Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management

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# Assessing the effect of potential tax regimes on investment incentives in future marine minerals projects on the Norwegian continental shelf from a corporate and a regulatory perspective

## A dynamic programming approach based on simulations

Master's thesis in Industrial Economics and Technology Management
Supervisor: Verena Hagspiel
Co-supervisor: Maxime Lesage and Farida Mustafina
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# Abstract

Global demand for metals has risen rapidly in the past few decades. The global energy transition is likely to increase the need for metals even more. To meet the forecasted demand the world needs to find new sources of metal. A possible alternative could be deep-sea mining. Mineral resources on the Norwegian continental shelf (NCS) have been mapped since the late 1990s by public actors. So far, private companies have not been given the opportunity to explore or mine for minerals on the NCS, but today the process of opening the NCS to commercial actors is well underway. It is expected that the application process for minerals exploration licenses on the NCS will open in 2023. However, many questions related to the specifics of opening the NCS for commercial exploration and potential exploitation are still open. One of these is the question on how companies operating on the NCS will be taxed.

In order to create insight important to the ongoing process of opening the NCS for mineral activity, we study how potential tax regimes would impact commercial interest. For this purpose we develop a methodology to assess the economic potential of a project of mining seafloor massive sulphides (SMS) deposits on the NCS, taking into consideration potential tax regimes that may apply to the Norwegian deep-sea mining industry. We take the perspective of a private operator company seeking to mine the NCS. We construct a valuation framework that accounts for multiple decision stages in the exploration process, as well as the decision whether to eventually mine the remaining prospects of interest by taking a dynamic programming approach based on simulations. Accounting for different potential tax regimes when calculating a project's expected net present value (NPV), we can analyse how different tax regimes affect the economic incentive of an operator company as well as the resulting expected net tax balance of a project from the perspective of the Norwegian state. We can also assess how various tax regimes affect the risk of a project from a corporate and a regulatory perspective. By performing a number of simulation runs we can analyse how a marine minerals project's economic downside risk compares to the upside potential the company and for the state.

Our results suggest that both operator companies and the state could benefit from sharing the risks associated with mineral exploration and extraction. A taxation system corresponding to the Norwegian petroleum tax (NPT) regime, however at lower tax and refund rates, appears to yield relatively high expected NPV for an operator company as well as relatively high net tax balance for the state. The project's economic upside potential with this type of system is relatively high for both the operator company and the state, while the downside risk is lower for both parties compared to alternative regimes. The exact NPT regime on the other hand is expected to be very economically unfavourable for the operator company, but has low downside risk. The NPT regime is also relatively economically unfavourable and risky for the state. Moreover, the Norwegian standard corporate tax (SCT) regime is expected to be quite economically favorable for the operator company but with high risk, yet economically unfavourable for the state but without risk. Tax regimes with a similar structure to the NPT regime, but at lower tax and refund rates, seem to demonstrate robustness in various investment environments. These tax regimes perform relatively well in terms of expected NPV and expected net tax balance across all tested economic conditions, compared to the NPT regime and the SCT regime. The NPT regime seems particularly ill suited in low and moderately favorable economic environments in terms of expected NPV and expected net tax balance. We also find that metal prices have the strongest impact on the economic viability of a marine minerals project.

Our main contribution is that we present a framework and results that can provide insight for the Norwegian government on relationship between the tax regime applied to the Norwegian marine minerals industry and private companies' incentives to invest in exploration and extraction projects.

# Sammendrag

Global etterspørsel etter metaller har økt raskt de siste tiårene. Den globale energiomstillingen vil trolig øke behovet for metaller ytterligere. For å imøtekomme den estimerte etterspørselen må man finne nye kilder til metaller. En mulig kilde er havbunnsmineraler. Mineralressurser på den norske kontinentalsokkelen (NKS) har blitt kartlagt siden slutten av 1990-tallet av offentlige aktører. Hittil har private selskaper ikke hatt muligheten til å lete etter eller utvinne mineraler på NKS, men i dag er prosessen med å åpne NKS for kommersielle aktører underveis. Det er forventet at søknadsprosessen for letelisenser på NKS vil åpne i 2023. Det er imidlertid flere ubesvarte spørsmål knyttet til detaljene rundt åpningen av NKS for kommersiell leting og potensiell utvinning. Et av spørsmålene er hvordan mineralselskaper som opererer på NKS vil bli beskattet.

