Average natural mortality index[b]	1.194 [+1.3%]	1 [–15.2%]
		Average weight index[c]	1 [+7.3%]	1 [+7.3%]

Note: The four model versions are Endogenous Weight and Endogenous Natural Mortality; Endogenous Weight and Exogenous Natural Mortality; Exogenous Weight and Endogenous Natural Mortality; and Exogenous Weight and Exogenous Natural Mortality. [a] In square brackets: Percentage difference from the Endogenous, Endogenous results (upper left quadrant). [b] The natural mortality index is a measure of the modeled steady-state sum of natural mortality rates for age groups 3 and 4 relative to the observed average sum of natural mortality rates for age groups 3 and 4. A number higher than 1 indicates steady-state natural mortality rates higher than the observed average. [c] The weight index is a measure of the modeled steady-state sum of weight at age for age groups 5–11 relative to the observed average sum of weight at age for age groups 5–11. A number higher than 1 indicates steady-state weights at age higher than the observed average.

eliminated (stock number of individuals → natural mortality rate → natural deaths → stock number of individuals). Hence, the natural net growth of the stock will be higher for higher stock levels compared with the case where natural mortality and weight at age are endogenous (Endogenous M and W). This enables the modeled system to sustain a higher stock. These biological differences give rise to an increase in the potential sustainable yield and economic yield. The latter happens through an increase in harvest and a reduction in costs per kilogram harvested because of the characteristics of the harvest functions and the increased number of individuals in the age chain. However, weight at age is still considered endogenous in the Exogenous M case. This exists as a balancing effect that limits the stock's potential in biological and economic terms.

When weight at age is assumed constant (Exogenous W), an increase in the number of individuals in the stock will not affect the weight at age. In other words, the relationship between stock numbers at age and weight at age in figure 1 is absent. Hence, the stock biomass will grow to higher levels when compared with the case where both natural mortality and weight at age are considered endogenous. This leads to an increase in both potential sustainable yield and economic yield. However, natural mortality is endogenous in the Exogenous W case, limiting the stock's potential through the previously mentioned balancing feedback loop.

The total effects of treating both features exogenously (Exogenous W and M) on steady-state harvest and spawning stock biomass are higher than the additive effect of each isolated case. If both natural mortality and weight at age are assumed constant, both balancing effects are absent. The elimination of the balancing feedback loops and the balancing effect in figure 1 result in significant overestimation of biological and economic potential.

Online appendix tables A17–A19 give a detailed overview of the optimization results from the alternative model versions. Key things to note regarding these results include the following: (1) Assumptions of exogenous natural mortality and weight significantly affect optimal fishing mortality, harvest, SSB, and NPV in both MSY and MEY scenarios. (2) Assumptions of exogenous natural mortality and weight have greater implications for fishing mortality, SSB, and NPV in MSY scenarios than in MEY scenarios. (3) Assumptions of exogenous natural mortality and weight have bigger implications for harvest in MEY scenarios than in MSY scenarios. (4) As opposed to the baseline results, the scenario that maximizes sustainable yield without constraints on the distribution of the TAC (scenario 5) does not consistently give the highest annual profit among the MSY scenarios. (5) As opposed to the baseline results, the scenario that gives the highest economic yield (scenario 12) is not consistently the scenario that gives the highest yearly harvest among the MEY scenarios. (6) As opposed to the baseline results, the economic return in the MEY scenarios is no longer consistently higher than in any scenario where sustainable yield is maximized. (7) The optimal fleet composition is not entirely robust to changes in the assumptions regarding natural mortality and weight at age.

In summary, the above results show that assumptions of exogenous natural mortality and weight lead to significant *underestimation* of optimal fishing mortality, and significant *overestimation* of corresponding harvest, SSB, and NPV, in both MSY and MEY scenarios. The underestimation of optimal fishing mortality, and the corresponding overestimation of SSB and NPV, is more significant in MSY scenarios than in MEY scenarios, while the overestimation of harvest is more significant in MEY scenarios than in MSY scenarios. Moreover, the optimal fleet composition is not completely robust to changes in the assumptions regarding natural mortality and weight.

SENSITIVITY

The previous section gives insight into how various natural mortality and weight assumptions affect MSY and MEY results. However, the projections of alternative management scenarios also rely on other factors, and several of these are uncertain. Therefore, we test the sensitivity of our baseline results to changes in various factors, including the catchability coefficients, costs, price, and recruitment.

First, since we suspect that the estimated catchability coefficients may be somewhat biased to the advantage of the Norwegian conventional fleet (ref. discussion in the model section), we test the sensitivity of the baseline results to a 20% increase in the harvest efficiency of the trawler fleets for age groups 8–13+. A detailed overview of the results, scenario by scenario, with percentage differences from the baseline results, is found in online appendix table A20.

When the objective is to maximize sustainable yield, the optimal fleet structures remain robust to the changes in the catchability coefficients. In other words, the fleet structure that maximizes the sustainable yield does not change, indicating significant differences between the fleets' ability to realize the growth and harvest potential of the stock. However, under management where the harvest rule is designed to maximize the sustainable yield, the Norwegian trawler fleet turns out to be more profitable than the Norwegian conventional fleet despite its still existent disadvantage in terms of a more inefficient selection pattern. Also, it is important to mention that the OC trawler fleet still infers a negative bioeconomic impact on the harvest of the fishery as a whole and the NPV of the Norwegian part of the fishery because of its still inefficient selection pattern.

When the objective is to maximize economic yield, the Norwegian trawler fleet steps forward as an almost superior producer when the harvest efficiencies of the trawler fleets increase by 20%. The Norwegian trawler fleet is clearly the optimal fleet to use when the objective is to maximize economic yield and the international distribution of the TAC is rigid. However, it proves optimal to use a mixed fleet composition, with a high trawl share and a low conventional share, when the OC trawler fleet does not participate. The fact that the OC trawler fleet harms the Norwegian part of the fishery remains robust also in the MEY scenarios.

Second, we test the sensitivity of the baseline results to a 20% increase in all costs for all fleets. A detailed overview of these results is found in online appendix table A21. Naturally, the fishery becomes less profitable. Otherwise, the MSY results remain the same as in the baseline results, which makes sense since we are only considering a change in an economic parameter. Interestingly, the optimal fishing mortality goes down in the MEY scenarios. Because of higher costs, it becomes more important to make use of the benefit of an increased stock on catch per unit of effort, despite the associated effects on natural mortality and weight. The results regarding the fleet composition remain mostly robust to these changes in costs. The only exception is when the objective is to maximize economic yield and the OC trawler fleet does not participate. In that scenario it proves optimal to use a mixed fleet composition, with a high conventional share and low trawl share.

Third, we test the sensitivity of the baseline results to a 20% increase in price. A detailed overview of these results is found in online appendix table A22. Naturally, the fishery becomes more profitable in response to an increase in price. Otherwise, the MSY results are the same as in the baseline model version, which makes sense since we only consider a change in price, which does not matter to the objective of maximizing sustainable yield. Moving on, in all MEY scenarios, the optimal harvest goes up, while the associated SSB goes down. Consequently, natural mortality goes down, while weights at age go up. The results regarding the fleet composition remain entirely robust to the increase in price.

Lastly, we test the sensitivity of the baseline results to a 20% increase in recruitment for any SSB level. A detailed overview of these results is found in online appendix table A23. Naturally, an increase in recruitment leads to an increase in yield, SSB, and NPV in both MSY and MEY scenarios. Consequently, the associated natural mortality goes up, while the weight at age goes down. Otherwise, the optimal fleet composition remains robust to changes in recruitment in all scenarios.

CONCLUDING REMARKS

Most importantly, our results show that assumptions of exogenous natural mortality and weight lead to significant underestimation of optimal fishing mortality, and significant overestimation of corresponding harvest, SSB, and NPV, in both MSY and MEY scenarios. In other words, optimal fishing mortality decreases, and the corresponding harvest, SSB, and NPV increase, with the exogenous mortality and growth assumptions. The underestimation of optimal fishing mortality, and corresponding overestimation of SSB and NPV, is more significant in MSY scenarios than in MEY scenarios, while the overestimation of harvest is more significant in MEY scenarios than in MSY scenarios. Moreover, the optimal fleet composition is somewhat sensitive to the assumptions regarding natural mortality and weight. All this makes it clear why cannibalism mortality and weight at age should be considered endogenous in age-structured bioeconomic models for long-lived cannibalistic and commercial species, especially when interested in providing somewhat realistic bioeconomic estimates and proper management advice.

Otherwise, our results indicate that the Northeast Arctic cod fishery has the potential to increase sustainable yield and economic yield through changes in the fleet composition and fishing pressure. The results show that the fishery can achieve gains in terms of increased harvest by altering the selection pattern through changes in the fleet composition. The Norwegian conventional fleet has the most efficient selection pattern, while the Norwegian trawler fleet has the second-most efficient selection pattern, and the OC trawler fleet has the most inefficient selection pattern. Naturally, the sustainable yield can be increased by allocating more of the TAC to the fleets with the more efficient selection pattern. However, it seems unlikely that the OC fleet, which has the most inefficient selection pattern, is actually willing to give up its share of the TAC. Allocating more of the Norwegian share of the TAC to the Norwegian conventional fleet seems like the only realistic opportunity in this regard. Alternatively, or at the same time, one could encourage the OC fleet to change its selection pattern, for example by operating more actively farther west in the Barents Sea. Such changes could lead to an increase in sustainable harvest.

Furthermore, our results indicate that the fishery can achieve significant economic gains by reducing the overall fishing pressure and changing the fleet composition. The Norwegian conventional fleet has the most efficient selection pattern, which gives it a bioeconomic advantage. However, the Norwegian trawler fleet compensates for a more inefficient selection pattern with a cost advantage. The OC trawler fleet has the most inefficient selection pattern, and our results clearly indicate that the use of this fleet has a negative bioeconomic impact on the Norwegian part of the fishery. However, as already mentioned, it seems unlikely that the OC fleet will give up its share of the TAC. Thus, the only model-based and policy-relevant suggestion is to reduce the overall fishing pressure if interested in increasing economic yield, potentially combined with the previously mentioned suggestion to encourage alteration of the OC trawler fleets' selection pattern. At the same time, we have no basis to argue that the OC fleet would favor any of these changes.

At a national level, our analyses show that the economically most beneficial Norwegian fleet composition varies with circumstances. Although interesting, the baseline and sensitivity results indicate that it is not of great economic significance whether the Norwegian conventional fleet or Norwegian trawler fleet is being used. Our baseline results largely favor the Norwegian conventional fleet as the economically most beneficial producer. However, they also show that the Norwegian trawler fleet is not far behind. Furthermore, our discussion regarding the validity of the harvest functions and estimated catchability coefficients, along with the corresponding sensitivity tests, indicates that the Norwegian trawler fleet could potentially be the most beneficial fleet to use. Considering also that the fleets operate at different parts of the year, and that the fleets experience mixed catches, especially the trawler fleet, and that we do not consider the possible increasing marginal costs associated with changes in the fleet composition, it seems reasonable to argue that a mixed Norwegian fleet composition is perhaps the best option after all—not only when the TAC is set to maximize sustainable yield and the international distribution of the TAC is rigid (as suggested by our baseline model), but in general.

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APPENDIX

Table A1. IMR Catch at Age by Fleet Data

Catch number in thousands by age and fleet for 2015:

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1	10	20	4	34
2	210	270	159	639
3	930	840	2545	4315
4	4130	3090	24163	31383
5	2750	2150	36281	41181
6	5110	3240	42859	51209
7	3440	3670	26635	33745
8	2660	3440	16430	22530
9	1460	7240	14909	23609
10	4810	12290	7453	24553
11	7010	7140	1921	16071
12	830	1220	460	2510
13		420	48	468
14	20	110	4	134
15+	30	210	14	254

Catch number in thousands by age and fleet for 2014

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1	10		7	17
2	300	30	294	624
3	1090	560	3584	5234
4	3220	1360	14646	19226
5	5400	2090	30917	38407
6	2500	2600	31533	36633
7	4120	2490	23291	29901
8	7980	12150	35979	56109
9	5430	17080	25030	47540
10	4920	10800	7018	22738
11	440	2120	1157	3717
12	90	740	339	1169
13	190	80	43	313
14		210	0	210
15+	20	130	7	157

Catch number in thousands by age and fleet for 2013:

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1		0	1	1
2		10	228	238
3	490	170	2243	2903
4	3370	770	9519	13659
5	4130	1920	16702	22752
6	3560	1850	15610	21020
7	8990	6470	38771	54231
8	10240	16580	47631	74451
9	11400	17700	18024	47124
10	900	4460	3783	9143
11	240	1690	1033	2963
12	20	380	294	694
13	40	310	99	449
14		60	29	89
15+	90	50	5	145

Catch number in thousands by age and fleet for 2012:

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1			44	44
2			167	167
3	410	230	2055	2695
4	1800	670	7992	10462
5	3330	940	12376	16646
6	6300	3790	30282	40372
7	10610	10620	48784	70014
8	7990	13650	26675	48315
9	1540	5800	4986	12326
10	320	3250	1644	5214
11		1210	716	1926
12	10	750	364	1124
13	30	200	87	317
14	10	40	20	70
15+		20	4	24

Catch number in thousands by age and fleet for 2011:

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1	14	14	10	38
2	216	45	172	433
3	201	234	983	1418
4	2601	1334	4100	8035
5	5571	3600	23304	32475
6	11248	8539	51158	70945
7	13110	12653	48127	73890
8	2228	7401	11507	21136
9	1722	6314	3683	11719
10	1088	2684	1292	5064
11	876	1531	832	3239
12	10	370	220	600
13	120	249	65	434
14				12
15+				

Table A2. Numerical Specification of the Maturity Parameters

Parameter	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13+
k_a	0	0.003	0.050	0.274	0.578	0.810	0.937	0.985	0.995	0.997	1

Table A3. Numerical Specification of Natural Mortality Parameters for Age Class 3 and 4

Age group	α_a^M	α_a^M: p > |t|	β_a^M	β_a^M: p > |t|	R^2
3	.2369	0.000	2.86e-07	0.002	0.253
4	.2030	0.000	1.54e-07	0.000	0.445

Table A4. Numerical Specification of Parameters in the Weight at Age Functions

Age group	α_a^W	α_a^W: p > |t|	β_a^W	β_a^W: p > |t|	R^2
5	1.372	0.000	-4.77e-07	0.052	0.110
6	2.299	0.000	-7.64e-07	0.012	0.176
7	3.526	0.000	-1.26e-06	0.001	0.276
8	5.043	0.000	-1.61e-06	0.002	0.255
9	6.915	0.000	-1.82e-06	0.019	0.156
10	9.371	0.000	-2.59e-06	0.045	0.116
11	11.111	0.000	-2.29e-06	0.116	0.058

Table A5. Numerical Specification of the Catchability Coefficients in the Harvest Functions ($q_{1,a}$, $q_{2,a}$, $q_{3,a}$) and Corresponding Coefficients of Determination for Each Fleet and the Fishery as a Whole

Parameter	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13+
$q_{1,a}$	6.56E-08	4.81E-07	7.58E-07	1.01E-06	1.55E-06	2.07E-06	2.81E-06	3.4E-06	3.34E-06	3.28E-06	1.23E-06
$q_{2,a}$	4.22E-09	2.41E-08	4.56E-08	8.42E-08	1.62E-07	3.64E-07	6.21E-07	8.32E-07	1.23E-06	8.93E-07	5.6E-07
$q_{3,a}$	4.92E-08	3.45E-07	8.71E-07	1.34E-06	1.66E-06	2.09E-06	1.42E-06	6.87E-07	4.45E-07	5.23E-07	1.04E-07
R^2_1	-0.12	0.60	-0.52	0.90	0.87	0.80	0.55	0.89	0.50	0.41	-0.60
R^2_2	-0.21	0.29	0.89	0.94	0.95	0.94	0.79	0.96	0.98	0.91	0.78
R^2_3	0.76	0.98	0.76	0.83	0.60	0.76	0.78	0.56	0.75	-2.55	-3.88
R^2_{total}	0.57	0.96	0.74	0.83	0.66	0.78	0.75	0.85	0.73	0.55	0.51

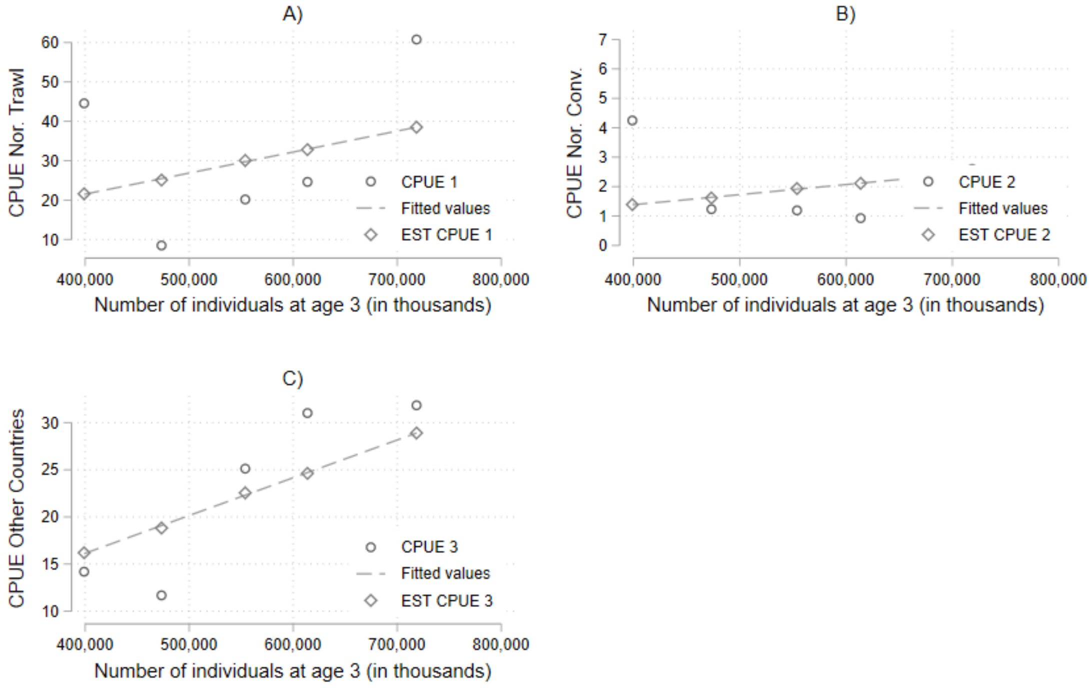

Figure A6. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 3

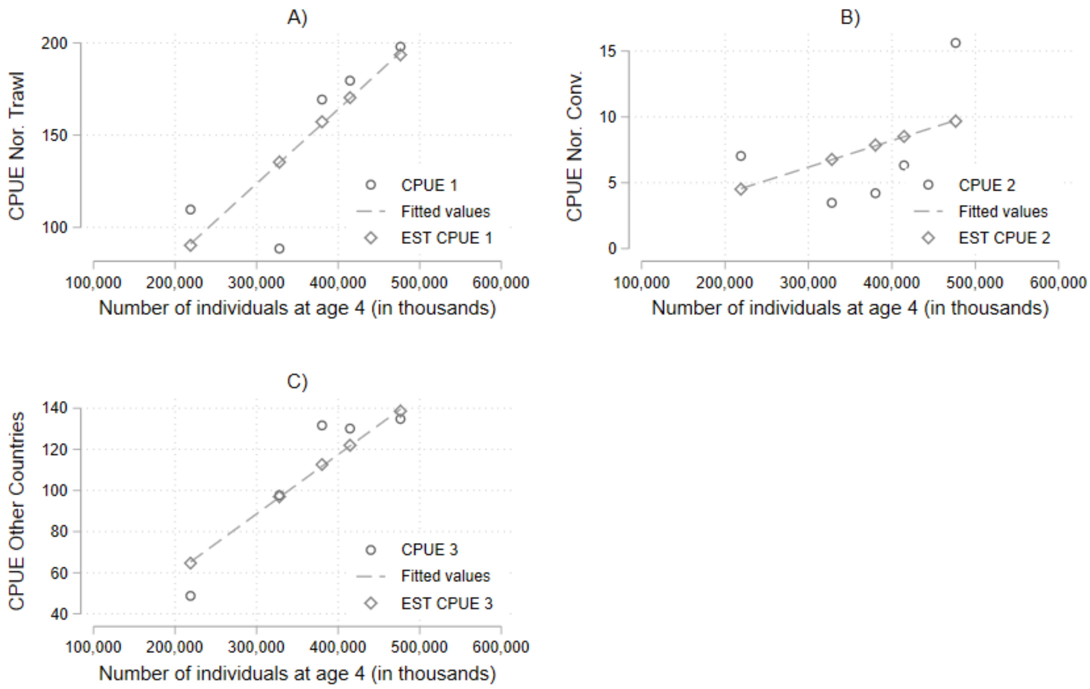

Figure A7. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 4

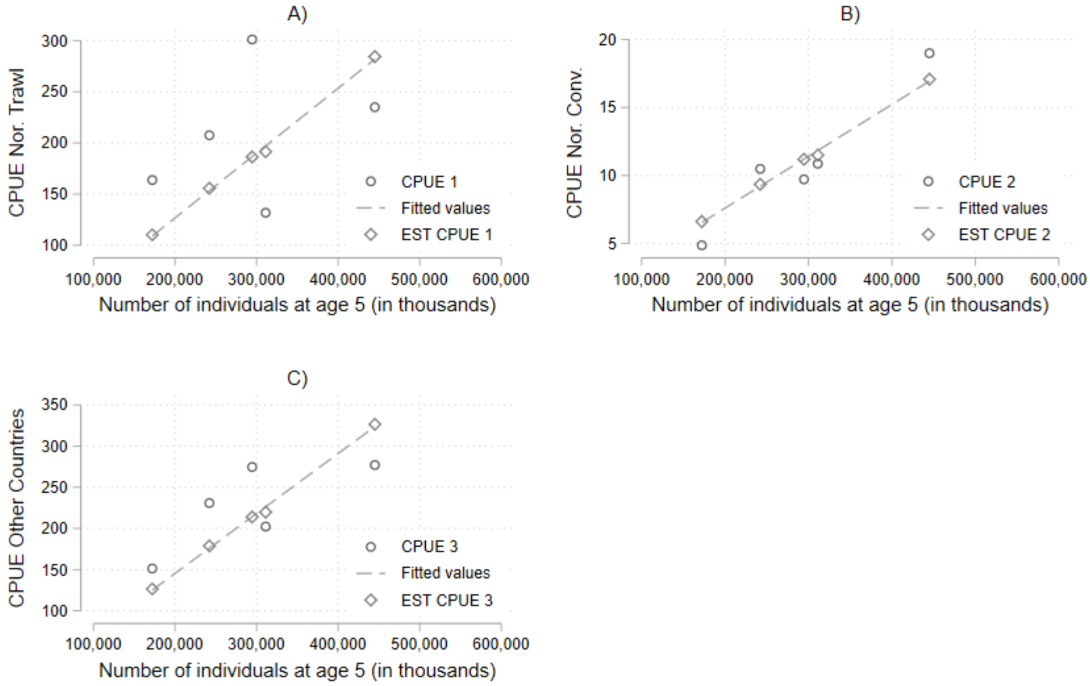

Figure A8. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 5

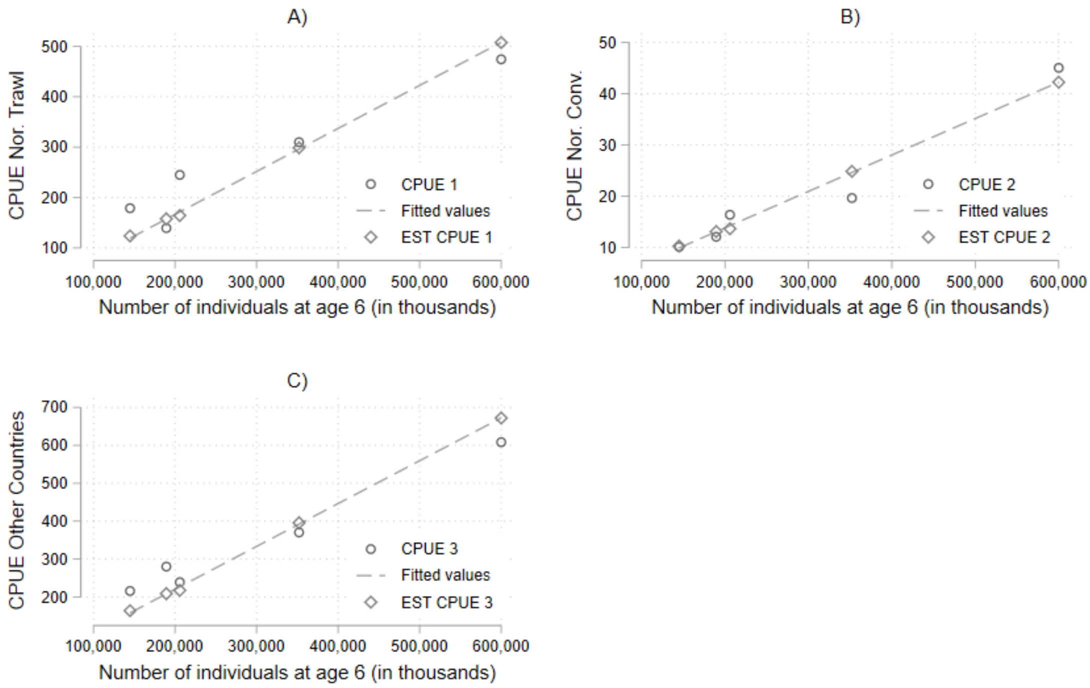

Figure A9. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 6

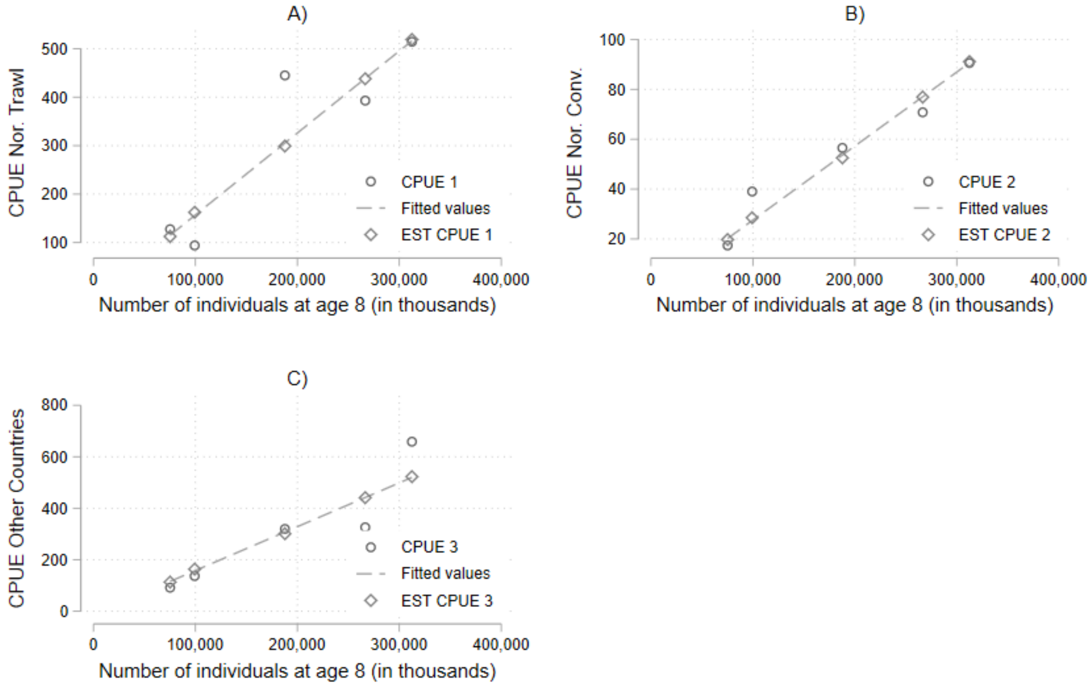

Figure A10. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 8

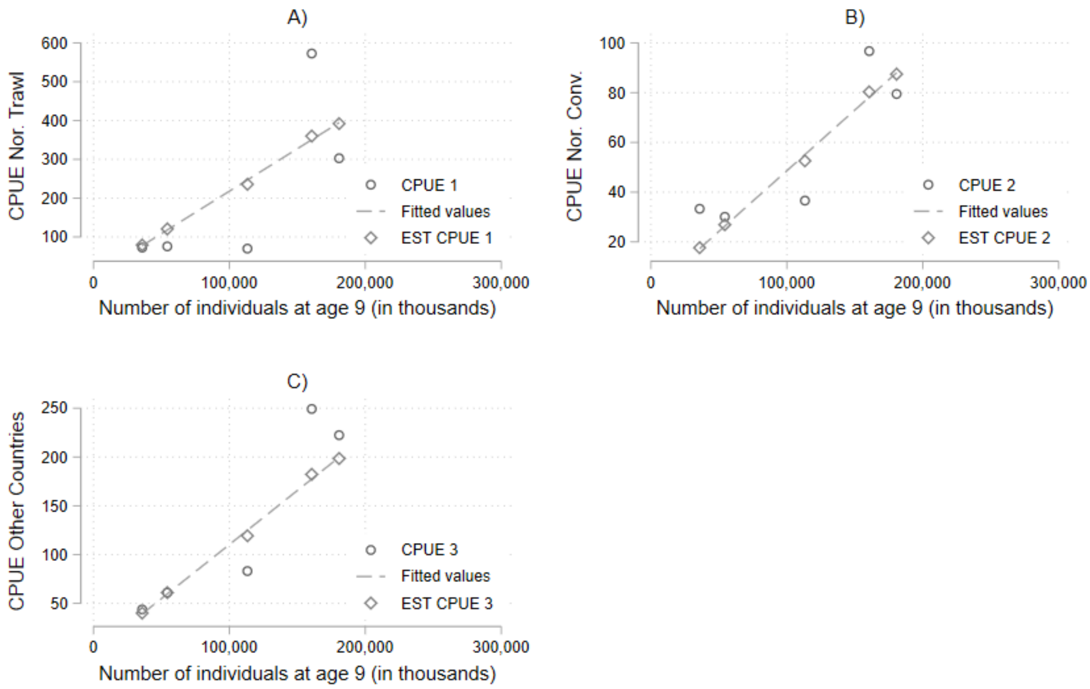

Figure A11. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 9

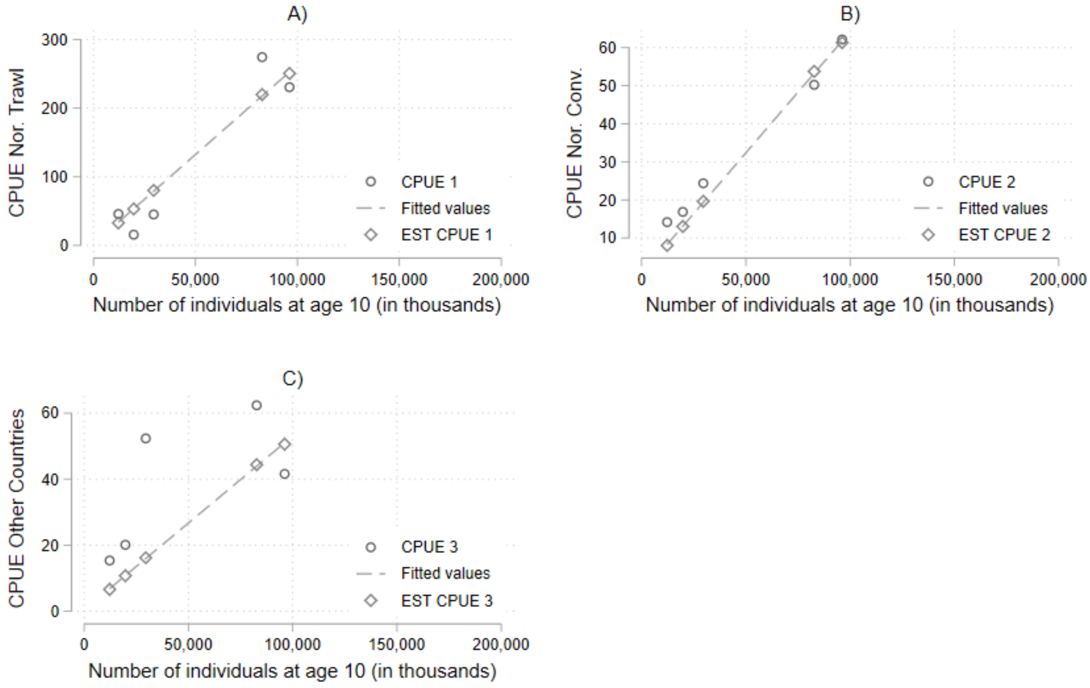

Figure A12. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 10

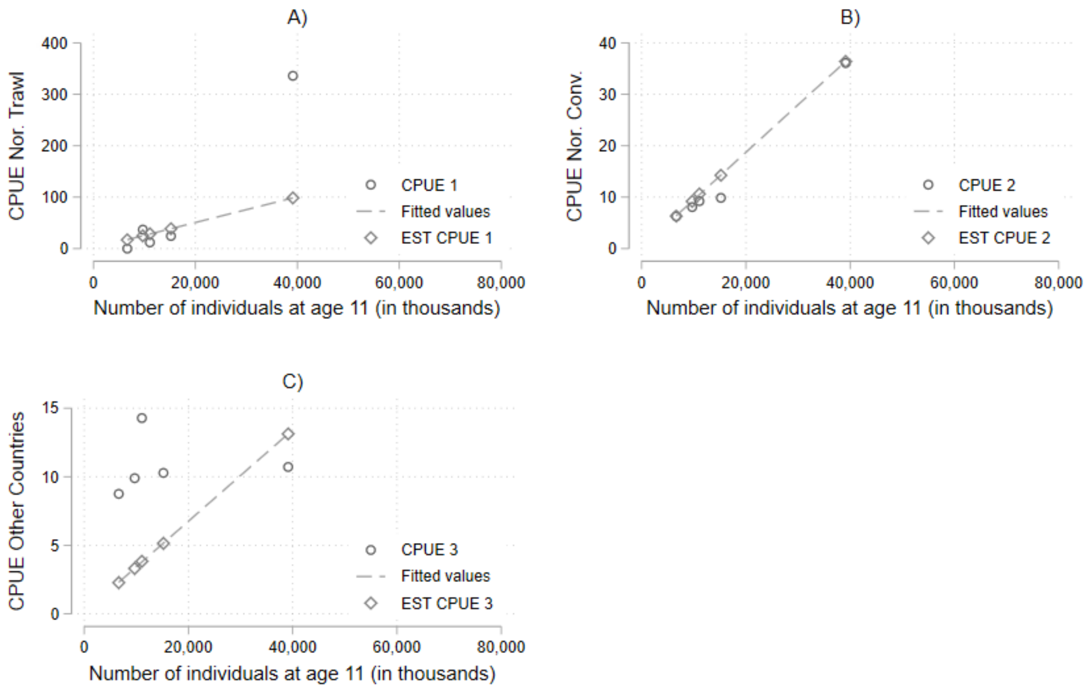

Figure A13. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 11

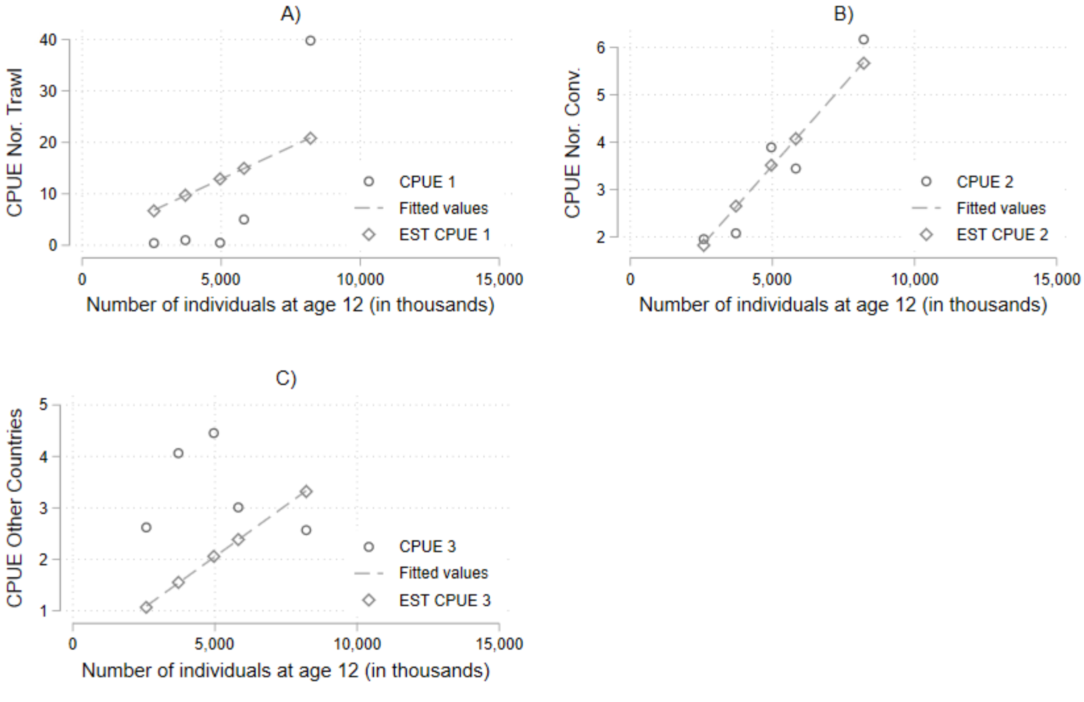

Figure A14. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 12

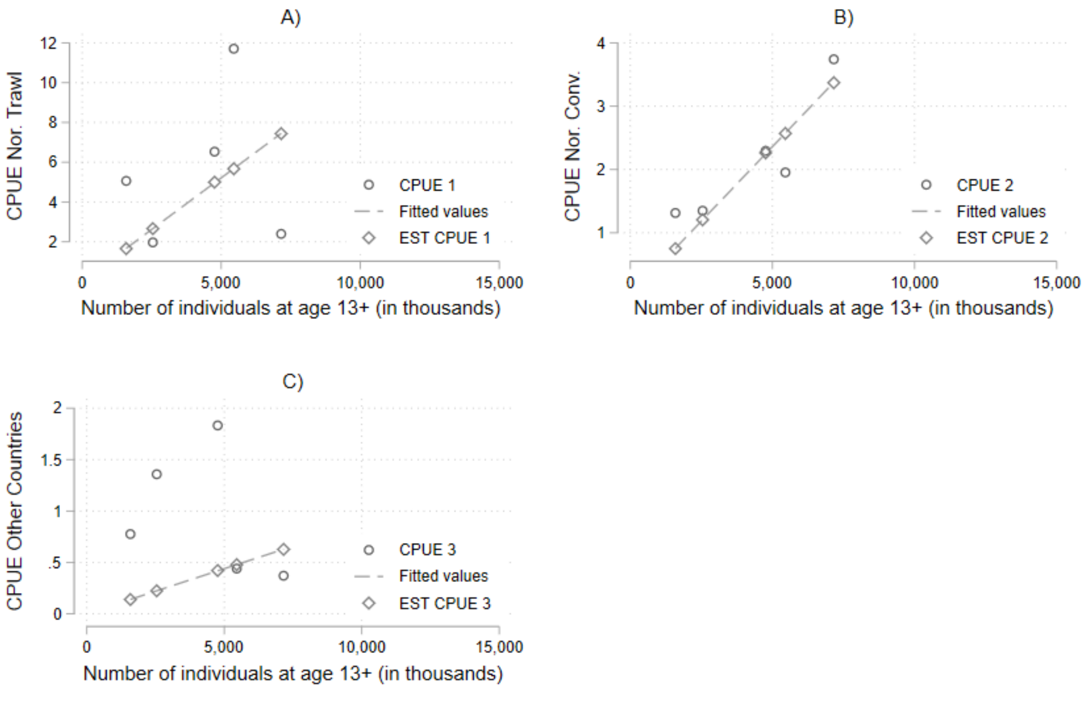

Figure A15. Observed vs. Estimated Catch per Unit Effort by Fleet for Age Group 13

Table A16. Numerical Specification of the Parameters in the Cost Functions

Parameter	Parameter value
C_1^D	4 696 213 NOK
C_2^D	528 189 NOK
C_1^E	12 473 NOK
C_2^E	1118 NOK
C_1^L	0.354
C_2^L	0.46
$E_{1, avg}$	305
$E_{2, avg}$	155

Table A17. Maximum Sustainable Yield and Maximum Economic Yield Results (Exo. M)

Scenario	Objective	Constraints on the Distribution of the TAC: International TAC Distribution (Nor. share, OC share)	Constraints on the Distribution of the TAC: Norwegian TAC distribution (Nor Trawl share, Nor Conv. share)	Economic Results: NPV (Billion NOK)[2]	Biological Results: TAC (Thousand tons)	Biological Results: SSB (Thousand tons)	Biological Results: F_{SSB}	Biological Results: Weight Index[1]
1	Max. Sustainable Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	30 [+52%]	704 [+3.5%]	2149 [+40%]	0.33 [-25%]	0.93 [-4.12%]
2			Optimal (0%, 100%)	30.6 [+56%]	724 [+4%]	2174 [+39%]	0.33 [-25%]	0.93 [-3.1%]
3			Nor Trawl (100%, 0%)	28 [+55%]	663 [+2.5%]	2149 [+43%]	0.31 [-28%]	0.93 [-4.1%]
4		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	36.2* [+40%]	848 [+12%]	3091 [+48%]	0.27 [-25%]	0.91 [-2.2%]
5			Optimal (0%, 100%)	35.7* [+37%]	894 [+14.5%]	3267 [+48%]	0.27 [-23%]	0.9 [-2.2%]
6			Nor Trawl (100%, 0%)	36* [+49%]	759 [+8.3%]	2836 [+50%]	0.27 [-27%]	0.91 [-4%]
7		OC Trawler Fleet (0%, 100%)	-	-	584 [-1%]	1781 [+38%]	0.33 [-28%]	0.95 [-4%]
8	Max. Economic Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	32.2 [+6%]	664 [+7.4%]	3613 [+30%]	0.18 [-18%]	0.91 [-1%]
9			Optimal (100%, 0%) [NEW]	33.1 [+7%]	625 [-1.7%]	3676 [+34%]	0.17 [-26%]	0.91 [-1%]
10			Nor Conv (0%, 100%) [NEW]	31.6 [+11%]	683 [+18.8%]	3630 [+23%]	0.19 [+0%]	0.91 [-1%]
11		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	39.9* [+16%]	800 [+14.4%]	4292 [+30%]	0.19 [-9.5%]	0.89 [+0%]
12			Optimal (38%, 62%) [NEW]	39.9* [+14%]	809 [+11.7%]	4324 [+27%]	0.19 [-9.5%]	0.89 [+1%]
13			Nor Trawl (100%, 0%)	39.4* [+22%]	729 [+14.1%]	4129 [+27%]	0.18 [-10%]	0.9 [+0%]

[1] The Weight Index indicates the sum of weights at age for individuals of age 5-11 relative to the sum of observed average weights at age for individuals of age 5-11. An index value less than 1 indicates that steady state weights at age are lower than the observed average weights, while an index value higher than 1 indicates that weights at age are higher than the observed average weights.