For å bidra med innsikt rundt åpningen av NKS for mineralvirksomhet undersøker vi hvordan potensielle skatteregimer vil påvirke kommersiell interesse. For dette formålet utvikler vi et rammeverk for å vurdere det økonomiske potensialet til et prosjekt bestående av leting og utvinning av havbunnsmineraler i form av sulfider på NKS, som tar i betraktning potensielle skatteregimer som kan gjelde for den norske industrien for havbunnsmineraler. Vi ser prosjektet fra et privat operatørselskap som ønsker å utvinne mineraler på NKS sitt perspektiv. Vi utvikler et rammeverk for prosjektverdsettelse som tar i betraktning flere beslutningsstadier i letefasen, samt den endelige beslutningen hvorvidt de respektive gruvene i selskapets portefølje skal utvinnes, ved bruk av dynamisk programmering basert på simuleringer. Ved å ta hensyn til ulike potensielle skatteregimer i beregning av prosjektets forventede netto nåverdi (NNV), kan vi analysere hvordan ulike skatteregimer påvirker de økonomiske insentivene til et operatørselskap, samt den resulterende forventede netto skattebalansen fra et prosjekt sett fra den norske stats perspektiv. Vi kan også vurdere hvordan ulike skatteregimer påvirker prosjektets risiko sett fra operatørselskapets og statens perspektiv. Ved å gjennomføre flere simuleringer kan vi analysere et prosjekts økonomiske risiko sammenlignet med det økonomiske potensialet for både operatørselskapet og staten.

Våre resultater antyder at både operatørselskaper og staten kan dra nytte av å dele risikoen knyttet til leting og utvinning av havbunnsmineraler. Et skattesystem med tilsvarende struktur som det norske petroleumsskattesystemet (NPT), men med lavere skatte- og refusjonssatser, ser ut til å resultere i relativt høy forventet NNV for et operatørselskap, samt relativt høy netto skattebalanse for staten. Prosjektets økonomiske potensial ved denne typen skattesystem er relativt høy både for operatørselskapet og staten, mens nedsiderisikoen er lavere for begge parter sammenlignet med andre regimer. Det eksakte NPT-regimet forventes derimot å være økonomisk ufordelaktig for operatørselskapet, men har lav nedsiderisiko. NPT-regimet gir relativt høy nedsiderisiko for staten og er i tillegg forventet å være relativt økonomisk ufordelaktig. Videre forventes det at standard norsk selskapsskatt (SCT) vil være økonomisk gunstig for operatørselskapet, men med høy risiko, samtidig som det er økonomisk ufordelaktig, men risikofritt, for staten. Skatteregimer med tilsvarende struktur som NPT-regimet, men med lavere skattesatser og refusjonsrater, ser ut til å demonstrere robusthet i ulike økonomiske scenarioer. Disse skatteregimene presterer relativt godt når det gjelder forventet NNV og forventet netto skattebalanse under samtlige økonomiske scenarier undersøkt i denne oppgaven, sammenlignet med NPT-regimet og SCT-regimet. NPT-regimet virker spesielt uegnet i ugunstige økonomiske scenarioer basert på forventet NNV og forventet netto skattebalanse. Vi kommer også frem til at metallpriser er den faktoren som virker å ha den sterkeste innvirkningen på det økonomiske utfallet av et prosjekt for marin mineralutvinning.

Vårt hovedbidrag er at vi presenterer et rammeverk og resultater som kan gi innsikt for den norske regjeringen i forholdet mellom skatteregimet som gjelder for den norske marine mineralindustrien og private selskapers insentiver til å investere i prosjekter for leting etter og utvinning av havbunnsmineraler.

# Preface

This thesis is submitted as the concluding part of our Master of Science degrees in Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU), with specialization in Financial Engineering.

The thesis is written in collaboration with Maxime Lesage, an industry expert from the company Green Minerals. Green Minerals was founded in 2020 and aims to be a leading company in marine minerals on the NCS. We have also gotten valuable input from Steinar Løve Ellefmo, professor in the Department of Geoscience and Petroleum at NTNU, as well as Rasmus Noss Bang, PhD candidate in the Department of Business and Management Science at the Norwegian School of Economics. This has been very helpful in the design of our framework and enabled us to understand the processes of marine minerals projects.

We would like to thank our supervisor, Verena Hagspiel, professor in the Department of Industrial Economics and Technology Management at NTNU, and our co-supervisors, Maxime Lesage, Chief Engineer at Green Minerals, and Farida Mustafina, PhD candidate in the Department of Industrial Economics and Technology Management at NTNU. They have provided us with great insight and knowledge of both economics and engineering as well as constructive feedback throughout this project.