*[2] Results marked with ' * ' are calculated based on the assumption that Fleet 3 gets 55% of the yearly profits even when it does not participate (equivalent to the share of the TAC that it receives in today's management). This is enforced because the OC Trawler Fleet does not generate any revenue, costs, nor profits within the model even when it participates (see description in the model section). Without the 55%-assumption, the yearly profits and NPV would be much higher in cases where the OC Trawler Fleet does not participate compared to cases where it participates simply because the first involves allocating the entire TAC to one or two fleets that generate economic output in the model, while the second involves allocating a share of the TAC to a fleet that does not generate any economic output in the model. The 55%-assumption makes all economic results directly comparable.*

Table A18. Maximum Sustainable Yield and Maximum Economic Yield Results (Exo. W)

Scenario	Objective	Constraints on the Distribution of the TAC: International TAC Distribution (Nor. share, OC share)	Constraints on the Distribution of the TAC: Norwegian TAC distribution (Nor Trawl share, Nor Conv. share)	Economic Results: NPV (Billion NOK)[1]	Biological Results: TAC (Thousand tons)	Biological Results: SSB (Thousand tons)	Biological Results: F_{SSB}	Biological Results: M_3	Biological Results: M_4
1	Max. Sustainable Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	27.7 [+41%]	708 [+4.1%]	1833 [+20%]	0.39 [-11%]	0.340 [+2.4%]	0.259 [+2%]
2			Optimal (0%, 100%)	27.4 [+40%]	727 [+4.5%]	1861 [+19%]	0.39 [-11%]	0.343 [+2.1%]	0.261 [+2%]
3			Nor Trawl (100%, 0%)	25.5 [+41%]	670 [+3.6%]	1822 [+21%]	0.37 [-14%]	0.336 [+3.1%]	0.257 [+2.4%]
4		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	33.8* [+31%]	814 [+7.3%]	2471 [+18%]	0.33 [-8%]	0.375 [+2.2%]	0.277 [+1.5%]
5			Optimal (0%, 100%)	33.9* [+30%]	848 [+8.6%]	2603 [+18%]	0.33 [-5.7%]	0.383 [1.9%]	0.282 [+1.4%]
6			Nor Trawl (100%, 0%)	31.8* [+31%]	742 [+5.8%]	2267 [+20%]	0.33 [-11%]	0.360 [+3.2%]	0.269 [+1.9%]
7		OC Trawler Fleet (0%, 100%)	-	-	600 [+1.7%]	1582 [+23%]	0.38 [-17%]	0.32 [+3.2%]	0.25 [+2.9%]
8	Max. Economic Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	33.97 [+12%]	663 [+7.3%]	3033 [+9%]	0.22 [+0%]	0.377 [+0.5%]	0.279 [+0.7%]
9			Optimal (0%, 100%)	34.4 [+12%]	684 [+7.5%]	2994 [+9%]	0.23 [+0%]	0.378 [+0.5%]	0.279 [+0.4%]
10			Nor Trawl (100%, 0%)	32.7 [+15%]	616 [+7.1%]	3228 [+9%]	0.19 [+0%]	0.380 [+0.8%]	0.280 [+0.7%]
11		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	39.5* [+15%]	768 [+9.9%]	3611 [+9%]	0.21 [+0%]	0.407 [+0%]	0.295 [+0%]
12			Optimal (0%, 100%)	40* [+15%]	801 [+10.6%]	3722 [+9%]	0.22 [+4.7%]	0.414 [-0.2%]	0.299 [+0%]
13			Nor Trawl (100%, 0%)	37.6* [+16%]	694 [+8.6%]	3538 [+9%]	0.2 [+0%]	0.398 [+0.5%]	0.290 [+0.3%]

*[1] Results marked with ' * ' are calculated based on the assumption that Fleet 3 gets 55% of the yearly profits even when it does not participate (equivalent to the share of the TAC that it receives in today's management). This is enforced because the OC Trawler Fleet does not generate any revenue, costs, nor profits within the model even when it participates (see description in the model section). Without the 55%-assumption, the yearly profits and NPV would be much higher in cases where the OC Trawler Fleet does not participate compared to cases where it participates simply because the first involves allocating the entire TAC to one or two fleets that generate economic output in the model, while the second involves allocating a share of the TAC to a fleet that does not generate any economic output in the model. The 55%-assumption makes all economic results directly comparable.*

Table A19. Maximum Sustainable Yield and Maximum Economic Yield Results (Exo. M and W)

Scenario	Objective	Constraints on the Distribution of the TAC		Economic Results	Biological Results		
		International TAC Distribution (Nor. share, OC share)	Norwegian TAC distribution (Nor Trawl share, Nor Conv. share)	NPV (Billion NOK)[1]	TAC (Thousand tons)	SSB (Thousand tons)	F_{SSB}
1	Max. Sustainable Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	35.8 [+82%]	763 [+12%]	2508 [+64%]	0.3 [-32%]
2			Optimal (0%, 100%)	36.1 [+84%]	787 [+13%]	2515 [+60%]	0.31 [-30%]
3			Nor Trawl (100%, 0%)	34.5 [+90%]	717 [+11%]	2543 [+69%]	0.28 [-35%]
4		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	44.5* [+72%]	926 [+22%]	3390 [+62%]	0.27 [-25%]
5			Optimal (0%, 100%)	45* [+73%]	977 [+25%]	3558 [+61%]	0.27 [-23%]
6			Nor Trawl (100%, 0%)	42* [74%]	825 [+17%]	3166 [+68%]	0.26 [-30%]
7		OC Trawler Fleet (0%, 100%)	-	-	627 [+6%]	2254 [+76%]	0.28 [-39%]
8	Max. Economic Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	38.7 [+28%]	741 [+20%]	3618 [+30%]	0.2 [-9.1%]
9			Optimal (0%, 100%)	38.9 [+26%]	766 [+20%]	3544 [+29%]	0.22 [-4.3%]
10			Nor Trawl (100%, 0%)	38 [+33%]	688 [+20%]	3897 [+32%]	0.18 [-5.3%]
11		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	47* [+36%]	902 [+29%]	4426 [+34%]	0.2 [-4.8%]
12			Optimal (0%, 100%)	47.6* [+36%]	953 [+31%]	4567 [+34%]	0.21 [+0%]
13			Nor Trawl (100%, 0%)	44.7* [+38%]	800 [+25%]	4348 [+34%]	0.18 [-10%]

*[1] Results marked with ' * ' are calculated based on the assumption that Fleet 3 gets 55% of the yearly profits even when it does not participate (equivalent to the share of the TAC that it receives in today's management). This is enforced because the OC Trawler Fleet does not generate any revenue, costs, nor profits within the model even when it participates (see description in the model section). Without the 55%-assumption, the yearly profits and NPV would be much higher in cases where the OC Trawler Fleet does not participate compared to cases where it participates simply because the first involves allocating the entire TAC to one or two fleets that generate economic output in the model, while the second involves allocating a share of the TAC to a fleet that does not generate any economic output in the model. The 55%-assumption makes all economic results directly comparable.*

Table A20. Maximum Sustainable Yield and Maximum Economic Yield Results (End. M and W with 20% Increase in the Harvest Efficiency of the Trawler Fleets for Age Groups 8-13+)

		Constraints on the Distribution of the TAC		Economic Results	Biological Results					
Scenario	Objective	International TAC Distribution (Nor. share, OC share)	Norwegian TAC distribution (Nor Trawl share, Nor Conv. share)	NPV (Billion NOK)[2]	TAC (Thousand tons)	SSB (Thousand tons)	F_{SSB}	M_3	M_4	Weight Index[1]
1			Today's (33.3%, 66.6%)	21.7 [+10.1%]	689 [+1.3%]	1564 [+2.1%]	0.44 [+0.2%]	0.335 [+0.9%]	0.256 [+0.8%]	0.97 [-0.5%]
2		Today's (45%, 55%)	Optimal (0%, 100%)	19.7 [+0.7%]	702 [+0.9%]	1597 [+1.9%]	0.44 [+0%]	0.338 [+0.6%]	0.258 [+0.7%]	0.96 [+0.2%]
3			Nor Trawl (100%, 0%)	24.2 [+33.6%]	661 [+2.1%]	1526 [+1.6%]	0.43 [0.7%]	0.329 [1.1%]	0.253 [+0.8%]	0.97 [+0.1%]
4	Max. Sustainable Yield		Today's (33.3%, 66.6%)	27.7* [+6.9%]	761 [+0.5%]	2102 [+0.7%]	0.36 [0.5%]	0.368 [0.3%]	0.274 [+0.3%]	0.93 [+0.2%]
5		Optimal (100%, 0%)	Optimal (0%, 100%)	26.0* [+0%]	781 [+0%]	2209 [+0%]	0.35 [+0%]	0.376 [+0%]	0.278 [+0%]	0.92 [+0%]
6			Nor Trawl (100%, 0%)	29.7* [+22.6%]	714 [+1.8%]	1914 [+1.5%]	0.37 [+0.8%]	0.353 [1.1%]	0.266 [+0.6%]	0.95 [-0.3%]
7		OC Trawler Fleet (0%, 100%)	-	-	603 [+2.2%]	1301 [+1.4%]	0.46 [+0.8%]	0.313 [+1%]	0.244 [+0.5%]	0.99 [-0.3%]
8			Today's (33.3%, 66.6%)	31.6 [+4.7%]	631 [+2.2%]	2754 [-1%]	0.23 [+4.2%]	0.376 [+0.2%]	0.278 [+0.3%]	0.92 [+0.4%]
9		Today's (45%, 55%)	Optimal (100%, 0%) [NEW]	32.4 [+5.1%]	605 [-4.9%]	2753 [+0%]	0.22 [-4.5%]	0.372 [-0.9%]	0.276 [-0.6%]	0.93 [+0.8%]
10			Nor Conv. (100%, 0%) [NEW]	31.0 [+8.7%]	642 [+11.7%]	2789 [-5.7%]	0.23 [+21.1%]	0.378 [+0.4%]	0.279 [+0.5%]	0.92 [+0.1%]
11	Max. Economic Yield		Today's (33.3%, 66.6%)	35.7* [+3.7%]	707 [+1.2%]	3267 [-1.2%]	0.22 [+3.1%]	0.407 [+0%]	0.295 [+0%]	0.89 [+0.2%]
12		Optimal (100%, 0%)	Optimal (95.5%, 4.5%) [NEW]	36.2* [+3.9%]	668 [-7.7%]	3081 [-9.4%]	0.22 [+3.2%]	0.394 [-5%]	0.288 [-3.7%]	0.90 [+2.8%]
13			Nor Conv (100%, 0%) [NEW]	34.9* [+7.7%]	724 [+13.4%]	3401 [+4.9%]	0.21 [+6.5%]	0.415 [+4.8%]	0.299 [+3.7%]	0.88 [-1.8%]

[1] The Weight Index indicates the sum of weights at age for individuals of age 5-11 relative to the sum of observed average weights at age for individuals of age 5-11. An index value less than 1 indicates that steady state weights at age are lower than the observed average weights, while an index value higher than 1 indicates that weights at age are higher than the observed average weights.

*[2] Results marked with ' * ' are calculated based on the assumption that Fleet 3 gets 55% of the yearly profits even when it does not participate (equivalent to the share of the TAC that it receives in today's management). This is enforced because the OC Trawler Fleet does not generate any revenue, costs, nor profits within the model even when it participates (see description in the model section). Without the 55%-assumption, the yearly profits and NPV would be much higher in cases where the OC Trawler Fleet does not participate compared to cases where it participates simply because the first involves allocating the entire TAC to one or two fleets that generate economic output in the model, while the second involves allocating a share of the TAC to a fleet that does not generate any economic output in the model. The 55%-assumption makes all economic results directly comparable.*

Table A21. Maximum Sustainable Yield and Maximum Economic Yield Results (End. M and W with 20% Increase in all Costs)

Scenario	Objective	Constraints on the Distribution of the TAC		Economic Results	Biological Results					
		International TAC Distribution (Nor. share, OC share)	Norwegian TAC distribution (Nor Trawl share, Nor Conv. share)	NPV (Billion NOK)[2]	TAC (Thousand tons)	SSB (Thousand tons)	F_{SSB}	M_3	M_4	Weight Index[1]
1	Max. Sustainable Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	1.8 [-90.8%]	680 [+0%]	1532 [+0%]	0.44 [+0%]	0.332 [+0%]	0.254 [+0%]	0.97 [+0%]
2			Optimal (0%, 100%)	1.1 [-94.6%]	696 [+0%]	1567 [+0%]	0.44 [+0%]	0.336 [+0%]	0.256 [+0%]	0.96 [+0%]
3			Nor Trawl (100%, 0%)	1.7 [-90.4%]	647 [+0%]	1501 [+0%]	0.43 [+0%]	0.326 [+0%]	0.251 [+0%]	0.97 [+0%]
4		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	9.9* [-61.7%]	757 [+0%]	2087 [+0%]	0.36 [+0%]	0.367 [+0%]	0.273 [+0%]	0.93 [+0%]
5			Optimal (0%, 100%)	9.4* [-63.7%]	781 [+0%]	2209 [+0%]	0.35 [+0%]	0.376 [+0%]	0.278 [+0%]	0.92 [+0%]
6			Nor Trawl (100%, 0%)	9.2* [-62%]	701 [+0%]	1886 [+0%]	0.37 [+0%]	0.349 [+0%]	0.264 [+0%]	0.95 [+0%]
7		OC Trawler Fleet (0%, 100%)	-		590 [+0%]	1283 [+0%]	0.46 [+0%]	0.310 [+0%]	0.243 [+0%]	0.99 [+0%]
8	Max. Economic Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	19.9 [-34.3%]	566 [-8.3%]	3370 [+21.1%]	0.17 [-23.6%]	0.392 [+4.6%]	0.287 [+3.6%]	0.91 [-1.4%]
9			Optimal (0%, 100%)	20.0 [-35.2%]	586 [-7.9%]	3313 [+20.4%]	0.18 [-23.1%]	0.392 [+4.6%]	0.287 [+3.6%]	0.91 [-1.4%]
10			Nor Trawl (100%, 0%)	19.4 [-31.9%]	522 [-9.1%]	3561 [+20.4%]	0.15 [-22.8%]	0.395 [+4.9%]	0.289 [+3.8%]	0.90 [-1.8%]
11		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	23.6* [-31.3%]	656 [-6.2%]	3773 [+14.2%]	0.17 [-17.2%	0.421 [+3.4%]	0.302 [2.5%]	0.88 [-1.3%]
12			Optimal (15%, 85%) [NEW]	23.7* [-32.2%]	670 [-7.4%]	3810 [+12%]	0.18 [-16.2%]	0.424 [+1.7%]	0.304 [+1.7%]	0.87 [-0.6%]
13			Nor Trawl (100%, 0%)	22.8* [-29.6%]	594 [-7.1%]	3750 [+15.7%]	0.16 [-20.8%]	0.412 [+4%]	0.297 [+2.9%]	0.89 [-1.4%]

[1] The Weight Index indicates the sum of weights at age for individuals of age 5-11 relative to the sum of observed average weights at age for individuals of age 5-11. An index value less than 1 indicates that steady state weights at age are lower than the observed average weights, while an index value higher than 1 indicates that weights at age are higher than the observed average weights.
*[2] Results marked with ' * ' are calculated based on the assumption that Fleet 3 gets 55% of the yearly profits even when it does not participate (equivalent to the share of the TAC that it receives in today's management). This is enforced because the OC Trawler Fleet does not generate any revenue, costs, nor profits within the model even when it participates (see description in the model section). Without the 55%-assumption, the yearly profits and NPV would be much higher in cases where the OC Trawler Fleet does not participate compared to cases where it participates simply because the first involves allocating the entire TAC to one or two fleets that generate economic output in the model, while the second involves allocating a share of the TAC to a fleet that does not generate any economic output in the model. The 55%-assumption makes all economic results directly comparable.*

Table A22. Maximum Sustainable Yield and Maximum Economic Yield Results (End. M and W with 20% Increase in Price)

Scenario	Objective	Constraints on the Distribution of the TAC: International TAC Distribution (Nor. share, OC share)	Constraints on the Distribution of the TAC: Norwegian TAC distribution (Nor Trawl share, Nor Conv. share)	Economic Results: NPV (Billion NOK)[2]	Biological Results: TAC (Thousand tons)	SSB (Thousand tons)	F_{SSB}	M_3	M_4	Weight Index[1]
1	Max. Sustainable Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	32.1 [+63%]	680 [+0%]	1532 [+0%]	0.44 [+0%]	0.332 [+0%]	0.254 [+0%]	0.97 [+0%]
2			Optimal (0%, 100%)	31.8 [+62%]	696 [+0%]	1567 [+0%]	0.44 [+0%]	0.336 [+0%]	0.256 [+0%]	0.96 [+0%]
3			Nor Trawl (100%, 0%)	31.0 [+71%]	647 [+0%]	1501 [+0%]	0.43 [+0%]	0.326 [+0%]	0.251 [+0%]	0.97 [+0%]
4		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	38.2* [+47.3%]	757 [+0%]	2087 [+0%]	0.36 [+0%]	0.367 [+0%]	0.273 [+0%]	0.93 [+0%]
5			Optimal (0%, 100%)	37.8* [+45.3%]	781 [+0%]	2209 [+0%]	0.35 [+0%]	0.376 [+0%]	0.278 [+0%]	0.92 [+0%]
6			Nor Trawl (100%, 0%)	37.0* [+52.7%]	701 [+0%]	1886 [+0%]	0.37 [+0%]	0.349 [+0%]	0.264 [+0%]	0.95 [+0%]
7		OC Trawler Fleet (0%, 100%)	-		590 [+0%]	1283 [+0%]	0.46 [+0%]	0.310 [+0%]	0.243 [+0%]	0.99 [+0%]
8	Max. Economic Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	40.4 [+33.7%]	638 [+3.2%]	2525 [-9.2%]	0.25 [+14.9%]	0.366 [-2.3%]	0.273 [-1.5%]	0.93 [+1.4%]
9			Optimal (0%, 100%)	40.7 [+32.3%]	654 [+2.9%]	2522 [-8.3%]	0.26 [+12.8%]	0.368 [-2.2%]	0.274 [-1.4%]	0.93 [+1.2%]
10			Nor Trawl (100%, 0%)	39 [+36.7%]	598 [+4%]	2647 [-10.5%]	0.23 [+19%]	0.367 [-2.7%]	0.273 [-1.8%]	0.93 [+1.4%]
11		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	45.2* [+31.3%]	715 [+2.4%]	3099 [-6.2%]	0.23 [+9.9%]	0.401 [-1.4%]	0.292 [-1.1%]	0.90 [+0.9%]
12			Optimal (0%, 100%)	45.3* [+29.8%]	734 [+1.5%]	3188 [-6.3%]	0.23 [+9.7%]	0.408 [-1.7%]	0.295 [-1.2%]	0.89 [+1.3%]
13			Nor Trawl (100%, 0%)	43.6* [34.5%]	658 [+3%]	2983 [-8%]	0.22 [+10.3%]	0.388 [-1.9%]	0.285 [-1.5%]	0.91 [+1.2%]

[1] The Weight Index indicates the sum of weights at age for individuals of age 5-11 relative to the sum of observed average weights at age for individuals of age 5-11. An index value less than 1 indicates that steady state weights at age are lower than the observed average weights, while an index value higher than 1 indicates that weights at age are higher than the observed average weights.

*[2] Results marked with ' * ' are calculated based on the assumption that Fleet 3 gets 55% of the yearly profits even when it does not participate (equivalent to the share of the TAC that it receives in today's management). This is enforced because the OC Trawler Fleet does not generate any revenue, costs, nor profits within the model even when it participates (see description in the model section). Without the 55%-assumption, the yearly profits and NPV would be much higher in cases where the OC Trawler Fleet does not participate compared to cases where it participates simply because the first involves allocating the entire TAC to one or two fleets that generate economic output in the model, while the second involves allocating a share of the TAC to a fleet that does not generate any economic output in the model. The 55%-assumption makes all economic results directly comparable.*

Table A23. Maximum Sustainable Yield and Maximum Economic Yield Results (End. M and W with 20% Increase in Recruitment)

Scenario	Objective	Constraints on the Distribution of the TAC		Economic Results	Biological Results					
		International TAC Distribution (Nor. share, OC share)	Norwegian TAC distribution (Nor Trawl share, Nor Conv. share)	NPV (Billion NOK)[2]	TAC (Thousand tons)	SSB (Thousand tons)	F_{SSB}	M_3	M_4	Weight Index[1]
1	Max. Sustainable Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	22.2 [+12.5%]	789 [+16.1%]	1650 [+7.7%]	0.48 [+8.8%]	0.344 [+3.6%]	0.261 [+2.7%]	0.96 [-1.4%]
2			Optimal (0%, 100%)	21.6 [+10%]	806 [+15.8%]	1695 [+8.2%]	0.48 [+8%]	0.349 [+3.8%]	0.263 [+2.9%]	0.95 [-0.9%]
3			Nor Trawl (100%, 0%)	21.5 [+18.6%]	753 [+16.4%]	1600 [6.6%]	0.47 [+9.5%]	0.336 [+3.2%]	0.257 [+2.3%]	0.96 [-0.7%]
4		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	29.5 [+13.9%]	865 [+14.2%]	2259 [+8.2%]	0.38 [+6.3%]	0.384 [+4.6%]	0.282 [+3.4%]	0.92 [-1.5%]
5			Optimal (0%, 100%)	29.1 [+12.1%]	889 [+13.8%]	2395 [8.4%]	0.37 [+6%]	0.395 [+5.1%]	0.288 [+3.7%]	0.90 [-1.7%]
6			Nor Trawl (100%, 0%)	28.3 [+17.1%]	808 [+15.2%]	2024 [+7.3%]	0.40 [+7.8%]	0.363 [+4%]	0.271 [+2.7%]	0.94 [-1.4%]
7		OC Trawler Fleet (0%, 100%)	-		692 [+17.3%]	1348 [+5.1%]	0.51 [+11.6%]	0.318 [+2.5%]	0.247 [+1.5%]	0.98 [-0.7%]
8	Max. Economic Yield	Today's (45%, 55%)	Today's (33.3%, 66.6%)	34.4 [+13.8%]	718 [+16.2%]	3017 [+8.4%]	0.24 [+8.2%]	0.392 [+4.5%]	0.287 [+3.5%]	0.91 [-1.4%]
9			Optimal (0%, 100%)	34.8 [+12.9%]	736 [+15.7%]	3004 [+9.2%]	0.25 [+6.5%]	0.394 [+4.8%]	0.288 [+3.5%]	0.91 [-1.6%]
10			Nor Trawl (100%, 0%)	33.1 [+16.2%]	672 [+16.9%]	3164 [+7%]	0.21 [+11.8%]	0.392 [+4.1%]	0.287 [+3.2%]	0.91 [-1.4%]
11		Optimal (100%, 0%)	Today's (33.3%, 66.6%)	39.0 [+13.4%]	801 [+14.7%]	3595 [+8.8%]	0.22 [+6.2%]	0.430 [+5.7%]	0.307 [+4.2%]	0.87 [-2.4%]
12			Optimal (0%, 100%)	39.2 [+12.4%]	826 [+14.2%]	3714 [+9.2%]	0.22 [+6%]	0.440 [+5.9%]	0.312 [4.5%]	0.86 [-2.4%]
13			Nor Trawl (100%, 0%)	37.4 [+15%]	739 [+15.7%]	3488 [+7.6%]	0.21 [+5.9%]	0.416 [+5%]	0.300 [+3.7%]	0.88 [-1.9%]

[1] The Weight Index indicates the sum of weights at age for individuals of age 5-11 relative to the sum of observed average weights at age for individuals of age 5-11. An index value less than 1 indicates that steady state weights at age are lower than the observed average weights, while an index value higher than 1 indicates that weights at age are higher than the observed average weights.

*[2] Results marked with ' * ' are calculated based on the assumption that Fleet 3 gets 55% of the yearly profits even when it does not participate (equivalent to the share of the TAC that it receives in today's management). This is enforced because the OC Trawler Fleet does not generate any revenue, costs, nor profits within the model even when it participates (see description in the model section). Without the 55%-assumption, the yearly profits and NPV would be much higher in cases where the OC Trawler Fleet does not participate compared to cases where it participates simply because the first involves allocating the entire TAC to one or two fleets that generate economic output in the model, while the second involves allocating a share of the TAC to a fleet that does not generate any economic output in the model. The 55%-assumption makes all economic results directly comparable.*

Preferred selectivity and optimal harvesting in bioeconomic age-structured predator-prey models*

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Abstract

This study presents a bioeconomic, age-structured, multi-fleet, predator-prey model. By solving the model for a range of scenarios and parameter values, we show that preferred selectivity and optimal harvesting change with the levels of predation and predation-weight conversion rates. While the model reproduces insight from age-structured single-species and biomass predator-prey models, it also shows that positive scaling of age-specific predation coefficients can shift the preferred selection pattern towards smaller predator individuals and increase the overall fishing pressure for the predator. This involves sacrificing utilization of predator growth potential to achieve better utilization of prey growth potential, both at an individual level and at the stock level. In addition, it involves sacrificing predator harvest efficiency to achieve better prey harvest efficiency. The model also shows that positive scaling of predation-weight conversion rates can counteract the abovementioned. To the best of our knowledge, this represents novel findings. The findings are important because they bring awareness to why managers should think twice before changing gear restrictions in direction of targeting bigger fish on basis of single-species analyses, in which selectivity studies are common. Moreover, they display the usefulness and value of age-structured multi-species modeling, which has received limited attention in the bioeconomic literature so far, as opposed to age-structured single-species modeling and biomass multi-species modeling.