Trondheim, 11 June 2023

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# List of abbreviations

| | |
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| **30-25 PT** | Adjusted Norwegian petroleum tax (regime) with total tax rate 30 % and refund rate 25 % |
| **45-40 PT** | Adjusted Norwegian petroleum tax (regime) with total tax rate 45 % and refund rate 40 % |
| **60-55 PT** | Adjusted Norwegian petroleum tax (regime) with total tax rate 60 % and refund rate 55 % |
| **AUV** | Autonomous underwater vehicle |
| **CAPEX** | Capital expenditures |
| **CF** | Cash flow |
| **DCF** | Discounted cash flow |
| **EIA** | Environmental impact assessment |
| **GDP** | Gross domestic product |
| **ISA** | International Seabed Authority |
| **JOGMEC** | Japan Oil, Gas and Metals National Corporation |
| **kt** | Kilo tonnes |
| **LoLB** | Life of licence block |
| **MPE** | The (Norwegian) Ministry of Petroleum and Energy |
| **Mt** | Mega tonnes |
| **NCS** | Norwegian continental shelf |
| **NPD** | Norwegian Petroleum Directorate |
| **NPT** | Norwegian petroleum tax (regime) |
| **NPV** | Net present value |
| **OPEX** | Operating expenses |
| **PIS** | Pacific Island states |
| **pp** | Percentage points |
| **ppm** | Parts per million |
| **ppb** | Parts per billion |
| **ROV** | Remotely operated vehicle |
| **R&D** | Research and development |
| **SCT** | Standard corporate tax (regime) |
| **SIP** | Japanese Cross-ministerial Strategic Innovation Promotion Program |
| **SMS** | Seafloor massive sulphides |
| **Std** | Standard deviation |
| **TAG** | Trans-Atlantic Geotraverse |
| **UiB** | The University of Bergen |

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# 1 Introduction

The global demand for metals has rapidly increased in the past few decades. Today's society relies on various metals to produce essential products and services (Elshkaki et al. 2018). Also, the world is currently undergoing an energy transition with the aim to mitigate the effects of global warming and pollution. This will require growth in metal dependent industries like battery production, solar power, wind power, and electric infrastructure (Rystad Energy 2020), which will likely lead to further increase in the global metals demand. For metals like copper and zinc it is estimated that the demand in 2050 will be two to three times that of 2010 (Elshkaki et al. 2018). Even if recycling efforts will be increased, this is not expected to be enough to cover the estimated increase in metals demand (Rystad Energy 2020). This calls for the world to find new sources of metals. A possible alternative could be deep-sea mining.

The prospect of mining the deep seas is not new. Deep-sea mining projects were already underway in the 1960s and in an advanced stage of development by the 1970s (Sparenberg 2019). However, they were deemed economically and technically unfeasible in the early 1980s (Koschinsky et al. 2018). Recently, however, several public and private institutions have rediscovered their interest in exploring the prospects of deep-sea mining (Koschinsky et al. 2018). The recent surge in interest in deep-sea mining may be attributed to the boom in commodity prices between 2004 and 2011 (Sparenberg 2019), which made the prospect of mining marine minerals more attractive than before.

With regards to realizing commercial mining of the deep sea, only a few attempts have been made so far. In 2011, the Canadian The Metals Company was granted an exploration contract for the Clarion Clipperton Zone outside the coast of Mexico and south of Hawaii (The Metals Company 2023a). The Metals Company states now that it aims to start commercial production of minerals in the form of polymetallic nodules in 2024, and is planning to submit its application for mineral extraction later in 2023 (The Metals Company 2023b). Another Canadian company, Nautilus Minerals, was the first to be granted an extraction license already in 2011 for mining the Solwara 1 seafloor massive sulphides (SMS) mineral deposit, located in the Bismarck Sea outside the coast of Papua New Guinea (AMC Consultants 2018). The company had taken the project through a final profitability and feasibility study and was well underway in defining and building the mining system. However, financial issues put an end to Nautilus Minerals' work in 2019 (NPD 2021b). Thus, no company has yet been able to mine the deep sea commercially. As for testing of technological feasibility, the world's first full-scale pilot mining of marine minerals was carried out by the Japan Oil, Gas and Metals National Corporation (JOGMEC) in September 2017, in the East China Sea (NPD 2021b). To the best of our knowledge, only one additional large-scale pilot mining campaign has been conducted to date, by JOGMEC in July 2020 (NPD 2021b).