JEL classification: Q2, Q22, Q28

Keywords: Age-structure, Predator-prey, Optimal harvesting, Selectivity

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Introduction

The importance of taking a holistic ecosystem view on bioeconomic modeling and marine management has been acknowledged for several decades (Larkin, 1996). The usefulness of single-species models should not be underestimated, but under many circumstances results become different, and offer more insight, when more than one species is included, which in turn can improve system understanding and management (Brekke & Moxnes, 2003; Ekerhovd & Steinshamn, 2017).

A first step toward ecosystem modeling is to replace traditional single-species models with models including two, or more, species. The most common types of multi-species models are arguably two-species predator-prey models based on extensions and variations of the Lotka-Volterra equations. Numerous articles investigating such models have appeared over the last five to six decades, focusing on mathematical, biological, and economic aspects.

Within mathematics and theoretical biology, there is a large literature on mathematical aspects of predator-prey population models, and new studies keep coming. Kar & Chakraborty (2010), Li et al. (2017), Liu et al. (2018), and Wikan & Kristensen (2019) represent some recent ones.

In the bioeconomic literature, variations of the predator-prey model outlined in the first (1976) edition of Colin Clark's iconic book "Mathematical Bioeconomics" (2010) are quite common. Among the bioeconomic population model papers, we will mention Hannesson (1983) and Flåten & Stollery (1996). Hannesson was one of the first to point out the importance of the relative price-relationship between the species, and he also pointed out that some of the conventional wisdom based on single-species models, does not apply to models with more than one species. Notably, that subsidizing fishing (of the predator) may sometimes be optimal; an increased discount rate may imply an increase in the optimal standing stock; higher price and/or lower cost of effort may increase the standing stock. Flåten & Stollery (1996) investigate economic losses related to reduced harvesting of the prey due to increased predator stock.

Age-structured predator-prey models are also quite common in the mathematical and biological literature. Smith and Mead (1974), Gurtin & Levine (1979), Cushing & Saleem (1982), Li (1990), and Wikan (2001, 2017) study phenomena like the existence and stability of equilibria, bifurcation, and chaos. In the biological literature age-structured multi-species simulation models have been used to analyze the consequences of various predetermined policies (Goto et al., 2021; Tjelmeland & Bogstad, 1998).

In the bioeconomic literature, the number of age-structured studies with more than one species are limited. Fister & Lenhart (2006) were among the first to propose a bioeconomic age-structured multi-species model. This is a fairly theoretical study where the emphasis is on the existence and uniqueness of optimal control combinations. Nieminen et al. (2015) apply a bioeconomic age-structured multi-species model to assess the cod, herring, and sprat fisheries in the Baltic Sea under different environmental conditions. Bertram & Quaas (2017) apply an age-structured multi-species model to Baltic Sea fisheries where they include the value of biodiversity in their objective function. Voss et al. (2022) also present an age-structured multi-species model for cod, herring, and sprat in the Baltic. They focus on the differences between maximizing sustainable and economic yield in an age-structured multi-species setting. Skonhoft & Friberg (2021) use an age-structured model to study predation on terrestrial stocks (both wild and livestock) by carnivorous predators like wolf.

Several of the abovementioned age-structured predator-prey studies only consider age-structure for one of the fish-stocks, while keeping the other fish-stock biomass-structured – Voss et al. (2022) is a notable exception. In this paper we use a bioeconomic predator-prey model, where both the predator and prey are represented by full-blown age-structured models. This is necessary as the purpose of the study is to analyze how optimal selectivity and harvesting change in response to changes in the absolute and relative strength of age-specific biological interactions, as well as changes in the relative prices.

There has been a significant focus on optimal selectivity in bioeconomic age-structured single-species studies (e.g., Bang & Steinshamn, 2022; Diekert et al., 2010; Helgesen et al., 2018; Reed, 1980; Skonhoft et al., 2012). However, the role of selectivity in bioeconomic age-structured multi-species settings is an under-researched topic. To the best of our knowledge, Voss et al. (2022) is the only bioeconomic age-structured multi-species study that touches upon the topic, and there are still many knowledge gaps to cover. Considering the importance of gear selectivity and regulations in modern fisheries, which is a key motivator for the single-species studies on the topic, this is surprising and highlights the need for more studies on the topic.

We look at two biological interactions. Firstly, we focus on the effects of two different versions of the predation profile, namely one where predation is proportional to the size/age of the predator, and one where the predation pressure increases more than proportionally with size/age. The rationale behind the latter is that larger fish swim longer and can cover a larger area in their search for food than smaller fish. Moreover, large predator fish tend to base more of their food consumption on prey fish than small predator fish–at least that is the case for cod and capelin (Holt et al., 2019).

Secondly, we investigate two age profiles for the conversion factor between prey and predator. One is uniform conversion after a certain predator age, the other is decreasing conversion after a certain predator age where it is assumed that the metabolism decreases with age down to a certain level. Also, for older fish, more of the energy go to spawning products and not to growth.

It is quite intuitive and demonstrated formally by Hannesson (1983) and others, that the relative price between predator and prey may have important implications for the optimal harvest pattern and stock levels. Therefore, as a sensitivity analysis, we also check how the results change when we move from a high-valued predator and a low-valued prey, such as cod-capelin, to the opposite.

Methods

We develop a deterministic, age-structured, multi-fleet, predator-prey optimization model. The model considers a sole owner who manages two fleets and two interacting commercial fish stocks–one fleet targets a predator stock and another targets a prey stock. The model considers two types of species interactions–predator-induced predation mortality for the prey, and predation-weight conversion for the predator.

Regarding the use of terminology, we distinguish between two types of natural mortality, natural mortality induced by the predator in the model, and other natural mortality. In the following, we simply refer to the two types of natural mortality as predation mortality and natural mortality, respectively, in which natural mortality should be understood as natural mortality excluding predation mortality.

Figure 1 provides a high-level overview of the model. The biological sub-model describes the processes of natural mortality, predation mortality, growth, maturation, and recruitment, while the economic sub-model describes fishing effort, and costs, revenue, and profits associated with harvest. The harvest functions bridge the biological and economic dimensions.

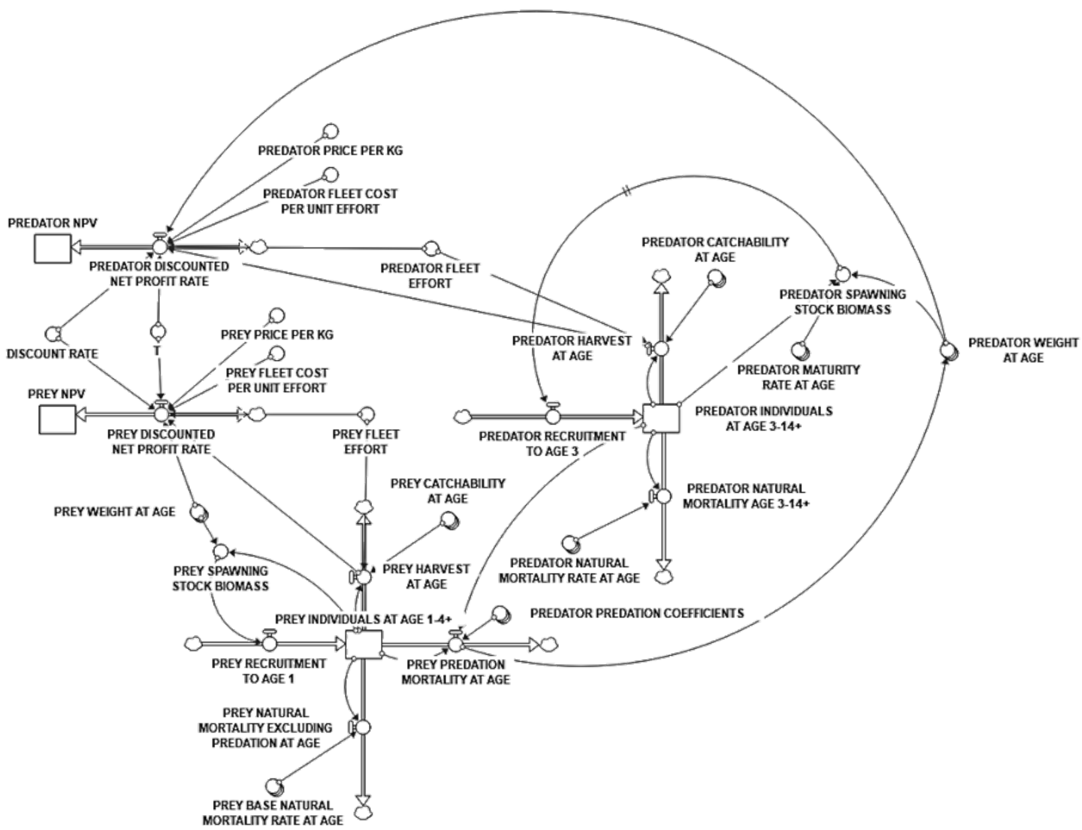

Figure 1: Simplified high-level stock and flow model overview

The modeled system structure and parameterization are inspired by cod and capelin in the North-East Arctic ecosystem, in which cod exists as the predator, and capelin exists as the prey. However, the model is intended for more encompassing conceptual and theoretical investigations. So, while the model is built on inspiration from cod and capelin, and while the analysis considers some scenarios that are directly relevant for cod and capelin, the model is also used to explore scenarios that are less relevant for cod and capelin, and more relevant for other predator-prey cases, e.g., cod and shrimp. The abstractions from the cod-capelin case particularly apply to various investigations regarding the relative price of predator to prey. Overall, the inspiration from cod and capelin is used more as a point of departure and for sensible grounding of the model, rather than being meant as an applied practical study of said fisheries.

Model parameters, variables, and equations

The model comprises a range of sets, parameters, variables, and equations. Table 1 gives an overview of all sets, parameters, and variables, while Table 2 gives a full overview of the model objectives, control variables, and equations. Tables 5-19 in the Appendix give a full overview of the parameter values and employed initial values.

Table 1: Model sets, parameters, and variables

Set	**Description**	**Units**
t	t represents time	Years
a	Predator age groups	Years
i	Prey age groups	Years
Parameter	**Description**	**Units**
T	T represents the end of the time horizon	Years
r	Discount rate	Dimensionless / Year
P_{pred}	Price per kilogram predator	NOK / kilogram
P_{prey}	Price per kilogram prey	NOK / kilogram
$q_{pred,a}$	Predator fleet catchability at age a	Predator harvest number of individuals in thousands / Predator effort * Predator number of individuals in thousands
$q_{prey,i}$	Prey fleet catchability at age i	Prey harvest number of individuals in thousands / Prey effort * Prey number of individuals in thousands
C_{pred}	Predator fleet cost per unit effort	NOK / Predator effort
C_{prey}	Prey fleet cost per unit effort	NOK / Prey effort
α_{pred}	Predator Beverton-Holt recruitment parameter	-
α_{prey}	Prey Beverton-Holt recruitment parameter	-
β_{pred}	Predator Beverton-Holt recruitment parameter	-
β_{prey}	Prey Beverton-Holt recruitment parameter	-
$M_{pred,a}$	Predator natural mortality at age i	Dimensionless / Year
$p_{pred,a,i}$	Predation coefficients for predators at age a for prey at age i	Kilogram / Predator Individual
$M_{prey,i}$	Prey natural mortality at age i (excluding predation mortality)	Dimensionless / Year
$w_{pred,a}$	Predator exogenous growth at age	Kilogram / Predator Individual
Υ_a	Predator-prey weight conversion factor at age a	Dimensionless
$W_{prey,i}$	Prey weight at age i	Kilogram / Predator Individual
$\upsilon_{pred,\ a}$	Predator maturity rate at age a	Dimensionless
$\upsilon_{prey,i}$	Prey maturity rate at age i	Dimensionless
SC_p	Predation scaling factor (used to scale predation up and down)	Dimensionless
SC_w	Predator-prey weight conversion scaling factor (used to scale conversion up and down)	Dimensionless
Variable	**Description**	**Units**
E_{pred}	Predator fleet effort	Predator fleet fishing days / Year
E_{prey}	Prey fleet effort	Prey fleet fishing days / Year
$y_{pred,a,t}$	Harvest number of predator individuals from age group a at time t	Predator harvest number of individuals in thousands / Year
$y_{prey,i,t}$	Harvest number of prey individuals from age group i at time t	Prey harvest number of individuals in thousands / Year
$R_{pred,t}$	Predator recruitment at time t	Predator number of individuals in thousands / Year
$R_{prey,t}$	Prey recruitment at time t	Prey number of individuals in thousands / Year
$N_{pred,a,t}$	Predator number of individuals in age group a at time t	Predator number of individuals in thousands
$N_{prey,i,t}$	Prey number of individuals in age group i at time t	Predator number of individuals in thousands
$\lambda_{prey,i,t}$	Prey predation mortality at age i	Dimensionless / Year
$\varphi_{pred,a,t}$	Predator prey biomass consumption at age a at time t	Kilograms
$W_{pred,a,t}$	Predator weight at age a at time t	Kilogram/Predator Individual
$SSB_{pred,\ t}$	Predator spawning stock biomass at time t	Thousand tons
$SSB_{prey,t}$	Prey spawning stock biomass at time t	Thousand tons

Table 2: Objective, control variables, and model equations

Description		Objective/Control Variables/Equation	Eq. no.
Objective		$\max \sum_{t=1}^{T} e^{-rt} \left(P_{pred} \sum_{a=3}^{14} y_{pred,a,t} W_{pred,a,t} + P_{prey} \sum_{i=1}^{4} y_{prey,i,t} W_{prey,i} - c_{predator} E_{predator} - c_{prey} E_{prey} \right)$	(1)
Control variables		$E_{pred},\ E_{prey}$	(2)
Harvest Predator	Age 3-14+	$y_{pred,a,t} = \frac{q_{pred,a} E_{pred}}{q_{pred,a} E_{pred} + M_{pred,a}} N_{pred,a,t} \left(1 - e^{-(q_{pred,a} E_{pred} + M_{pred,a})}\right)$	(3)
Harvest Prey	Age 1-4+	$y_{prey,i,t} = \frac{q_{prey,i} E_{prey}}{q_{prey,i} E_{prey} + M_{prey,i} + \lambda_{prey,i,t}} N_{prey,i,t} \left(1 - e^{-(q_{prey,i} E_{prey} + M_{prey,i} + \lambda_{prey,i,t})}\right)$	(4)
Predator population dynamics	Recruitment Age 3	$R_{pred,t} = \frac{\alpha_{pred} SSB_{pred,\ t-3}}{\beta_{pred} + SSB_{pred,t-3}}$	(5)
	Age 3-13	$N_{pred,\ a+1,\ t+1} = N_{pred,a,t} e^{-(M_{pred,a,t} + q_{pred,a} E_{pred})}$	(6)
	Age 14+	$N_{pred,14+,\ t+1} = N_{pred,13,t} e^{-(M_{pred,13} + q_{pred,13} E_{pred})} + N_{pred,14+,t} e^{-(M_{pred,14+} + q_{pred,14+,} E_{pred})}$	(7)
Prey population dynamics	Recruitment, Age 1	$R_{prey,t} = \frac{\alpha_{prey} SSB_{prey,t-1}}{\beta_{prey} + SSB_{prey,t-1}}$	(8)
	Age 1-3	$N_{prey,i+1,\ t+1} = N_{prey,i,t} e^{-(q_{prey,i} E_{prey} + M_{prey,i} + \lambda_{prey,i,t})}$	(9)
	Age 4+	$N_{prey,4+,\ t+1} = N_{prey,3,t} e^{-(q_{prey,3} E_{prey} + M_{prey,3} + \lambda_{prey,3,t})} + N_{prey,4+,t} e^{-(q_{prey,4+} E_{prey} + M_{prey,4+} + \lambda_{prey,4+,t})}$	(10)
Predator weight	Age 3	$W_{pred,a,t} = w_{pred,a}$	(11)
	Age 4-14+	$W_{pred,a,t} = W_{pred,a-1,t-1} + \frac{SC_w \Upsilon_{a-1} \varphi_{pred,a-1,t-1}}{N_{pred,a-1,t-1}} + w_{pred,a}$	
Predator prey biomass consum.	Age 4-14+	$\varphi_{pred,a,t} = \sum_{i=1}^{4} \frac{SC_p p_{pred,a,i} N_{pred,a,t}}{q_{prey,i} E_{prey,t} + M_{prey,i,t} + \lambda_{prey,i,t}} N_{prey,i,t} \left(1 - e^{-(q_{prey,i} E_{prey,t} + M_{prey,i,t} + \lambda_{prey,i,t})}\right) W_{prey,i}$	(12)
Predation mortality	Age 1-4+	$\lambda_{prey,i,t} = \sum_{a=3}^{14} SC_p p_{pred,a,i} N_{pred,a,t}$	(13)
Predator SSB		$SB_{pred,\ t} = \sum_{a=3}^{14} \upsilon_{pred,\ a} N_{pred,a,t} W_{pred,a,t}$	(14)
Prey SSB		$SSB_{prey,\ t} = \sum_{i=1}^{4} \upsilon_{prey,\ a} N_{prey,i,t} W_{prey,i}$	(15)

The sole owner's objective is to maximize the net present value of harvest (eq. 1 in Table 2) from the two fish stocks with respect to the effort of the two fleets (eq. 2 in Table 2) subject to the system (eq. 3-15 in Table 2). The control variables are restricted such that $E_t = E_{t+1}$ for both fleets in all periods t=0, 1, . . . , T-1. These control constraints enforce steady-state fishing schemes, which is what we focus on.

The harvest by each fleet from each age group in each stock is determined by classical Baranov catch equations, i.e., the harvest by each fleet from each age group in each fish stock is a function of effort and the number of individuals in each age group (eq. 3-4 in Table 2) (Baranov, 1918). Harvest is density-dependent and increases linearly by the size of the stock–that is, catch per unit effort-wise, there are benefits to having access to and maintaining abundant fish stocks.

Inspired by state-of-the-art modeling of North-East Arctic cod, the predator stock is split into 12 age groups, ranging from age group 3 to age group 14+, in which the first age group represents all individuals that are three years of age, while the last represents all individuals that are 14 years and older (Diekert et al., 2010; ICES, 2021; Kovalev & Bogstad, 2005). Similarly, inspired by state-of-the-art modeling of capelin, the prey stock is split into four age groups, ranging from age group 1 to age group 4+ (ICES, 2021).

The predator and prey individuals are both subject to natural mortality. In this model, both species are commercial, and thus also subject to fishing mortality (eq. 6-7 and 9-10 in Table 2). In addition, the prey is subject to predation mortality, which is separate from other natural mortality in the model (eq. 9-10 in Table 2).

The natural mortality rates are considered exogenous and constant. Bang & Steinshamn (2022) show that assumptions of exogenous natural mortality rates can lead to significant overestimation of the biological and economic potential of fish stocks, which makes it clear why such factors should be considered endogenously in models that are intended for applied and practical analysis. However, the focus in this study is more conceptual and theoretical than practical, and we choose to treat these factors exogenously to allow clear focus on the objectives of this study, which encompass the effects of predation, predation-weight conversion, and relative prices on optimal harvesting schemes and preferred selectivity.

The number of prey individuals that die from predation is determined by age-specific predation coefficients, the number of predator individuals at age, and the number of prey individuals at age (eq. 13 in Table 2). For intuition, the reader can think of the predator as a competing fishing fleet consisting of several vessel groups (age groups), each with its own efficiency and selection pattern in harvesting the prey (predation coefficients), and an employed effort (number of predator individuals at age). The predation functions have the same structure as the harvest functions, but as opposed to harvest, the predation functions generate no direct value for the fishing industry. The choice of density-dependent predation functions is motivated by the fact that cod has been shown to shift to alternative prey such as amphipods and krill when the capelin stock is low (Dalpadado et al., 2001; Holt et al., 2019)–i.e., when less capelin is available, cod is more likely to base more of its food consumption on alternative prey.

The weight at age for the predator in the current year is determined by the weight at age of that cohort in the previous year, predation-weight conversion rates, the biomass consumption of prey per predator individual, and an exogenous growth factor (eq. 11 in Table 2). It is well-known that predator species can have reduced feeding levels and smaller growth rates when the prey stock is at low levels, and vice versa (Gjøsæter et al., 2009; Holt et al., 2019; Mehl & Sunnanå, 1991).

The weight at age for the prey is assumed exogenous and constant. Like assumptions of exogenous natural mortality, this assumption can lead to overestimation of the biological and economic potential (Bang & Steinshamn, 2022). However, again, our intention here is not to provide accurate estimates on the biological and economic potential of either stock, but rather to provide a conceptual, theoretical, and broader contribution. As such, the simplification can be well-defended.

The recruitment to the predator and prey stocks are determined by Beverton-Holt recruitment functions, i.e., the recruitment to each stock is a concave function of spawning stock biomass (SSB), with positive horizontal asymptotes (eq. 5 and 8 in Table 2) (Beverton & Holt, 1957). The spawning stock biomass is calculated according to eq. 14 and 15 in Table 2.

The following subsection gives necessary insight to the numerical specification of the model. The reader is referred to tables 5-19 in the Appendix for a full description of the numerical specification of the model.

Model scenarios

This study focuses on how preferred selectivity and optimal harvesting change in response to changes in the absolute and relative strength of age-specific biological interactions, as well as changes in relative prices. To acquire the desired insight, the model is solved for 8 scenarios with 72 different combinations of scaling values that determine the strengths of the predator-prey interactions (ref. eq. 11-13 in Table 2) . In total, 576 runs are conducted to produce the results.

The scenarios apply various combinations of settings (modes) regarding the predator fleet selection pattern, predation coefficients, predation-weight conversion rates, and relative price of predator to prey. Table 3 gives an overview of the scenarios including the applied combination of modes, while Figure 2 shows the selectivity, predation, and conversion modes referred to in Table 3. Table 4 gives an overview of the applied scaling values.

Table 3: Overview of model scenarios

Scenario	Selectivity mode	Predation mode	Conversion mode	Relative price (Ppred/Pprey)
1	1	1	1	1
2	2	1	1	1
3	1	2	2	1
4	2	2	2	1
5	1	2	2	1.5
6	2	2	2	1.5
7	1	2	2	0.66
8	2	2	2	0.66

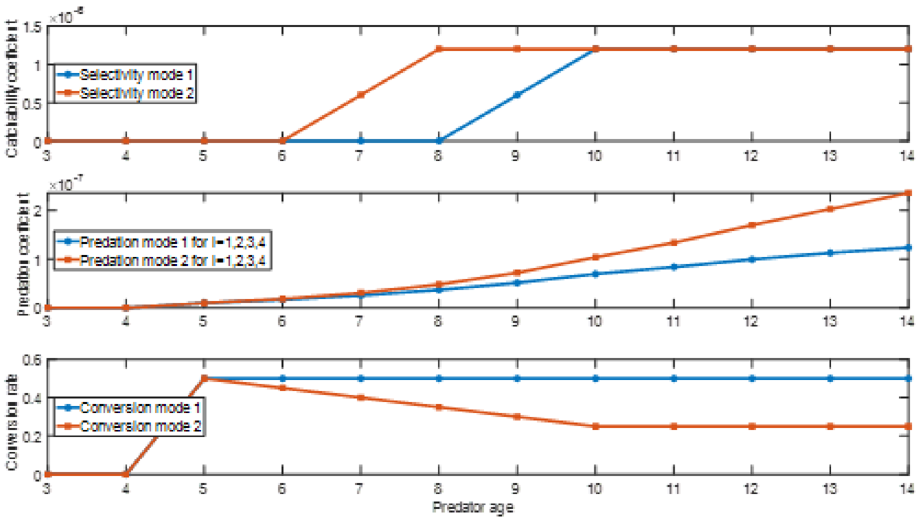

Figure 2: Selectivity, predation, and conversion modes. Selectivity coefficient values. 'Spare the young' (selectivity mode 1) and 'Take them early' (selectivity mode 2). Baseline predation coefficients (scaling factor = 1). Size-proportional (predation mode 1) and size-disproportional predation (predation mode 2). Baseline predation-weight conversion rates (scaling factor = 0.5). Uniform conversion rates (conversion mode 1) and non-uniform conversion rates (conversion mode 2)

With reference to the predator fleet selectivity modes (top plot in Figure 2), we apply one mode where the selection pattern is such that young fish are spared for future harvest. In age-structured single-species models, this is often optimal even though it may come at a cost in terms of reduced catch per unit effort and cost (Bang & Steinshamn, 2022; Diekert et al., 2010; Helgesen et al., 2018; Kovalev & Bogstad, 2005; Reed, 1980; Skonhoft & Friberg, 2021). In the second selectivity mode, the selection pattern is shifted such that younger individuals are targeted.

Regarding the predation modes (middle plot in Figure 2), we apply one mode where the predation coefficients are increasing proportionally with base weight at age, which is defined by the weight functions when the predation-weight conversion is set to zero (eq. 11). In the second predation mode, the predation coefficients are increasing disproportionally with base weight at age such that, e.g., a 5 kg predator consumes more than twice the amount of prey when compared to a 2.5 kg predator, ceteris paribus. Mehl (1986) states, "With increasing predator length fish prey become more and more important. For sizegroup 20-39 cm fish were the major prey in 2/3 of the investigated areas and periods. while for cod 60 cm fish always were the dominating prey category. And with increasing predator length the size and importance of larger fish prey increased gradually". Based on this, we conclude that the second mode is more realistic than the first. However, it is still interesting to consider the difference between the two.

Regarding the predation modes, note that within each predator age group, the predation coefficients are uniform for i=1,2,3,4 for all age groups–that is, a predator of age a has the same selectivity on prey of age 1 as prey of age 2, etc. This assumption is made for simplicity. In the real world, a predator of age 3 may for example have a higher selectivity for prey of age 1 than prey of age 4, while a predator of age 10 may have a higher selectivity for prey of age 4 than of age 1. Considering the latter part of the above quote from Mehl (1986), it is reasonable to think that large predators prefer larger prey than small predators.

For the predation-weight conversion rates, we apply one mode where the predation-weight conversion rates are uniform, and another where the predation-weight conversion rates are decreasing with age before stabilizing at a constant level (bottom plot in Figure 2). For each of the eight scenarios in Table 3, the optimization model is solved for 72 combinations of strengths in predation and predation-weight conversion rates. The strengths are determined by the product of baseline values multiplied by scaling values, in accordance with eq. 11-13 in Table 2. The combinations of scaling values used are displayed in Table 4.

Table 4: Overview of combinations of scaling values for use in solving each scenario

Combinations of scaling factors for use in solving each scenario								
	Conversion Scaling Factor							
Predation Scaling Factor	0,0	0, 0.1	0, 0.2	0, 0.3	0, 0.4	0, 0.5	0, 0.6	0, 0.7
	0.5, 0	0.5, 0.1	0.5, 0.2	0.5, 0.3	0.5, 0.4	0.5, 0.5	0.5, 0.6	0.5, 0.7
	1, 0	1, 0.2	1, 0.2	1, 0.3	1, 0.4	1, 0.5	1, 0.6	1, 0.7
	1.5,0	1.5, 0.2	1.5, 0.2	1.5, 0.3	1.5, 0.4	1.5, 0.5	1.5, 0.6	1.5, 0.7
	2, 0	2, 0.2	2, 0.2	2, 0.3	2, 0.4	2, 0.5	2, 0.6	2, 0.7
	2.5, 0	2.5, 0.2	2.5, 0.2	2.5, 0.3	2.5, 0.4	2.5, 0.5	2.5, 0.6	2.5, 0.7
	3, 0	3, 0.2	3, 0.2	3, 0.3	3, 0.4	3, 0.5	3, 0.6	3, 0.7
	3.5, 0	3.5, 0.2	3.5, 0.2	3.5, 0.3	3.5, 0.4	3.5, 0.5	3.5, 0.6	3.5, 0.7
	4, 0	4, 0.2	4, 0.2	4, 0.3	4, 0.4	4, 0.5	4, 0.6	4, 0.7

Solution approach

The model has been set up in MS Excel, and a combination of VBA programming and the GRG Nonlinear solving method have been used to solve the 576 optimization problems to generate the results. The model can be accessed through one of the author's github repository (link will be provided if the paper is accepted).

The GRG Nonlinear solver is designed for problems with nonlinear objectives and/or nonlinear constraints (Lasdon et al., 1974; Microsoft, 2021). The solver uses values within the spreadsheet model for its initial search for an optimum and considers small changes in the control variables to improve the objective. In this way, when the goal is to maximize, the solver climbs “uphill” until it reaches an optimal solution. This search procedure may get stuck on locally optimal solutions. Thus, to ensure that we report results that are de facto globally optimal, we have solved the problems several times with different initial search values for the control variables. Using this procedure, we observe that the solver converges towards the same solutions regardless of initial search values. The observation from the repetitive solving procedure goes a long way in validating the global optimality of the results.

Results and discussion

The model scenarios are designed to study how preferred selectivity and optimal harvesting respond to changes in the strength of two predator-prey interactions, namely predation mortality and predation-weight conversion, and to changes in the relative price of predator to prey. The main results are summarized in Figure 3-7 below. In this section, we go systematically through the results.

Figure 3 shows the results from scenarios 1 and 2 in Table 3. That is, the scenarios with predation coefficients that increase proportionally to base predator weights at age, and with uniform predation-weight conversion rates (ref. Figure 2).

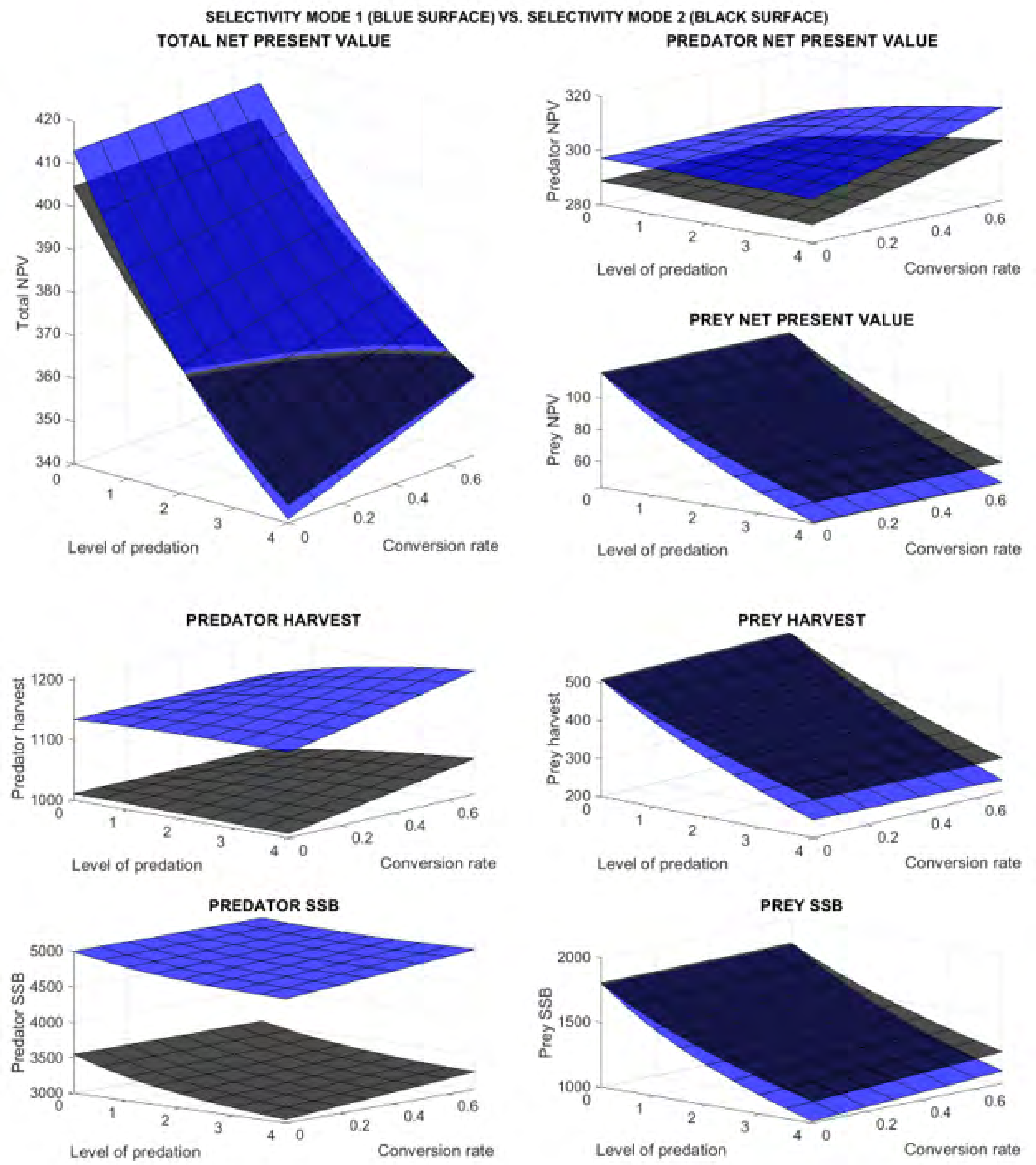

Figure 3: Key results from scenarios 1 and 2

First, consider the top left plot in Figure 3. This part of the figure gives high-level, but also key novel insight. Starting with zero predation and zero predation-weight conversion, the plot shows that the sole owner prefers selectivity mode 1–that is, the selectivity mode where young predator fish are spared for future harvest such that the individual predator growth potential is better utilized. This result is aligned with existing theory and research (Bang & Steinshamn, 2022; Diekert et al., 2010; Helgesen et al., 2018; Reed, 1980; Skonhoft et al., 2012). However, as predation increases (right-wards movement on the axis labeled 'Level of predation', which is defined by the scaling factor SC_P), the net benefit of applying selectivity mode 1 shrinks relative to the alternative selectivity mode 2, where smaller predator individuals are also targeted (ref. Figure 2). And after a certain point, it becomes optimal to apply selectivity mode 2.

As per expectation and reason, when the predation is zero, an increasing level of predation-weight conversion (right-wards movement on the axis labeled 'Conversion rate') has no effect upon the net present value of neither selectivity modes. However, as the level of predation increases, the plot shows that increasing predation-weight conversion dampens the negative effect of predation upon the net present value and delays the shift in optimal selectivity. These results and insights are intuitive because any additional mortality has a negative impact on the potential of the prey stock, and with no predation-weight conversion, there will be no counteracting positive effect with the predator. However, with predation-weight conversion, an increasing level of predation means that the predator will consume more, and gain weight as a result, which means higher potential harvest from the predator stock.

Regarding optimal harvesting given each of the selectivity modes, the results show that increasing predation yields higher optimal fishing pressure on the predator stock – the harvest goes up and the spawning stock biomass is stabilized at a lower level. This is done to limit the increase in natural mortality of the prey stock, and thereby limit the reduction in the net present value of the prey stock. Meanwhile, the harvest from the prey stock is reduced to compensate somewhat for the predation effect on the size of the stock. Overall, these changes in the optimal harvesting strategy correspond to findings in biomass predator-prey models.

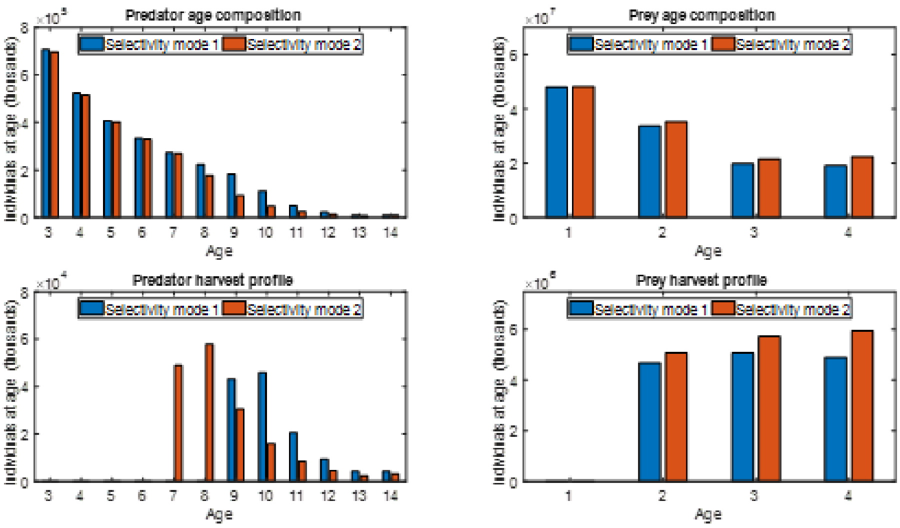

Figure 4: Optimal age compositions and harvest profiles in scenarios 1 and 2 for different selectivity modes with the level of predation set to 3 and the conversion rate set to 0

Figure 4 shows the optimal age compositions and harvest profiles in scenarios 1 and 2 with the level of predation set to 3 and the conversion rate set to 0. The figure clearly shows how the optimal age-composition and harvest profile given a selection pattern respond to changes in the selection pattern for high levels of predation. It is shown that shifting the selection pattern towards smaller predator individuals lead to a reduction in the overall size of the predator stock and a reduction in the relative number and harvest of large to small predator individuals, which also implies reduced harvest efficiency in terms of catch per unit effort. This result may be obvious to the reader. However, the figure also shows something more, which is less obvious. The changes in the overall size and age-composition of the predator stock yields an increase in the overall size of the prey stock and the relative number and harvest of large to small prey individuals. As such, the changes in the selectivity and harvesting policy does not only increase the gross harvest and catch per unit effort for prey, but it also improves the utilization of individual prey growth potential. In other words, the sole owner sacrifices utilization of individual predator growth potential not just to limit the overall predation of the prey stock, but also to improve the utilization of individual prey growth potential. This is an interesting detail and insight which cannot be gained from biomass predator-prey models.

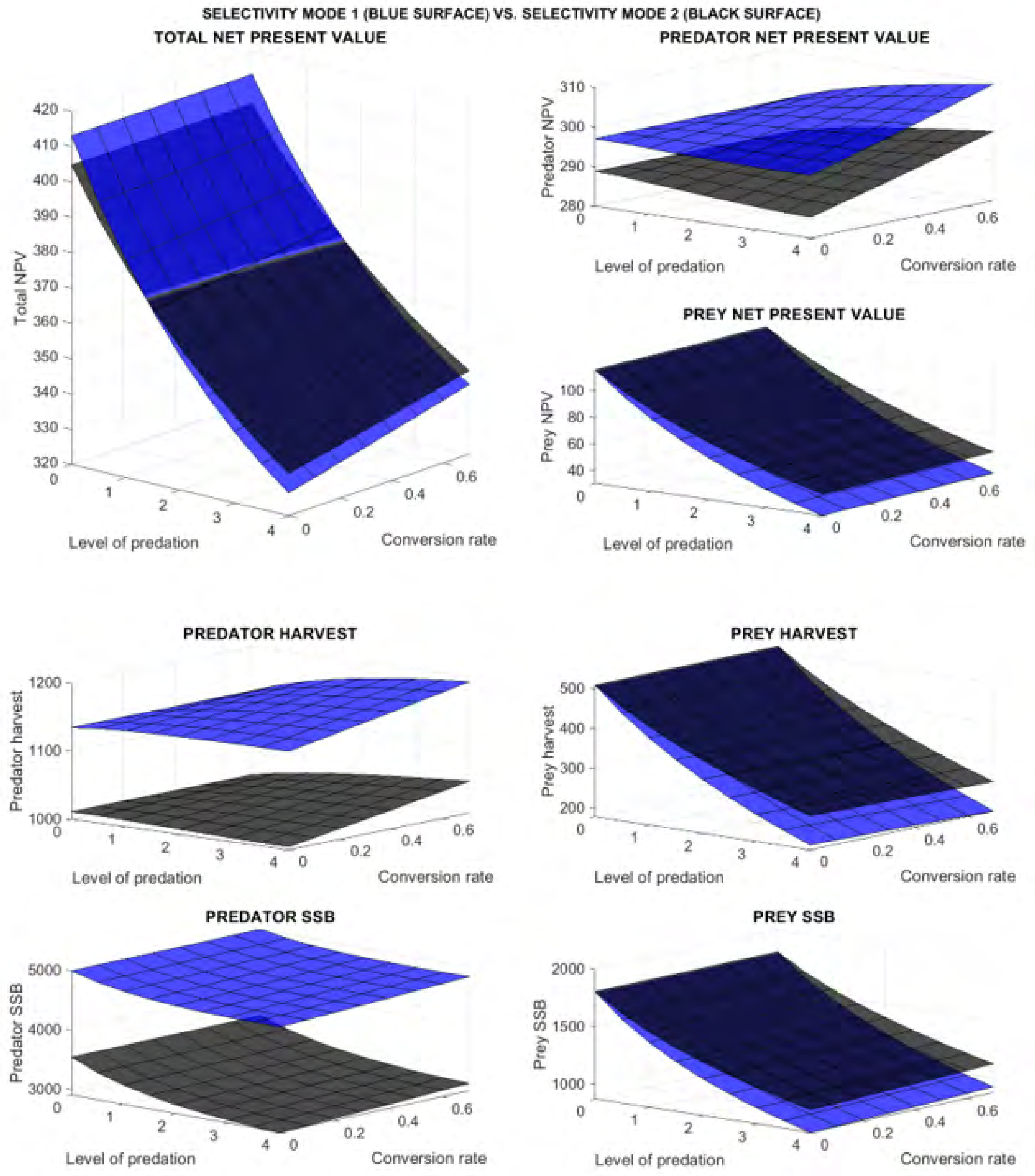

Figure 5: Key results from scenarios 3 and 4

Figure 5 shows the results from scenarios 3 and 4 in Table 3. That is, the scenarios with predation coefficients that increase disproportionally to base predator weights at age, and with non-uniform predation-weight conversion rates (ref. Table 3 and Figure 2). The results in Figure 5 go on to show that disproportional predation coefficients and non-uniform conversion rates leads to an earlier shift in preferred selectivity. Intuitively, this makes sense because of two phenomena. First, the cost of having many large predators in terms of reduced potential of the prey stock increases when large predator individuals eat relatively more prey than small predator individuals. Second, the benefit of having access to large predator fish becomes relatively smaller when compared to having access to small predator fish because the relative differences in weights between the small and large predator fish shrinks for high prey stock levels. Both phenomena explain the earlier shift in preferred selection pattern. Regarding optimal harvesting, we witness strengthened effects of what is observed in the results for scenarios 1 and 2.

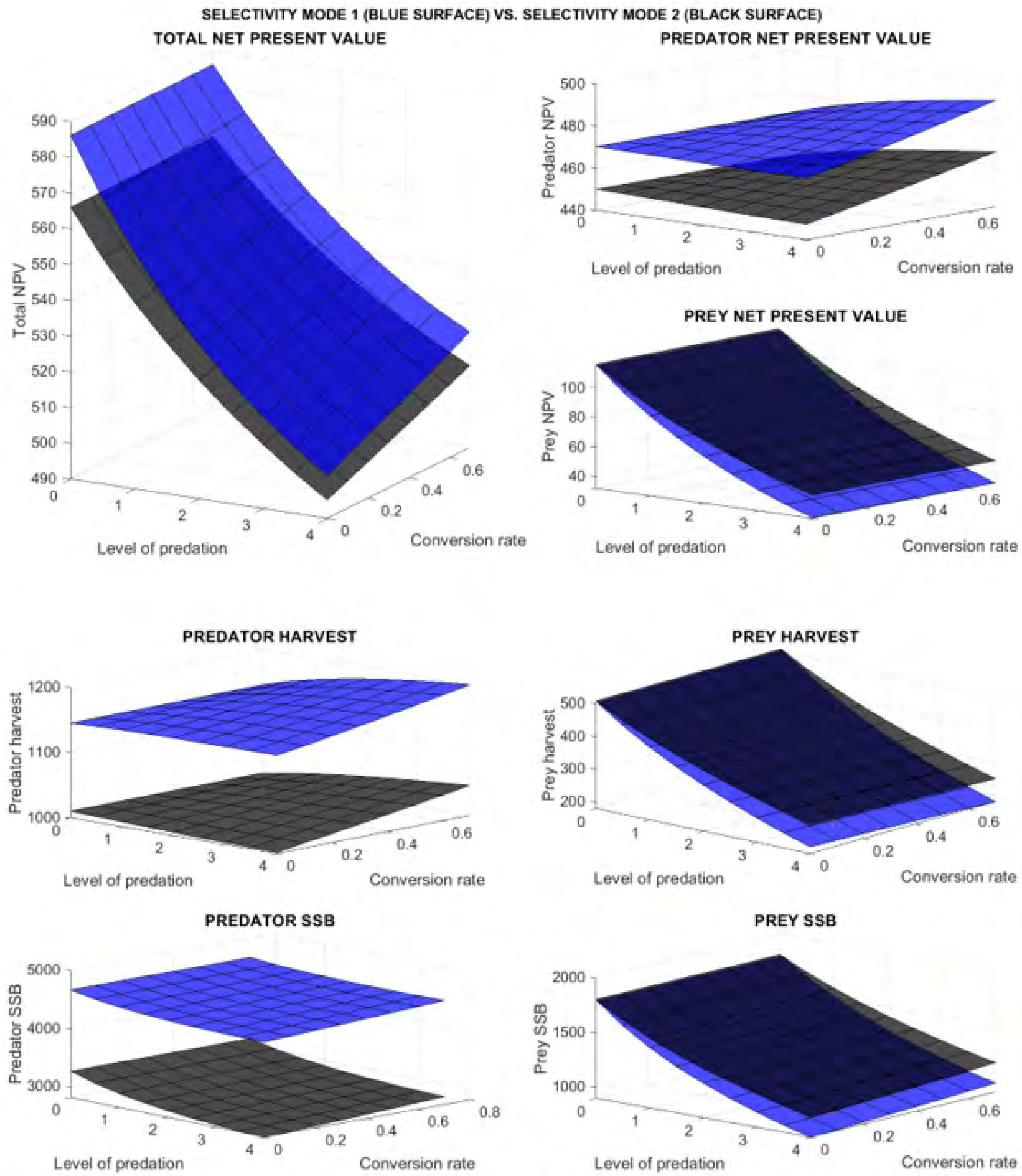

Figure 6: Key results from scenarios 5 and 6

Figure 6 shows the results from scenarios 5 and 6 in Table 3. That is, the scenarios with predation coefficients that increase disproportionally to base predator weights at age and non-uniform predation-weight conversion rates, and an increase in the relative price of predator to prey (ref. Table 3 and Figure 2). The results show that an increase in the relative price of the predator counteract the shift in optimal selection pattern observed in scenarios 1-4. Intuitively, this is reasonable because high predator harvest and good utilization of the predator growth potential becomes relatively more valuable when the price of the predator becomes relatively higher compared to the price of prey.