The process of facilitating for mining of marine minerals on the Norwegian continental shelf (NCS) is well underway. The Ministry of Petroleum and Energy (MPE) first submitted a proposal for legislation regarding mineral activity on the NCS in May 2017 (Regjeringen 2017). This legislation, the so-called Seabed Minerals Act, finally entered into force on 1 July 2019 (NPD 2022). However, exploration of minerals on the NCS has so far been exclusive to governmental actors. The first expedition dedicated to exploration of marine minerals on the NCS was conducted in 1998 by the University of Bergen (UiB) (NPD 2021b). Since then, the NPD, the Arctic University of Norway (UiT), NTNU, and UiB have all participated in expeditions on a nearly annual basis (NPD 2023). This has led to discovery of several potential seafloor massive sulphides (SMS) deposits as well as accumulations of manganese crusts on the NCS. Though, SMS have been the primary focus of recent research as the NPD has prioritised mapping of areas that exhibit the highest potential for significant mineral deposits based on the current knowledge, with SMS being the predominant type found in these areas (NPD 2023). The MPE has stated that it aims to present a white paper (Stortingsmelding) on the opening of the NCS for mineral activity by private companies in 2023 (Regjeringen 2022c). This in light of an impact assessment performed by the NPD, which was presented in 2022, with the conclusion that the impact from mineral activity on the NCS is manageable (MPE 2022). The MPE has stated that if the NCS is opened for commercial mineral activity, private companies will initially be given the opportunity to apply for exploration licenses for given areas (Regjeringen 2022a).

Even though the opening of the NCS for mineral activity is likely to happen in the near future, several of the framework conditions for potential deep-sea mining operators on the NCS are not defined. Among those, taxation is a crucial factor that has not been addressed in the Seabed Minerals Act (NPD 2021a), indicating that the Norwegian standard corporate tax (SCT) regime would apply. However, industry experts are sceptical whether such a tax regime would make a Norwegian marine minerals industry viable. The Norwegian Ministry of Finance has also indicated that a different tax regime, reminiscent of the regime that applies to the petroleum industry, could apply to deep-sea mining eventually (Regjeringen 2022b). The Norwegian petroleum tax (NPT) regime is very different to that of standard corporate tax (PWC 2022).

In light of the ongoing process of opening the NCS for mineral activity without a definite tax regime decided for the industry yet, we aim to analyse how different potential tax regimes might impact decision making in marine minerals projects. For this purpose we develop a methodology for valuating a project of mining seafloor massive sulphides (SMS) deposits on the NCS, that takes into consideration different tax regimes that may apply to marine minerals companies operating in Norway. We take the perspective of an operator company, i.e. a corporate decision maker, seeking to mine SMS deposits on the NCS. We construct a valuation framework that incorporates multiple decision stages within the exploration phase of a marine minerals project, including the decision whether to proceed with mining the remaining promising prospects in the operator company's portfolio. The resulting multi-stage decision problem is evaluated by taking a dynamic programming approach based on simulations. Specifically, we model the marine minerals project as a process consisting of four exploration stages prior to pilot- and full-scale mining. With each exploration stage, more geological information about the potential deposits in the operator company's portfolio can be unveiled. We account for several decision gates at which the operator decides for each potential deposit respectively whether to abandon or to progress to the next stage. The decision at each decision gate is based on the expected net present value (NPV), calculated using the obtained geological information at the time and simulations of the potential geological information that may be obtained in the future. Therewith, we can calculate the expected NPV of a minerals project consisting of several potential deposits from the operator's perspective. The framework also allows for calculation of the expected net tax balance from the perspective of the Norwegian state. This allows us to evaluate how different tax regimes for the Norwegian deep-sea mining industry affect the decisions made by the company in the different stages of a marine minerals project and the value of the project for both parties. We also evaluate how different tax regimes affect the risk of a marine minerals project on the NCS, both from a corporate and a regulatory perspective. This is made possible by stochastic modeling of geological uncertainties for the SMS deposits on the NCS, and by conducting multiple simulations within our framework for different tax regimes respectively. Thus, we obtain ranges of calculated NPVs for the operator company and net tax balances for the state, indicating the downside risk and upside potential of the marine minerals project under different tax regimes. Hence, the modeled framework allows us to gain insight into how various tax regimes incentivize investment in exploration and extraction of marine minerals on the NCS.

Our main contribution is that we present a framework that can provide insight for the Norwegian government on the relationship between tax regime and investment incentives in the Norwegian marine minerals industry. The framework also provides the Norwegian government with information about the results of its legislation, with regards to the state's net tax balance. To the best of our knowledge, we are the first to analyse how a regulator can incentivise commercial exploration and extraction of marine minerals through the tax regime it applies to the industry. We assume that a variety of the regime that has made the Norwegian oil and gas industry flourish may be applicable to the deep-sea mining industry as well. The framework presented in this thesis allows for analysis of this.

This thesis is organised as follows. Section 2 positions this contribution in the literature. Section 3 provides background information about deep-sea mining in general and specifically on the NCS as well as an introduction to tax regimes. Section 4 presents the decision problem studied and the developed modeling framework, and describes the solution approach. Section 5 present all data used for the base case calculations. Section 6 presents the results for the base case as well as the sensitivity analyses for all considered tax regimes together with discussions and critical reflections. Section 7 concludes our work.