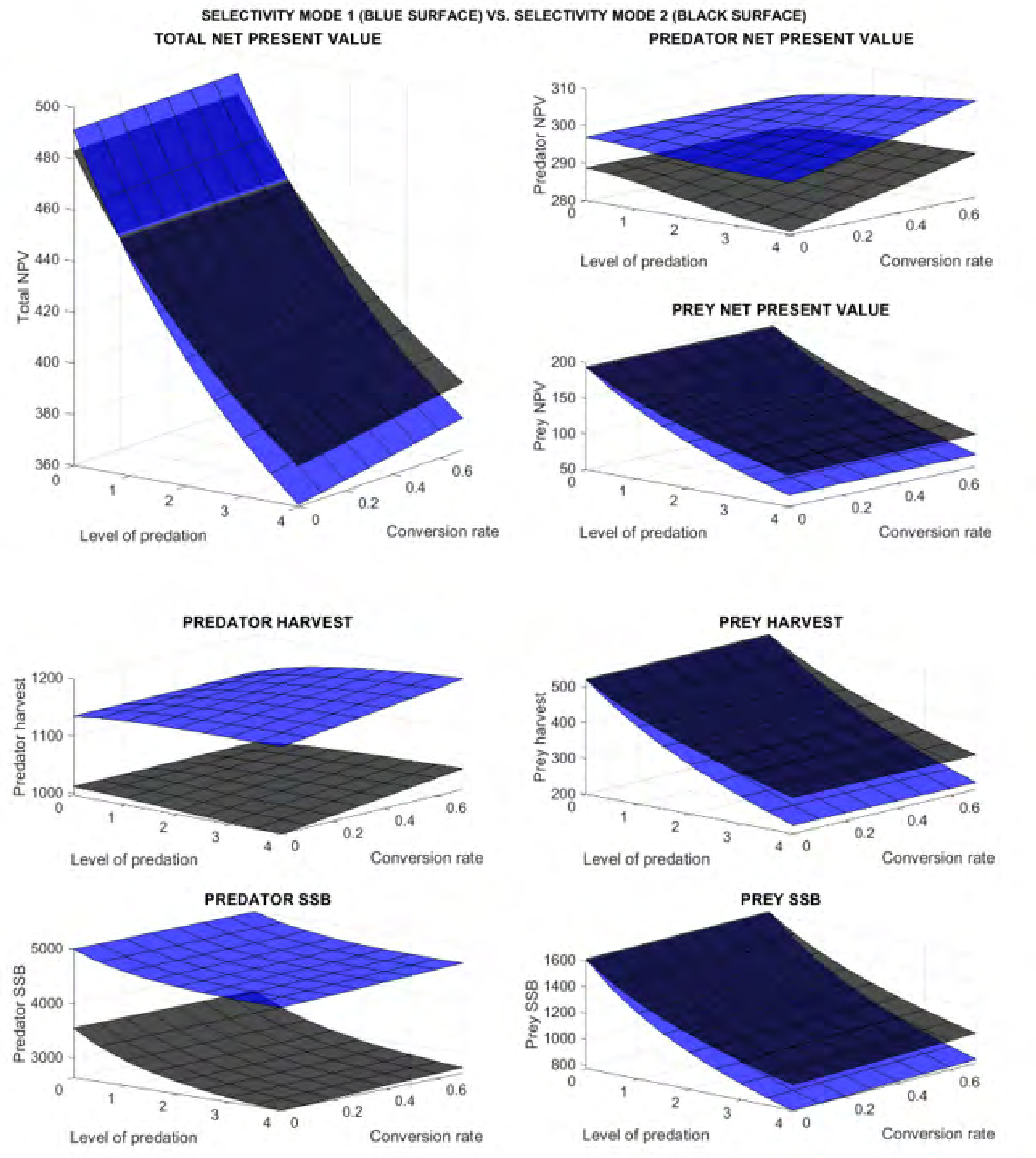

Figure 7: Key results from scenarios 7 and 8

Figure 7 shows the results from scenarios 7 and 8 in Table 3. That is, the scenarios with predation coefficients that increase disproportionally to base predator weights at age, and with non-uniform predation-weight conversion rates, and a decrease in the relative price of predator to prey (ref. Table 3 and Figure 2). As per expectation and reason, the results in Figure 7 shows the opposite of the results from scenarios 5 and 6. This makes sense because high predator harvest and good utilization of the individual predator growth potential becomes relatively less valuable when the price becomes relatively lower.

Conclusion

This study applies dynamic optimization in an age-structured, multi-fleet, predator-prey model. While we reproduce insight from age-structured single-species bioeconomic models, we also show that preferred selectivity and optimal harvesting change with the level of predation and predation-weight conversion rates.

In single-species age-structured models, a classical and recurring finding is that it is optimal to spare young fish for future harvest. For zero predation, our results confirm this. However, for increasing levels of predation, the benefits of targeting large predators are counteracted by disadvantages in terms of higher prey mortality, worsened utilization of individual growth potential for the prey, and lower catch per unit effort for the prey. At some point, the disadvantages can outweigh the benefits of targeting only large predators, thereby making it optimal to target smaller predator individuals and increase the overall fishing pressure for the predator. Further, it is shown that increasing predation-weight conversion rates can counteract this, more so when assuming uniform predation-weight conversion rates than when assuming predation-weight conversion rates that decrease with age, which is more realistic. Biomass models cannot give such insights because they do not describe age-specific details, including e.g., age-specific catchability, predation, and weight at age.

The findings are interesting and important because they bring awareness to why managers should think twice before changing gear restrictions in direction of targeting bigger fish on basis of single-species analyses. Moreover, they display the usefulness and value of age-structured multi-species modeling, which has not received much attention in the research literature.

For future research, we may suggest investigating the effects of predation coefficients that are age-specific for both predator and prey. To narrow the focus of this study, we assumed predation coefficients that are age-specific for predator, but age-unspecific for prey–that is, a predator of age a has the same selectivity on prey of age 1 as prey of age 2, etc. In the real world, a predator of age 3 may for example have a higher selectivity for prey of age 1 than prey of age 4, while a predator of age 10 may have a higher selectivity for prey of age 4 than of age 1. It could be interesting to study the implications of this for optimal selectivity and harvesting.

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Appendix

Table 5: Predator natural mortality rates

Age	3	4	5	6	7	8	9	10	11	12	13	14
$M_{pred,a}$	0.3	0.25	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Table 6: Prey base natural mortality rates

Age	1	2	3	4
$M_{prey,i}$	0.2	0.2	0.2	0.2

Table 7: Predator exogenous growth factors

Age	3	4	5	6	7	8	9	10	11	12	13	14
$w_{pred,a}$	0.2	0.4	0.666	0.863	1.116	1.439	1.824	2.286	1.81	2.017	1.649	1.43

Table 8: Prey weights

Age	1	2	3	4
$W_{prey,i}$	0.004	0.01	0.02	0.03

Table 9: Predator and prey recruitment parameters

Parameter	Numerical specification
α_{pred}	725 000
α_{prey}	128 000
β_{pred}	50 000 000
β_{prey}	50 000

Table 10: Predator maturity

Age	3	4	5	6	7	8	9	10	11	12	13	14
$\upsilon_{pred,a}$	0	0.003	0.049	0.27	0.58	0.81	0.94	0.98	0.99	1	1	1

Table 11: Prey maturity

Age	1	2	3	4
$\upsilon_{prey,i}$	0	0.5	1	1

Table 12: Predation mode 1 with scaling factor SC_p set to 1

Age	3	4	5	6	7	8	9	10	11	12	13	14
$p_{pred,a,1}$	0	0	1.00E-08	1.68E-08	2.56E-08	3.70E-08	5.14E-08	6.95E-08	8.38E-08	9.97E-08	1.13E-07	1.24E-07
$p_{pred,a,2}$	0	0	1.00E-08	1.68E-08	2.56E-08	3.70E-08	5.14E-08	6.95E-08	8.38E-08	9.97E-08	1.13E-07	1.24E-07
$p_{pred,a,3}$	0	0	1.00E-08	1.68E-08	2.56E-08	3.70E-08	5.14E-08	6.95E-08	8.38E-08	9.97E-08	1.13E-07	1.24E-07
$p_{pred,a,4}$	0	0	1.00E-08	1.68E-08	2.56E-08	3.70E-08	5.14E-08	6.95E-08	8.38E-08	9.97E-08	1.13E-07	1.24E-07

Table 13: Predation mode 2 with scaling factor SC_p set to 1

Age	3	4	5	6	7	8	9	10	11	12	13	14
$p_{pred,a,1}$	0	0	1.00E-08	1.85E-08	3.08E-08	4.81E-08	7.20E-08	1.04E-07	1.34E-07	1.70E-07	2.03E-07	2.36E-07
$p_{pred,a,2}$	0	0	1.00E-08	1.85E-08	3.08E-08	4.81E-08	7.20E-08	1.04E-07	1.34E-07	1.70E-07	2.03E-07	2.36E-07
$p_{pred,a,3}$	0	0	1.00E-08	1.85E-08	3.08E-08	4.81E-08	7.20E-08	1.04E-07	1.34E-07	1.70E-07	2.03E-07	2.36E-07
$p_{pred,a,4}$	0	0	1.00E-08	1.85E-08	3.08E-08	4.81E-08	7.20E-08	1.04E-07	1.34E-07	1.70E-07	2.03E-07	2.36E-07

Table 14: Conversion modes with scaling factor SC_w set to 0.5

Age	3	4	5	6	7	8	9	10	11	12	13	14
Mode 1 Υ_a	0	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Mode 2 Υ_a	0	0	0.5	0.45	0.4	0.35	0.3	0.25	0.25	0.25	0.25	0.25

Table 15: Predator fleet catchability modes

Age	3	4	5	6	7	8	9	10	11	12	13	14
Mode 1 $q_{pred,a}$	0	0	0	0	0	0	6.00E-07	1.20E-06	1.20E-06	1.20E-06	1.20E-06	1.20E-06
Mode 2 $q_{pred,a}$	0	0	0	0	6.00E-07	1.20E-06	1.20E-06	1.20E-06	1.20E-06	1.20E-06	1.20E-06	1.20E-06

Table 16: Prey fleet catchability

Age	1	2	3	4
$q_{prey,i}$	0.00E+00	5.00E-07	1.00E-06	1.00E-06

Table 17: Economic parameters

Economic Parameters	Numerical specification
T	100
r	0.05
P_{pred}	Scenarios 1-4 and 7-8: 15 Scenarios 5-6: 22.5
P_{prey}	Scenarios 1-6: 15 Scenarios 7-8: 22.5
C_{pred}	5000
C_{prey}	5000

Table 18: Predator initial values

Age	3	4	5	6	7	8	9	10	11	12	13	14
$N_{pred,\ a,t=0}$	705521	522663	407050	333265	272854	223394	182899	106845	44534	18562	7737	6754
$W_{pred,\ a,t=0}$	0.2	0.6	1.26	2.14	3.276	4.74	6.59	8.91	10.77	12.82	14.51	15.97

Table 19: Prey initial values

Age	1	2	3	4
$N_{prey,\ a,t=0}$	48443982	30465415	18558716	22190726

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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 $x_{2,\,t+1} = x_{2,\,t} - u_{2,\,t}$, $k_{2,\,t+1} = k_{2,\,t} - d_2 k_{2,\,t} + I_{2,\,t}$,

$u_{2,t} \le A_2 k_{2,t} x_{2,t}$, $x_{2,t} \ge 0$, $k_{2,t} \ge 0$, 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:

- $\text{Max}_{u_{1,t}\ge 0, I_{1,t}\ge 0} \sum_{t=0}^{T} e^{-rt}\left(\frac{P_{max}}{1+P_c\sum_{i=1}^{2}u_{i,t}}u_{1,t} - \frac{\alpha_1 u_{1,t}}{A_1 x_{1,t}} - \beta_1 I_{1,t}^{\gamma_1}\right)$ subject to $x_{1,t+1} = x_{1,t} - u_{1,t}$, $k_{1,t+1} = k_{1,t} - d_1 k_{1,t} + I_{1,t}$, $u_{1,t} \le A_1 k_{1,t} x_{1,t}$, $x_{1,t} \ge 0$, $k_{1,t} \ge 0$, 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.
- $\text{Max}_{u_{2,t}\ge 0, I_{2,t}\ge 0} \sum_{t=0}^{T} e^{-rt}\left(m_2 u_{2,t} + \frac{P_{max}}{1+P_c\sum_{i=1}^{2}u_{i,t}}u_{2,t} - \frac{\alpha_2 u_{2,t}}{A_2 x_{2,t}} - \beta_2 I_{2,t}^{\gamma_2}\right)$ subject to $x_{2,t+1} = x_{2,t} - u_{2,t}$, $k_{2,t+1} = k_{2,t} - d_2 k_{2,t} + I_{2,t}$, $u_{2,t} \le A_2 k_{2,t} x_{2,t}$, $x_{2,t} \ge 0$, $k_{2,t} \ge 0$, 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.

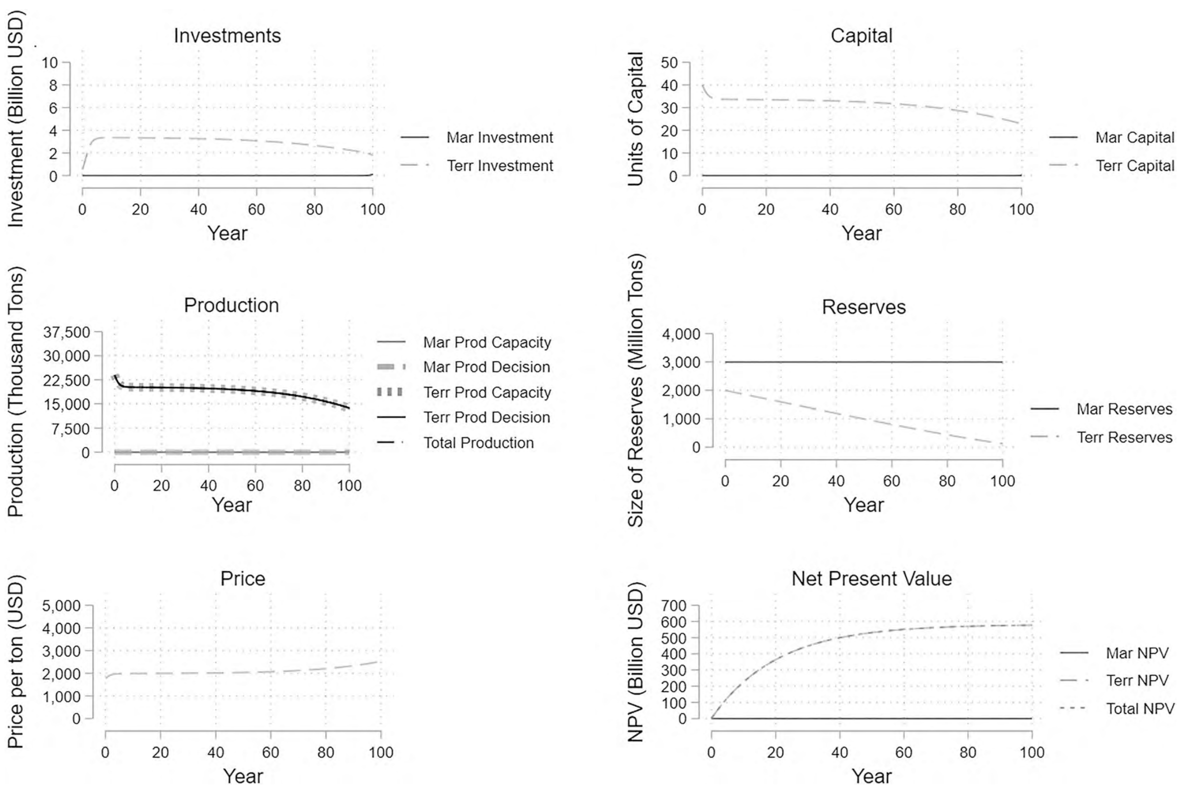

Fig. 1 Solution to problem 1: reserve-independent capital efficiency, no competition, and no mineral security considerations

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

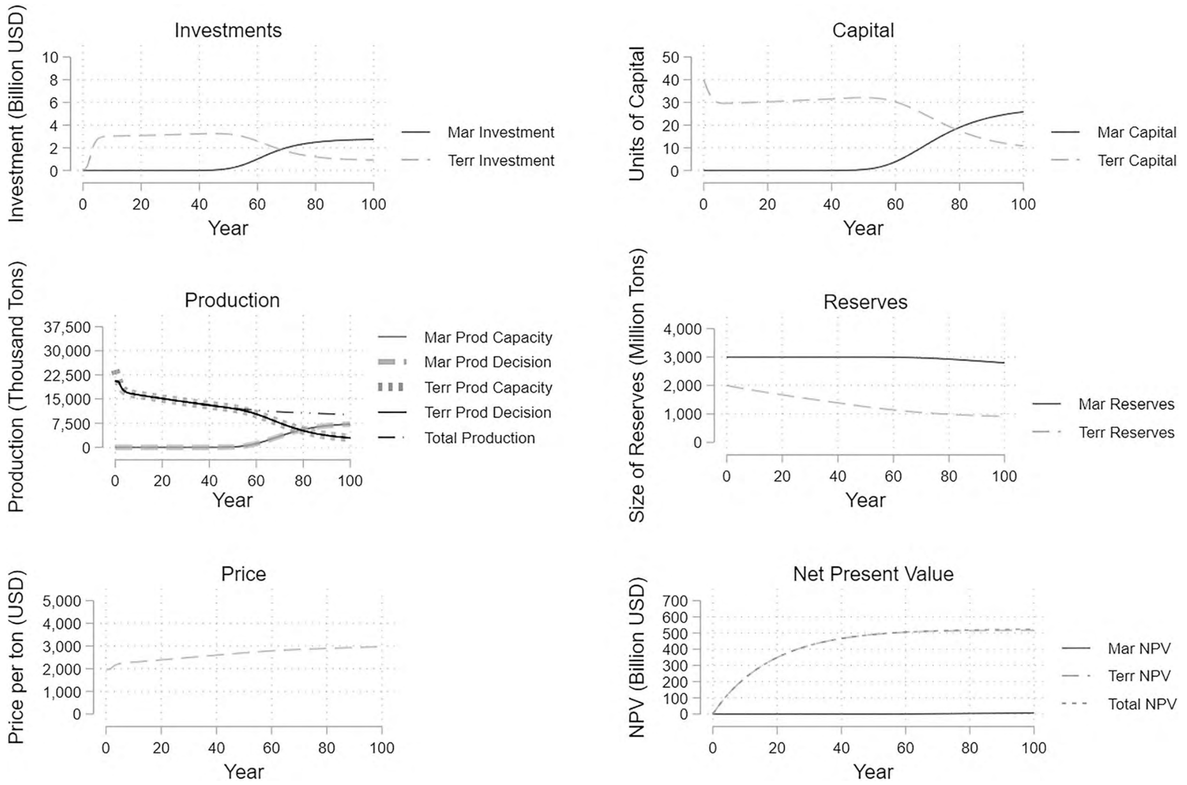

Fig. 2 Solution to problem 2: reserve-dependent capital efficiency, no competition, and no mineral security considerations

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.

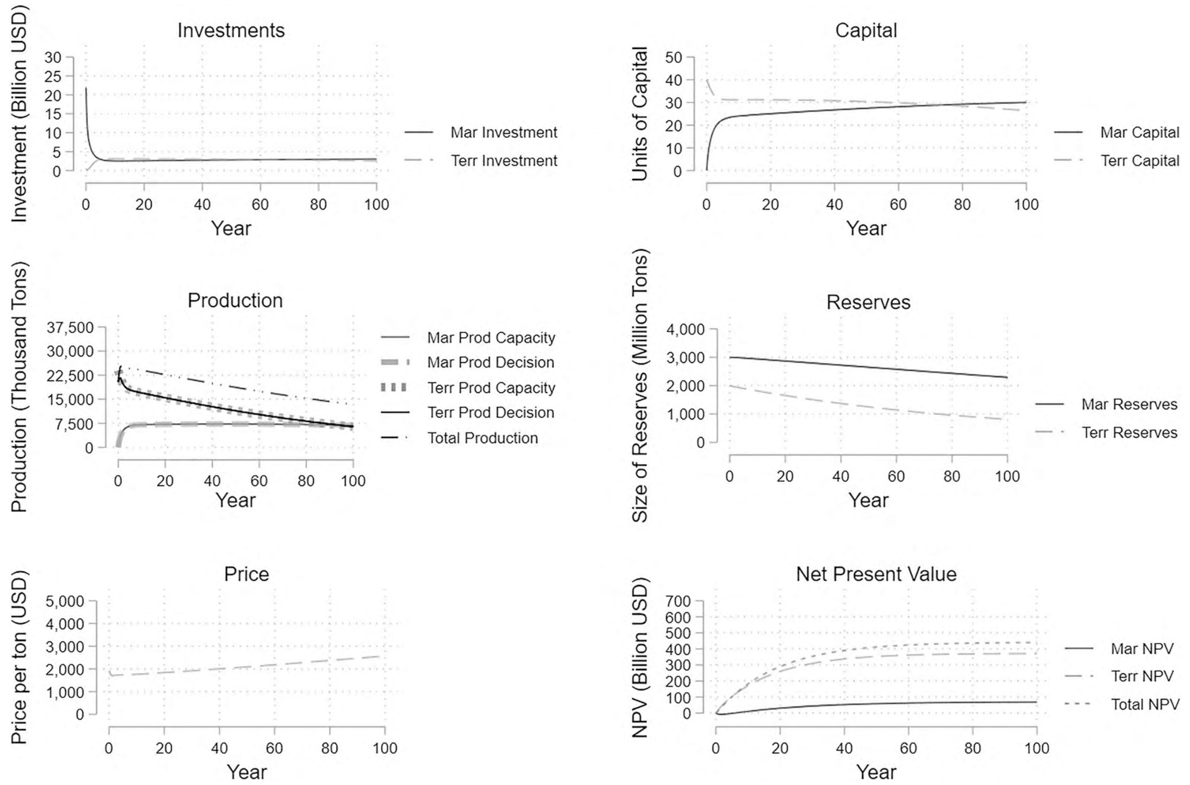

Fig. 3 Solution to problem 3: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

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

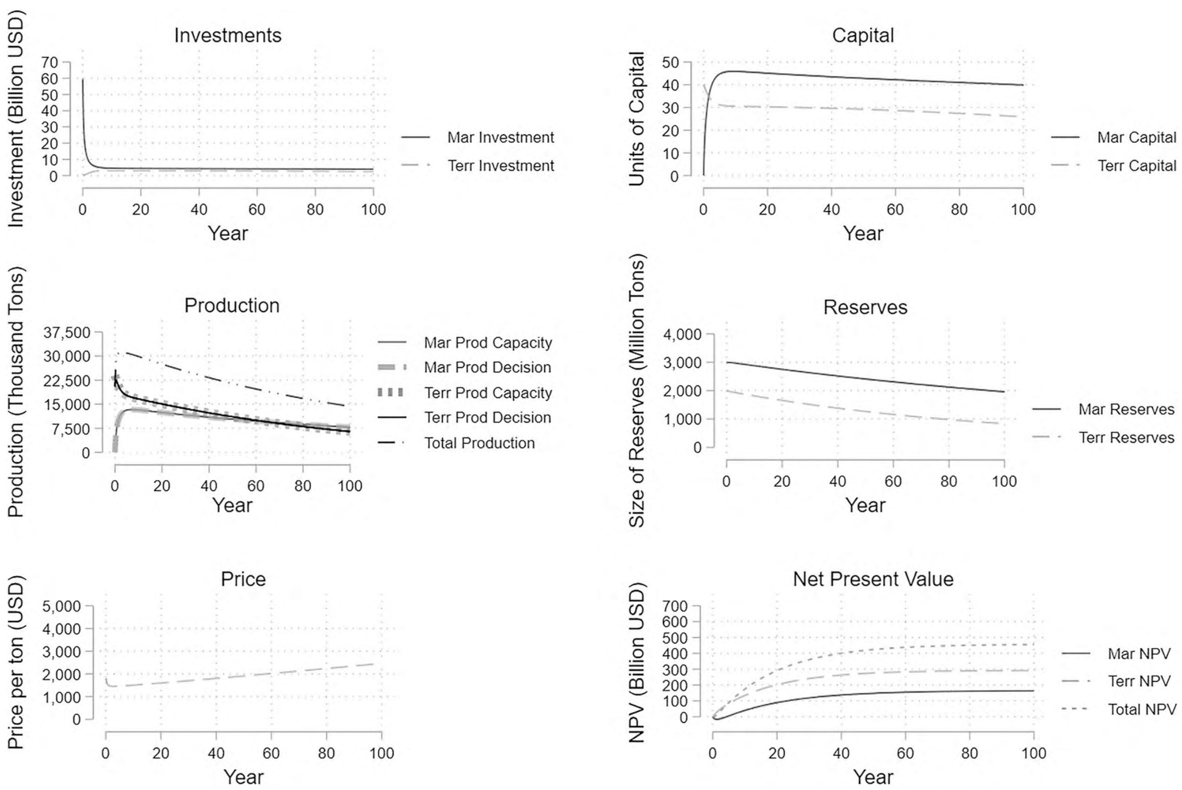

Fig. 4 Solution to problem 4: reserve-dependent capital efficiency, cross-sector competition, and asymmetric mineral security considerations

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

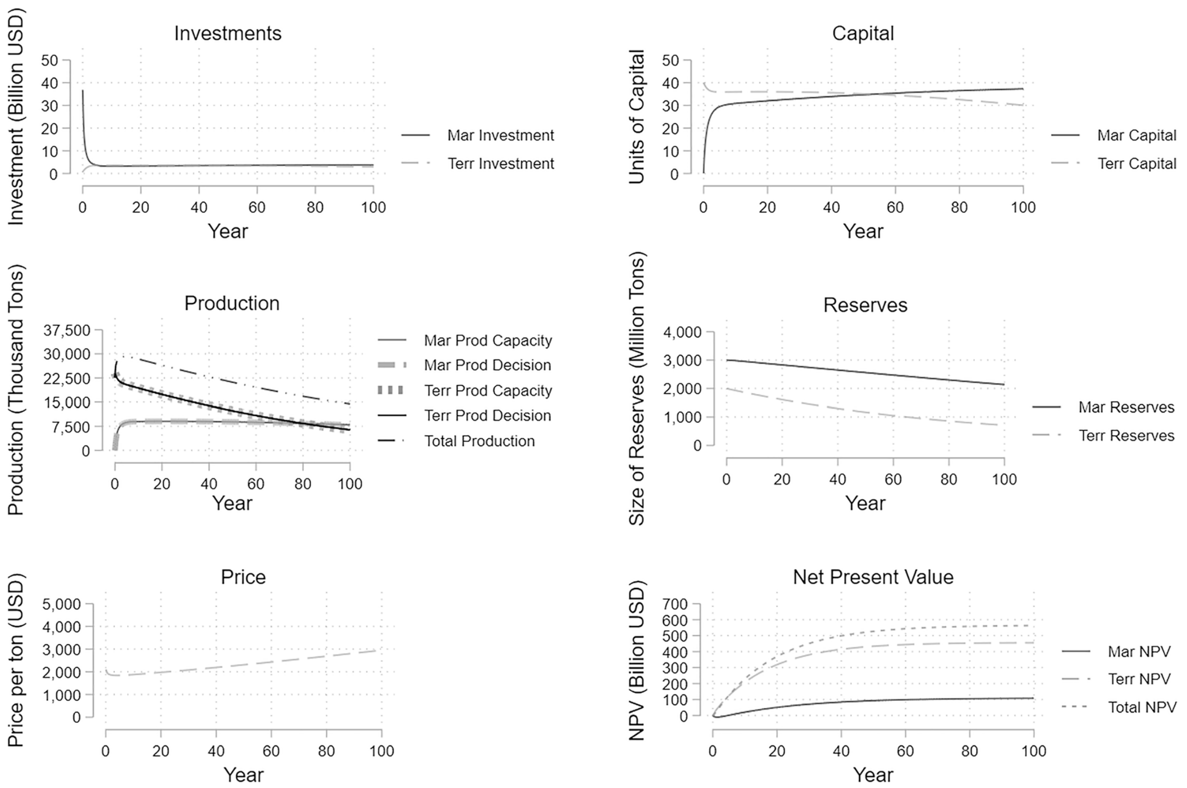

Fig. 5 Solution to problem 3 with 20% increase in P_{max}: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

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

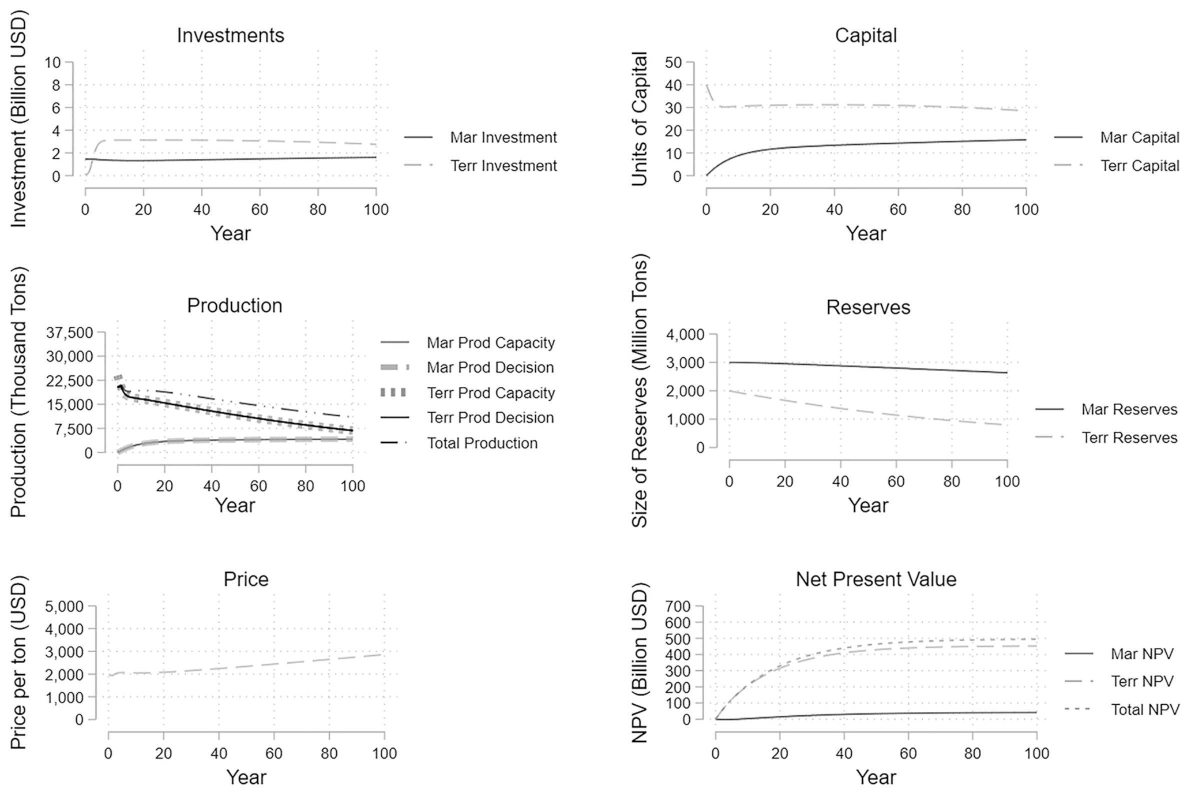

Fig. 6 Solution to problem 3 with doubling of γ_2: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

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,

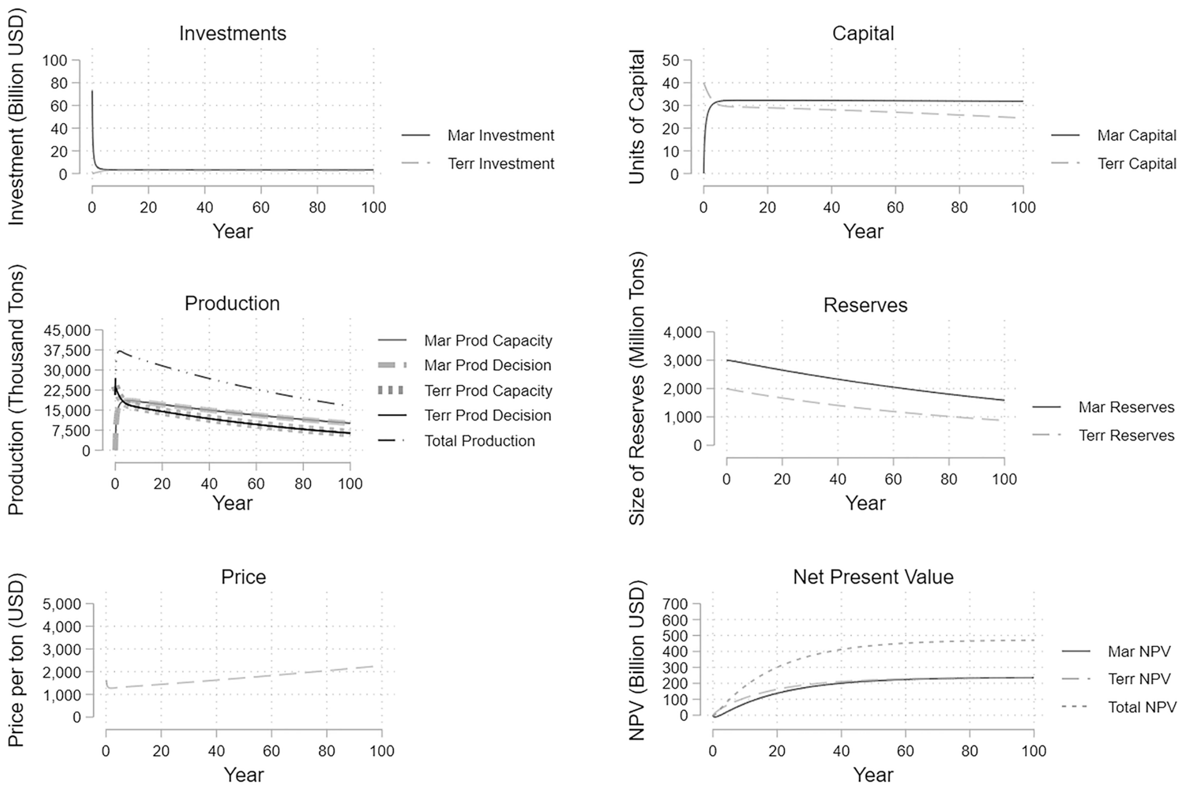

Fig. 7 Solution to problem 3 with doubling of A_2: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

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

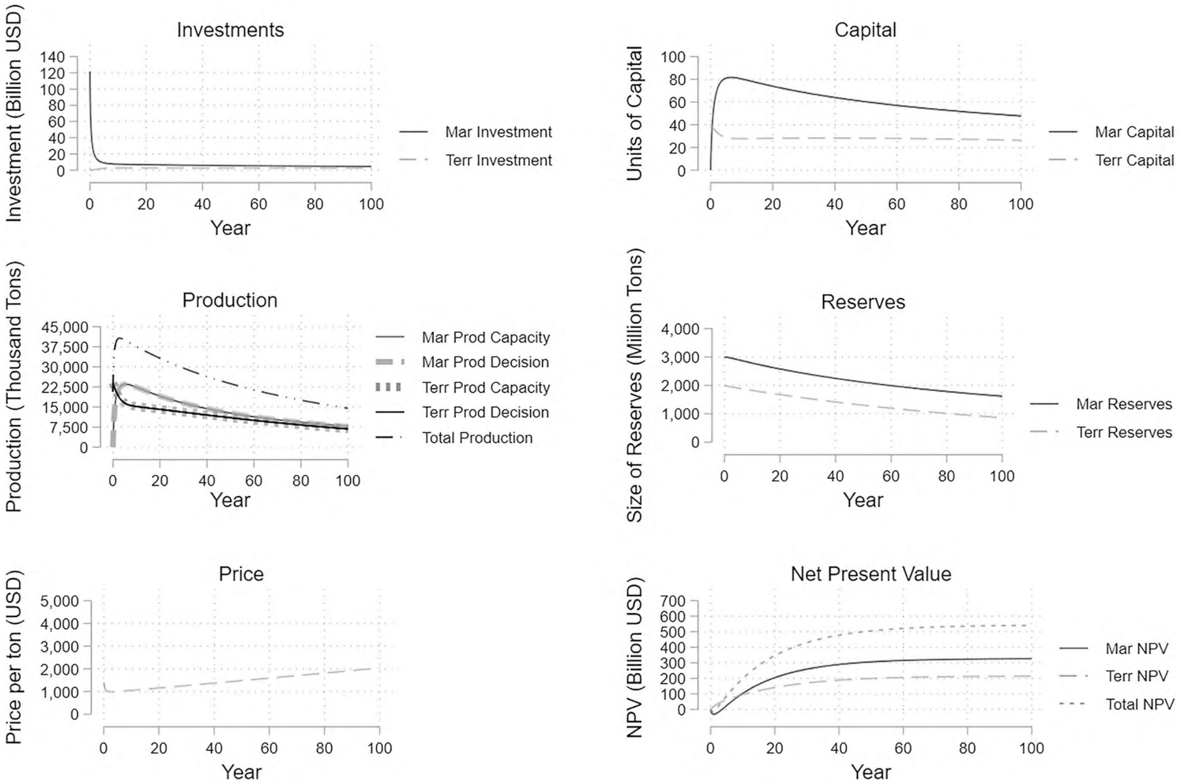

Fig. 8 Solution to problem 4 with doubling of m_2: reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations

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

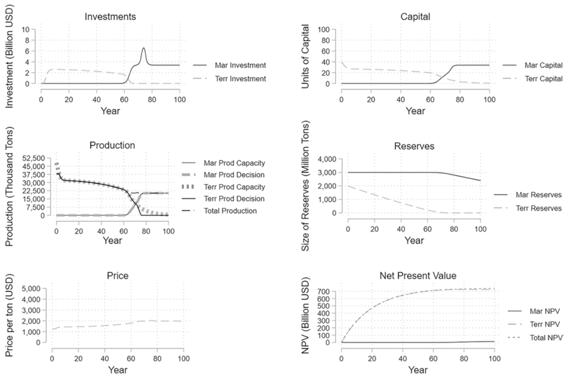

Fig. 9 Solution to problem 1 with doubling of A_1 and A_2: reserve-dependent capital efficiency, no competition, and no mineral security considerations

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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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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.

JEL classification: C63, D24, D25, Q30, Q32, Q33, Q34

Keywords: Deep-sea mining, marine minerals, seafloor massive sulfides

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Introduction

Global commercial supply of critical minerals is based on onshore mining and recycling (Kaluza, Lindow, & Stark, 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, Rühlemann, & Vink, 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 & Trellevik, 2022b).

The deep sea may be earth's final frontier – it is poorly explored and the knowledge gaps are significant (Lusty & Murton, 2018). Nevertheless – the deep sea is known to hold significant deposits of critical minerals (Hein, Mizell, Koschinsky, & Conrad, 2013; Petersen et al., 2016; Sharma, 2017). Marine mineral deposits were first identified in the 1870s (Sparenberg, 2019; Volkmann & 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 have yet been commercially successful (Childs, 2020; Hyman, Stewart, Sahin, Clarke, & Clark, 2022; Toro, Robles, & Jeldres, 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 & 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.

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 modeling, 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 JW, 1992; Luna-Reyes & 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.

Since the numerical and written databases for mineral resources and deep-sea mining on the NCS is 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 allow 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.

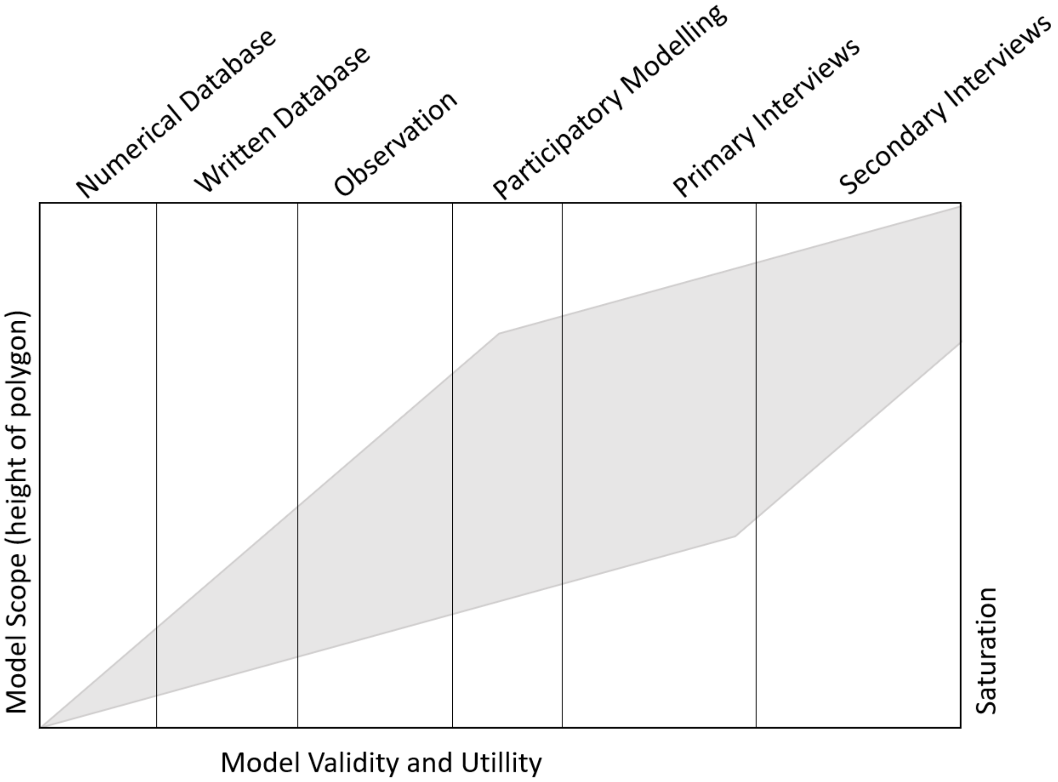

Figure 1: Illustration of the model development process and how it relates to model scope, saturation as well as model validity and utility

Repenning (2002), and later, Kopainsky and Luna-Reyes (2008) asserts that the system dynamics approach to developing models have many similarities with the concept of theory building. In this perspective, the methodology and modeling 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 modeling 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 Warnaars (2015), and Sharma (2017). Other sources worth mentioning include Jankowski et al. (2010) and Stanton & Yu (2010).

Observation

Observation is a valuable qualitative approach in the field of system dynamics (Luna-Reyes & Andersen, 2003b). Over a period of three 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 modeling, Group Model Building or Participatory Systems Mapping, are common knowledge elicitation methods within system dynamics (Hovmand et al., 2012; Vidal, Rostom, François, & Giraud, 2019; Videira, Antunes, Santos, & Lopes, 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 & 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 two hours. 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 & 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 modeling 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.

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 & Andersen, 2003a). Iterative disconfirmatory interviews allows 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 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 III.

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, 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 & Carpenter, 1990; Ford & 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 & 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 affords 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 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 & 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 degrees. 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; Rolf B Pedersen, Thorseth, Nygard, Lilley, & Kelley, 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 degrees Celsius – 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 & Bjerkgård, 2016).

Considering the vastly different properties of SMS deposits and Ferro-manganese 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 & 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 represents 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 meters 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 meters 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 hours at 3000 meters water depth – and with a charge, service, and data-download turnover of about 12 hours. 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-meter-deep drill-cores. One single core will require about 48 hours 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 have 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 & 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 & 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 I. 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).