# 2 Literature review

In this section, we position this thesis in the literature. First, we discuss the literature on economic assessment of marine minerals projects in the form of SMS. Second, we present different methodologies for valuating natural resource projects through the exploration phase.

## 2.1 Economic assessments of seafloor massive sulphides minerals projects

Several economical assessments of SMS minerals projects have been published. However, to the best of our knowledge, few of these assessments address the costs or the decision making of the exploration process for marine minerals, and thus the costs of the exploration process are in many cases are regarded as sunk. Also, most of the economic assessments published are based on discounted cash flow (DCF) approaches that are static in nature. For our case study in this thesis, we use data provided by several of the contributions discussed below.

Nautilus Minerals' attempt to mine the Solwara 1 deposit outside the coast of Papua New Guinea is the closest anyone has gotten to commercially mine an SMS deposit in the deep seas. Therefore the economic assessments of this project may be the most extensive available publicly. SRK Consulting (2010), which were consulting for Nautilus Minerals, provided detailed capital expenditures (CAPEX) and operating expenses (OPEX) estimates for the project at an early stage, taking into account procurement of all equipment necessary for operating a mine. However, the cost of exploration is not considered as most exploration of Solwara 1 had already been completed at the time of the report's publishing. AMC Consultants (2018), another consulting firm hired by Nautilus Minerals, present a detailed overview of the expected revenues and costs of almost all aspects of the Solwara 1 project, given a resource estimate based on the extensive exploration already performed by Nautilus Minerals. This overview includes procurement of all required equipment. Capital sunk prior to the time of release of the report is not considered, meaning that the cost of exploration is not considered. The results in terms of project value presented in the report are based on applying a DCF with a risk adjusted discount rate, based on Nautilus Minerals' preliminary mining plan. In this analysis taxation is considered by applying the Papua New Guinean marine minerals tax regime, which unlike the Norwegian tax regime for marine minerals mining, is already established and definitively determined. We adopt the OPEX estimates from SRK Consulting (2010) and AMC Consultants (2018) in our case study.

Pacific Community (2016) describe a preliminary economic cost-benefit analysis of deep-sea mining in the Pacific Island region. A framework is presented that is used to assess whether a mineral activity has the potential to increase welfare. Benefits and costs are defined as increase and decrease of social well-being, respectively. Monetary values to these benefits and costs are estimated. The following two metrics are used in this study to assess whether a mining project is beneficial to the Pacific Island region. The net social benefits, which equals the difference between the total present value of benefits and the total present value of costs, and the benefit-cost ratio, which equals the total benefits divided by the total costs. Both metrics take the perspective of the Pacific Island region, meaning that the revenues and costs of a mining company are not part of the benefits-costs analysis. However, the benefits and costs of a mining company are estimated in order to determine marine mineral mining's viability and the magnitude of payments to the host government through taxes and royalties. The framework is illustrated on the case of Nautilus Minerals' Solwara 1 project in Papua New Guinea, using large parts of the parameter set presented by SRK Consulting (2010). This study calculates the net social benefit and the benefit-cost ratio of the Solwara 1 project based on a DCF approach with a risk adjusted discount rate. Testing the sensitivity of the project value with respect to the discount rate they find that this parameter does not impact the net social benefit considerably. This is because the considered time horizon of the Solwara 1 project is quite short from the perspective of the Papua New Guinean government, being only the two years that Nautilus Minerals are assumed to be mining and thus generating revenue which are paid taxes and royalties on. However, in the estimates of Nautilus Minerals' costs for the project, the costs of exploration also are taken into account, in contrast to the studies mentioned above. To the best of our knowledge, this report is the only one adressing SMS marine minerals that considers the state's revenues and costs from a project in detail. Compared to the study of Pacific Community (2016) we focus on the state's perspective in terms of the effect of different regulatory choices and their expected consequences in terms of the state's net tax balance.

With regards to SMS projects on the NCS, several assessments of their economic potential and viability have been presented. Frimanslund (2016) proposes a production system concept for the Loki's Castle SMS deposit on the NCS, based on the proposed system for Nautilus Mineral's Solwara 1 project, presented in SRK Consulting (2010). Just like in SRK Consulting (2010), Frimanslund (2016) include procurement of all required equipment for exploitation in the total CAPEX, but exploration costs are disregarded. As in the previously introduced reports the project's NPV is calculated based on a DCF method with a risk-adjusted discount rate, given a proposed mining plan. As this may be the most detailed mining plan published for an SMS deposit on the NCS to this date, we adopt the proposed annual production from this report. Frimanslund (2016) considers two tax regimes for the Norwegian marine minerals industry in the DCF calculations, the SCT regime and the NPT regime. Performing sensitivity analysis on the metal prices under both tax regimes, the author finds that under the standard corporate tax regime, the project yields a negative NPV even for the highest considered metal price scenario. Under the petroleum tax regime, however, the project yields a positive NPV for the mean and the high metal price scenarios tested because losses early in the project corresponding to equipment procurement CAPEX are partly covered by the state. To the best of our knowledge, this is the most extensive analysis published on tax regimes for the Norwegian marine minerals industry. However, since the analysis does not consider exploration it does not cover how different tax regimes incentivize corporate decision makers through this process, in contrast to our analysis. Also, Frimanslund (2016) does not cover other unique tax regimes that may apply to the Norwegian marine minerals industry.