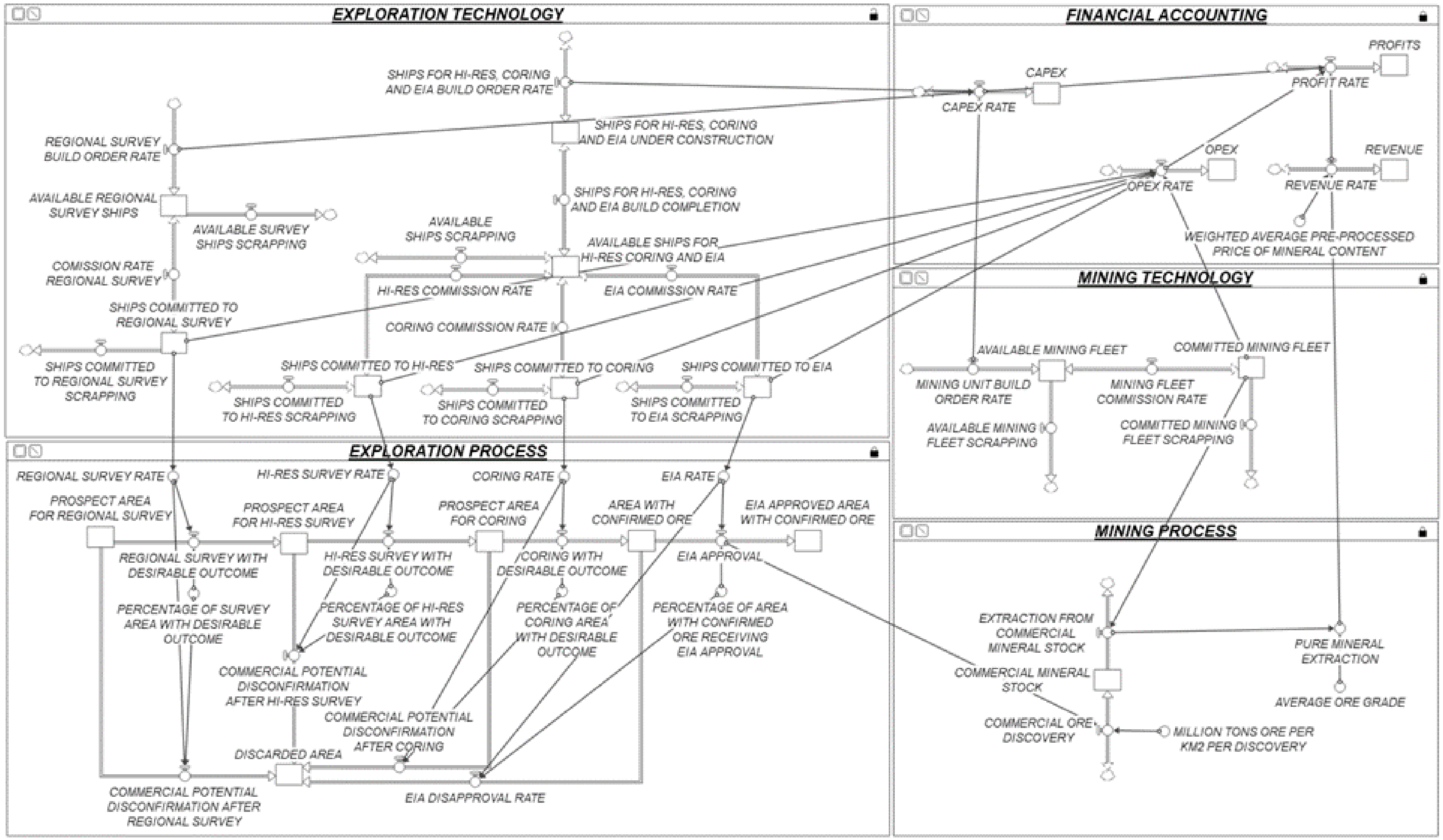

Figure 2: Simplified High-level Model Overview

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 square kilometers 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 figure x), 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 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 I. 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 I.

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 I. 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 include 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 I.

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 I.

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 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

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

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 I for further details). The baseline results are shown in Table 1 below.

The simulations 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, expects 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 lie 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.

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 accumulate 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 starts 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.

Fig. 3 below 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.

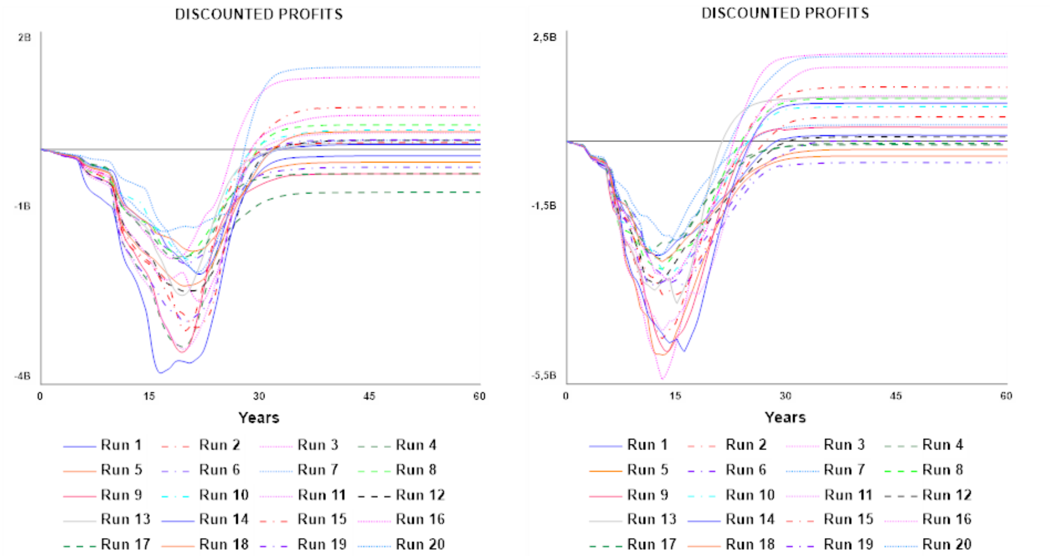

Figure 3: Discounted Profit Trajectories over a Random Selection of Monte Carlo Runs in the Medium Average Ore Grade Scenario with the 'Wait and See' policy (left) and the 'Anticipatory' policy (right)

Fig. 4 below 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" scenario. 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.

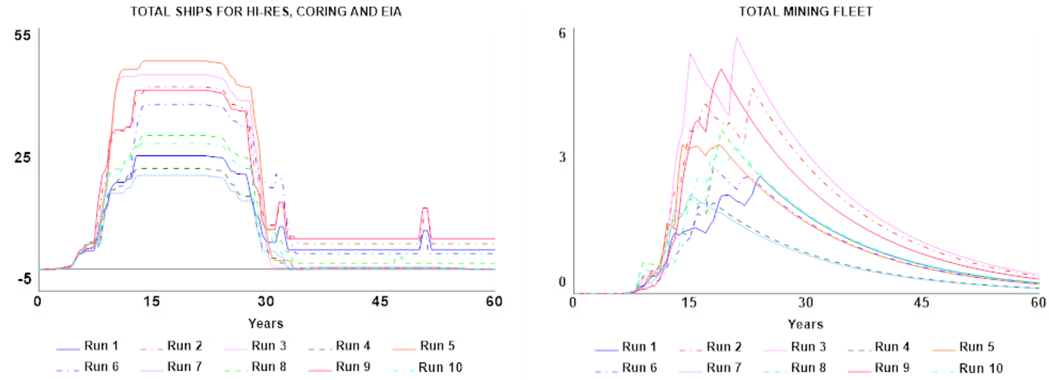

Figure 4: Total Ships and Mining Units Trajectories over a Random Selection of Monte Carlo Runs in the Medium Average Ore Grade Scenario with the 'Anticipatory' policy

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 include 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 is projected to increase demand for minerals (Boomsma & Warnaars, 2015; Haugan & Levin, 2019; International Energy Agency (IEA), 2021; Kaluza et al., 2018; NPD, 2021; Petersen et al., 2016; Ragnarsdóttir, 2008).

Although the study presented here include 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 reader is encouraged to further explore sensitivity, and the model in general (Bang & Trellevik, 2022a).

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

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]

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 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 scenario is the only scenario 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.

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]

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.

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]

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.

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]

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 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 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 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 commence 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 returns 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 transform 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 meters, 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.

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Appendix I

Detailed Model Description

Detailed Stock-and-Flow Diagrams for the Exploration Process and Exploration Technology

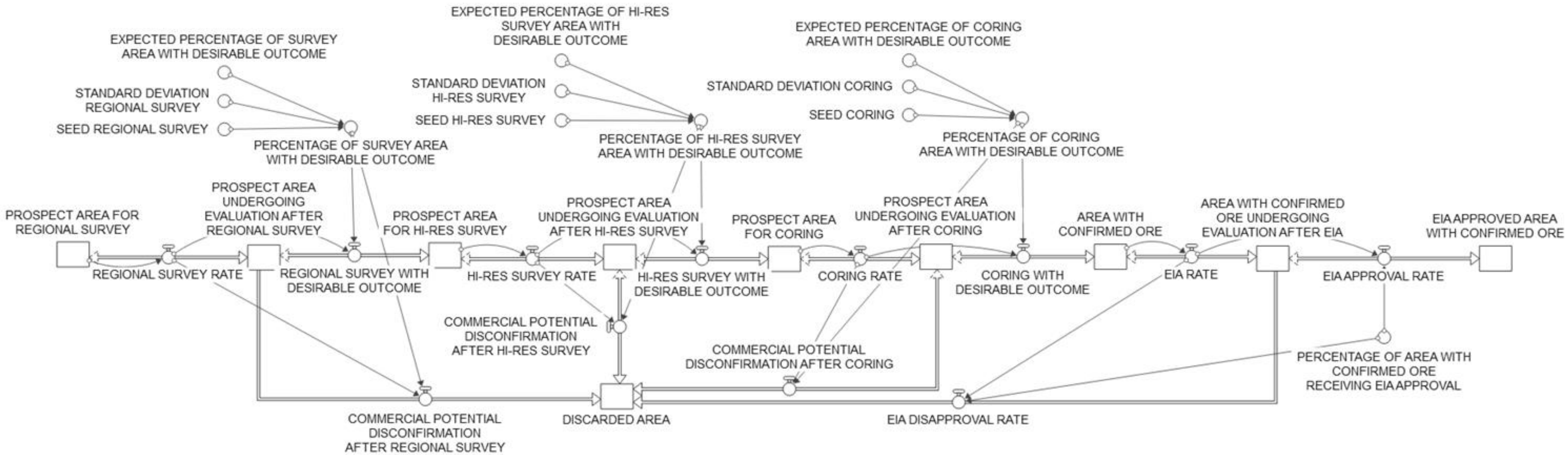

Fig. A1 Stock-and-Flow Diagram of the Exploration Process

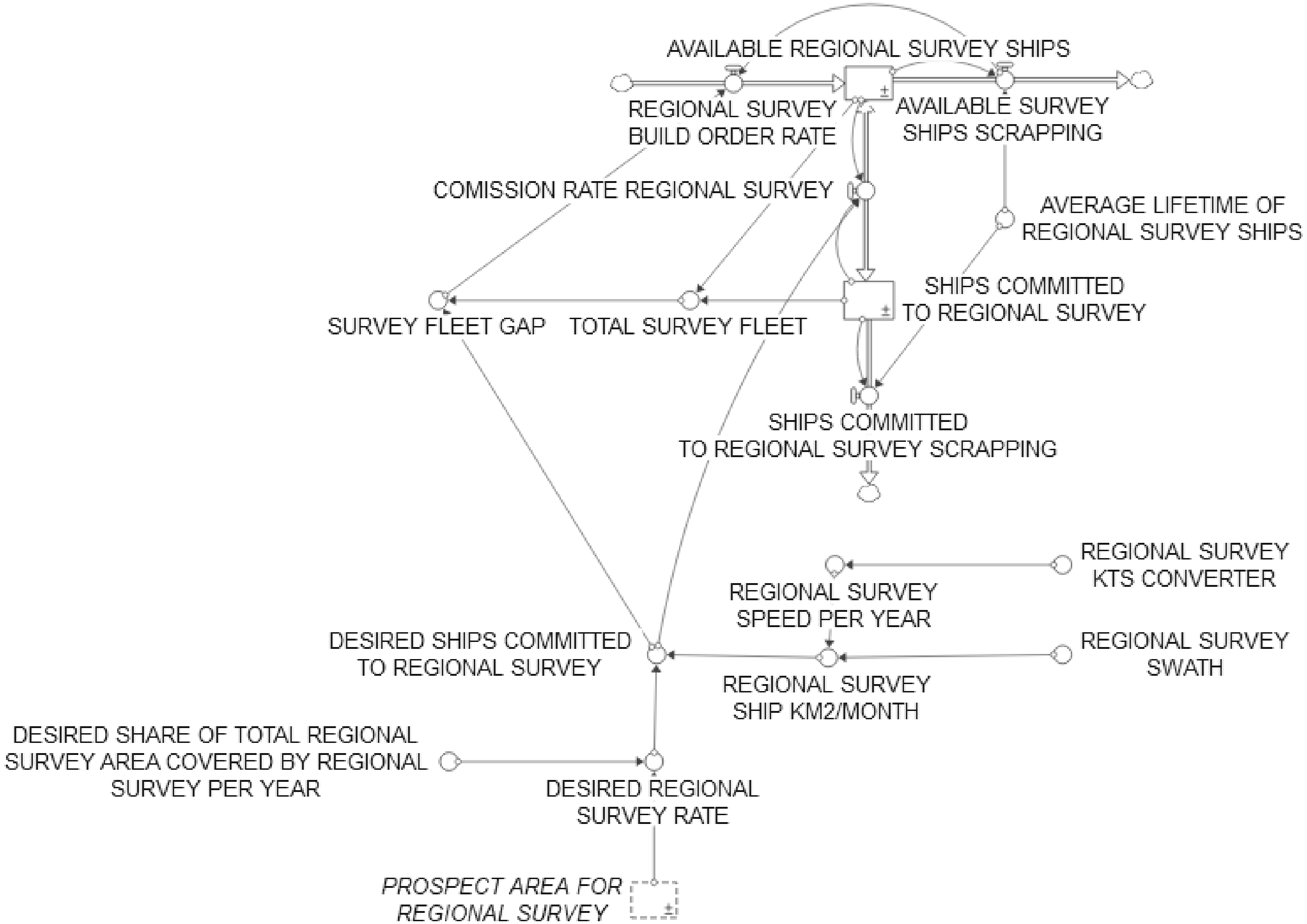

Fig. A2 Stock-and-Flow Diagram for Regional Survey Capital Structure

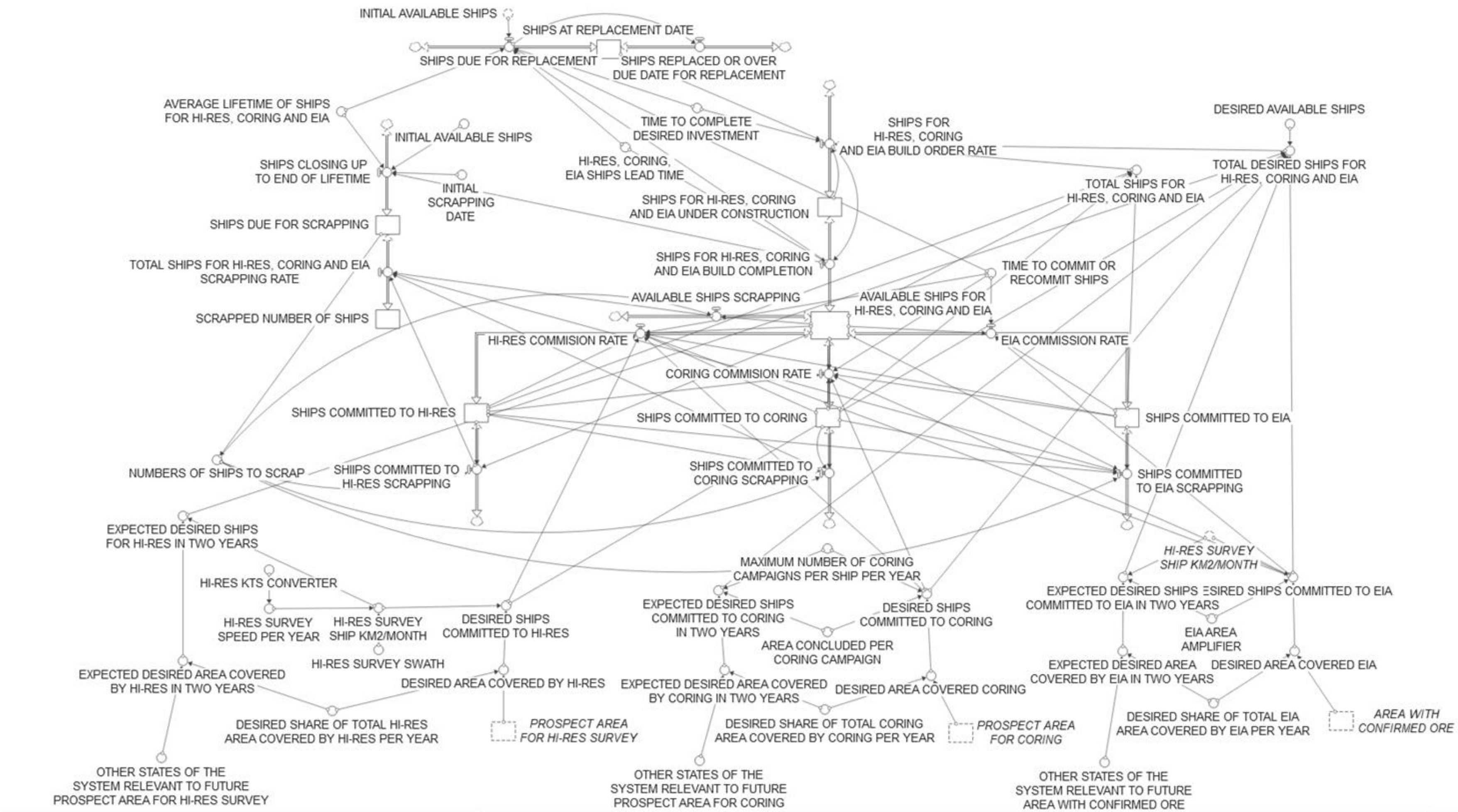

Fig. A3 Stock-and-Flow Diagram for Hi-Res, Coring and EIA Capital Structure

Detailed SFD for the Mining Process and Mining Technology

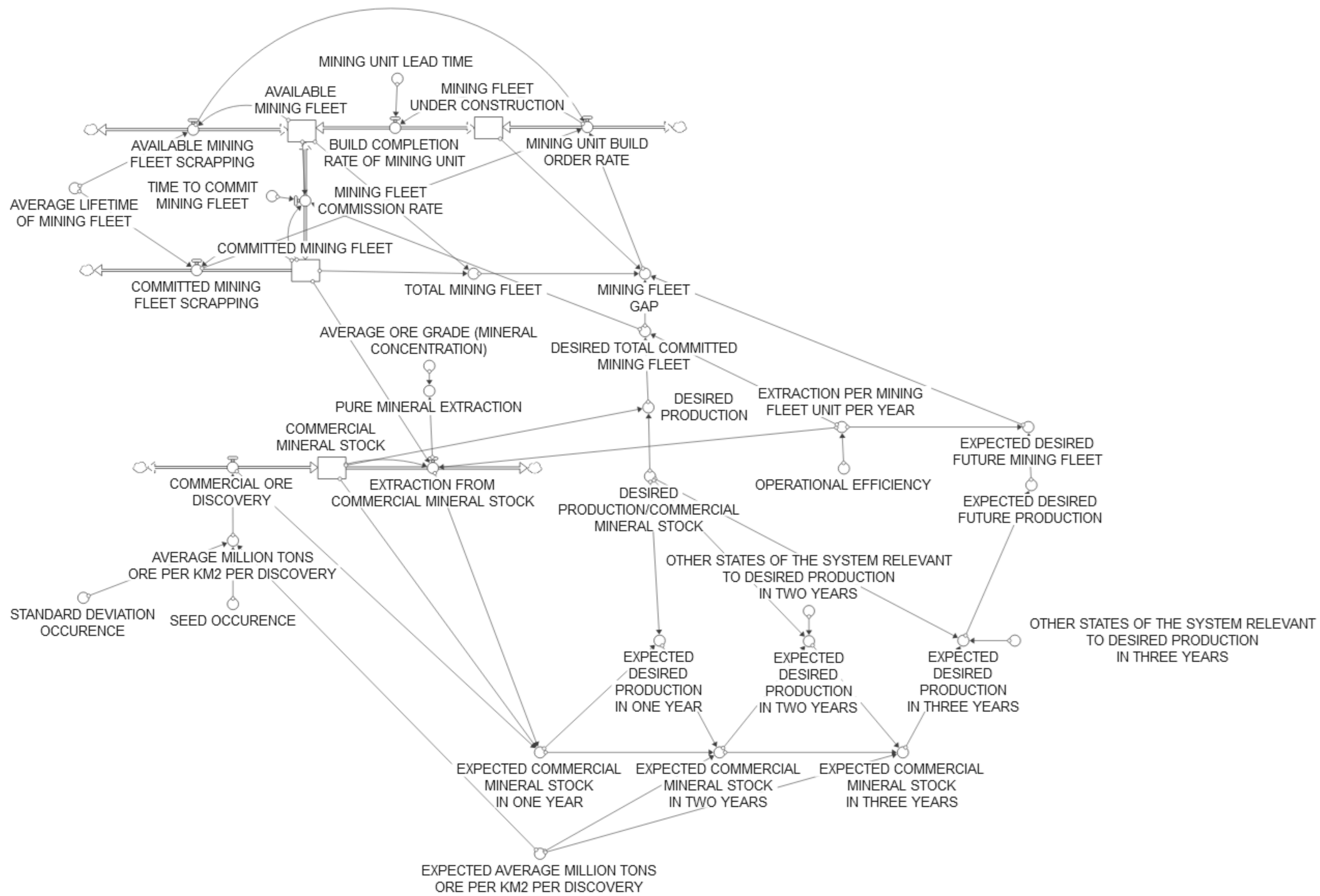

Fig. A4 Stock-and-Flow Diagram for the Mining Process and Technology

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 = 80000	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 hour 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.
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.
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. 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.
"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-		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)<0 THEN -"SHIPS_COMMITTED_TO_HI-RES"/TIME_TO_COMMIT_OR_RECOMMIT_SHIPS ELSE 0		
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.
"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.
"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_EI	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.

A_BUILD_COMPLETIO N"			
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.
"AVAILABLE_SHIPS_F OR_HI-RES,_CORING_AND_EI A"(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_F OR_HI-RES,_CORING_AND_EI A" = INITIAL_AVAILABLE_S HIPS	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_SC RAPPING	IF NUMBERS_OF_SHIPS_TO_SCRAP>0 AND "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA">NUMBERS_OF_SHIPS_TO_SCR AP 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_SCR AP 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_EI A_UNDER_CONSTRUC TION"(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_EI A_UNDER_CONSTRUC TION" = 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_SCR APPING(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_SCR APPING = 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.
"AVERAGE_LIFETIME_ OF_SHIPS_FOR_HI-RES,_CORING_AND_EI A"	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.
"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.
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.
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"-		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.

	(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_FOR_HI-RES,_CORING_AND_EIA"-(DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA)))/TIME_TO_COMMIT_OR_RECOMMIT_SHIPS ELSE 0		
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.
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.
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.
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.
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 km2 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_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.
"ORE_GRADE_(MINERAL_CONCENTRATION)"	0,04 | 0,05 | 0,06		The initial total extraction is set to 0.
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.
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-		The initial mining fleet under construction is set to 0.

	COMMITTED_MINING_FLEET>AVAILABLE_MINING_FLEET THEN AVAILABLE_MINING_FLEET/TIME_TO_COMMIT_MINING_FLEET ELSE 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.
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			
VARIABLES AND 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.
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*1000000	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	38808		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.
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	1000000000		The cost of procuring and commissioning deep-sea mining unit. The parameter is suggested 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	150000000		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"	100000000		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"	140000*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	140000*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	140000*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.
AVERAGE_COST_OF_REGIONAL_SURVEY_SHIP	35000000		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	82500*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
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
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 II

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 III

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?**		