Lesage et al. (2019) present an economic block-model framework to value the Loki's Castle SMS deposit on the NCS. The framework is designed to allow the deposit's volume to be split into blocks of a given dimension. This way, each block can be valued individually, depending on the metals each block is assumed to contain. The paper considers only operational costs related to the mineral extractions of the deposit. The value of the deposit is calculated as the difference between revenues, calculated within a so called net smelter return methodology, and costs. Neither taxation on a mining company's profits or discounting on the generated cash flows is applied as elements in the valuation of the deposit. To our case study, we adopt the methodology presented by Lesage et al. (2019) in the current work to valuate the revenues of extracted ore. We also adopt the OPEX of the ore processing operation itself from this study.

Ellefmo and Søreide (2019) present an economic assessment of the value of the total resource potential of the extended NCS. The study provides resource estimates of the considered mineral accumulations in the form of probability distributions. In our thesis, we adopt the probability distributions presented by Ellefmo and Søreide (2019) for the number of SMS deposits per seabed surface area of permissive tract, ore tonnage per SMS deposit and metal grade of copper, zinc, gold and silver per SMS deposit on the NCS. In the book's valuation of the resource potential, the costs of extracting the minerals on the NCS are not considered. This study may be considered more geological than economic.

Bang and Trellevik (2022) present a stochastic dynamic simulation model for exploration and extraction of SMS mineral deposits on the NCS. The aim of the paper is to valuate the total resource potential in the form of SMS on the NCS. Bang and Trellevik (2022) model the exploration phase as a four-stage process where a successively smaller area of the NCS is explored as geological information is incrementally unveiled. Thus, unpromising areas are abandoned at each exploration stage and promising areas are progressed to the next exploration stage. This work motivates our choice to model exploration in terms of four stages. We also adopt the area-approach for the first two exploration stages to our model. Bang and Trellevik (2022) assume that investments are made in both exploration and mining equipment, so that the resulting CAPEX incorporates this. In contrast, we take the perspective of a pure operator company and therefore do not consider such investments. The revenues and costs corresponding to running a marine minerals project that considers the total resource potential of the NCS are found through Monte Carlo simulations on the whole project process. The exploration process involves decision gates, where it is decided on how large the area is that will undergo the consecutive exploration stage and thereafter mineral extraction. Thus, the CAPEX of the exploration process and the revenue and OPEX from the extraction process are derived using Monte Carlo simulations. However, the CAPEX and OPEX of exploration and extraction are not influenced by the applied metal grades in the model. This has the effect that the metal grades of the considered SMS deposits do not affect decision making on how large the area is that progressed through each stage in the exploration phase. This is something we address in our model, as the metal grades of deposits will affect decision making in a real-life scenario. In the model (Bang and Trellevik 2022) propose, the DCF method is used to valuate the resource potential of the NCS, using a risk-adjusted discount rate. However, taxation is not taken into account.

Andreassen and Borge (2022) present a framework for valuing an SMS minerals project on the NCS by taking a real options approach based on Monte Carlo simulations. In their framework, it is assumed that an initial mapping of an operator company's portfolio has been completed, meaning that the number of deposits, tonnage estimates and metal grade estimates are already obtained. Then, the company is given the option to either start production of its full portfolio, abandon the full portfolio, or to explore one deposit. The authors assume that exploration only consist of one activity that reveals all information about the explored deposit's ore tonnage and metal grades, and that the exploration activity takes exactly one year. If the option to explore is exercised, the company is assumed to have the option to start production of its full portfolio, abandon the full portfolio, or to explore one more deposit one year later with more information about the portfolio's value potential. If the option to explore one more deposit is chosen every year until there are no remaining deposits in the portfolio to explore, the company will have to decide whether to start production of its full portfolio or abandon the full portfolio. Monte Carlo simulations are performed to generate different metal price paths and to sample different ore tonnage and metal grades parameters from probability distributions. For each decision that must be made on whether to produce, abandon or explore, a separate Monte Carlo simulation is performed, where the DCF method is used with a risk-free discount rate to valuate the project for each simulation. We have taken inspiration from this for our framework. However, we use simulations in the form of a spanning tree rather than Monte Carlo because we assume independence between the different nodes in our spanning tree. Also, we do not consider market risk, like risk related to future metal prices. Andreassen and Borge's (2022) analysis result in a DCF distribution at each decision situation in the model of Andreassen and Borge (2022). Whether the company opts for production, abandonment or exploration is decided by thresholds for the DCF distribution. This is similar to how we use a k-th percentile rule at our modeled decision gates.

As evident from the contributions discussed above, most studies on marine minerals projects in the form of SMS apply a static DCF methodology for project valuation. Also, most existing studies do not consider the exploration process, and if they do so the majority of models presented fail to capture the intricate stages that comprise this process. In order to develop a comprehensive valuation framework for marine minerals projects that accurately reflects the realities of the industry, it is essential to consider the inherent risks associated with such projects and the decisions that take place at various stages.

## 2.2 Methods used to assess the value of natural resources through exploration under uncertainty

In valuating marine minerals projects on the NCS, it is in our opinion important to consider the exploration process as well as the extraction process, given the current developments. This is due to the fact that the MPE aims at opening the NCS for mineral activity in 2023 by initially allow private companies to apply for exploration licences. Valuating the projects that correspond to these licences should be of great interest for both private companies and the Norwegian state. Valuation of these projects requires modeling of a multi-stage exploration process with a certain degree of detail and incorporation of the managerial decision making this process involves. The resulting sequential decision problem a company would be faced with in a project could then be seen as a compound option.

Although the method is commonly applied, multiple sources highlight that valuing projects using the traditional DCF method has clear weaknesses (Dixit and Pindyck 1994; Humphreys 1996; Kim et al. 2017). Dixit and Pindyck (1994) state that a key weakness of the DCF method is the assumption of reversibility of all investments, meaning that investments can somehow be undone and the expenditures recovered should market conditions turn out to be worse than anticipated. Humphreys (1996) points out that the traditional DCF method fails to incorporate the managerial flexibility that decision makers in real-life projects have and that the necessity of employing exceedingly high discount factors to incorporate risk into the valuation process is not adequate, and that these weaknesses lead to undervaluation of projects. Kim et al. (2017) state that the traditional DCF method can be useful as a project valuation tool, but not in the case of highly volatile and uncertain investments, for projects in emerging markets, such as marine minerals mining. These sources suggest that a real options approach to valuate projects gives a more realistic estimate of a project's real value, which accounts for the managerial flexibility of real-life projects. Through a real options approach, it is also possible to illustrate the optimal investment decisions of the decision maker through completion or abandonment of successive stages of a complex multi-stage project (Dixit and Pindyck 1994), which can be helpful to capture the exploration process of marine minerals in project valuations.

Cortazar et al. (2001) present a real options model for valuing natural resource exploration investments, that can be applied to oil or copper for instance, with joint price and geological-technical uncertainty. The exploration project modeled in this paper can be seen as an infinitely compounded American option, however the approach is illustrated on a case with compounding of four stages. In the paper, one mine is considered and the model is structured such that a successful several-stage exploration phase leads to a development investment and then an extraction phase. If one exploration fails, the exploration is abandoned. Otherwise, the project could be temporarily abandoned or resumed depending on the expected value of the mine at the given time, which again depends on the current commodity price and geological-technical expectations. We adopt parts of the options approach presented in the study of Cortazar et al. (2001) to our model. We, however, view the multi-stage exploration project as a finitely compounded European option, as we do not account for the opportunity for early exercise of the option to progress a deposit to the successive stage. Cortazar et al. (2001) consider a less comprehensive exploration model where all required investments and probabilities for successful exploration are known up-front, which makes it easier to consider the possibility to delay a decision.Also, the study of Cortazar et al. (2001), along with most real options contributions, primarily focus on modeling market risk, in the form of commodity prices for instance. In contrast, we focus on modeling private risk in terms of geological risk related to resource based uncertainty and incorporate the market risk as a premium in the discount rate. Due to the constraints inherent in applying a real options framework to adequately capture the required level of complexity in our modeling objectives, as outlined by the study of Cortazar et al. (2001), we deviate from the conventional approach of real options. Traditional real options approaches are based on methods originally developed for financial option pricing and therefore, naturally focus on accounting for market risk like commodity prices. The framework we develop to assess the outlined multi-stage decision problem instead applies a dynamic programming approach based on simulations.

# 3 Background

In this section, we provide background knowledge that we consider essential to understand the model presented in this thesis. First, we briefly introduce the concept of deep-sea mining with regards to mineral resources on the NCS, as well as the process of exploring and extracting these minerals. Then, we present the current policies associated with the mining of marine minerals on the NCS. Last, we introduce different tax regimes that we view as candidates to apply for the Norwegian deep-sea mining industry.

## 3.1 A brief introduction to deep-dea mining

Deep-sea mining refers to the process of retrieving marine mineral resources (Koschinsky et al. 2018). Mining the deep ocean floor several thousand meters below the surface has regained strong interest in the later years and is considered a necessity to deal with the world's increasing metals demand (Elshkaki et al. 2018). To this day, however, no company has been able to commercially mine the deep seabed (Miller et al. 2021). Currently, there are still many uncertain factors about the potential of deep-sea mining, related to mineral occurrences, technology and legislation among others.

### 3.1.1 Marine mineral deposits and resources on the Norwegian continental shelf

Generally, deposits of marine minerals can be grouped into three types: Seafloor massive sulphides (SMS), polymetallic manganese crusts and polymetallic manganese nodules (NPD 2021b). The geological processes that form SMS are fundamentally different from the ones that form crusts and nodules. As earlier stated, only SMS deposits are considered in this thesis because this has been the primary focus of recent research and exploration on the NCS. Thus, only this type of deposit is further assessed in our work.

On the NCS, marine minerals have mainly been explored for and assessed in the form of SMS (NPD 2023). Figure 3.1 shows the confirmed mineral occurrences in the form of SMS and their location on the NCS. The confirmed SMS are mainly found along the volcanic Mohns Ridge between Jan Mayen and Bear Island, but indicated sulphide accumulations may also be found along the Knipovich Ridge, which joins the Mohns Ridge in the east and stretches north towards Svalbard (Brekke 2021). Both of the mentioned ridges are part of the Arctic Mid-Ocean Ridge and go as deep as about 3500 meters below sea level. They are characterised by tectonic and volcanic activity (NPD 2021b), which is a prerequisite for the formation of SMS deposits (Ellefmo and Søreide 2019). The metals found in the sulphide ores along these ridges are primarily lead, zinc, barium, copper, cobalt, gold and silver (NPD 2020).

There has been conducted dedicated exploration for marine minerals on the NCS for 25 years by now. UiB conducted the first exploration for marine minerals on the NCS in 1998 (NPD 2021b). Since then, expeditions have been carried out by NPD, the Norwegian Arctic University (UiT), NTNU, and UiB on nearly an annual basis (NPD 2023). These efforts have so far led to the discovery of the active and inactive hydrothermal accumulations on the NCS shown in Figure 3.1. Both types of hydrothermal accumulations confirm the presence of SMS accumulations (Brekke 2021).

### 3.1.2 Exploration for marine minerals

As in onshore mining of mineral deposits, marine mineral deposits first have to be explored before they can be mined, in order to map their resource potentials and to assess the economic viability of mining them. As deep-sea mining is such a new phenomena in a commercial setting, there still reigns uncertainty regarding the details of how the exploration process will look like in the future. However, we see the exploration of marine minerals in the form of SMS deposits as a four

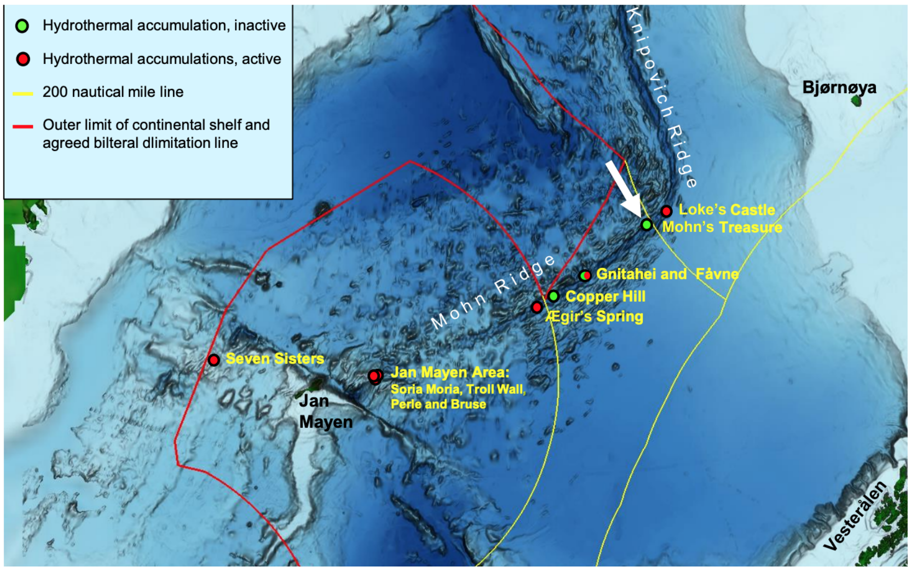


Figure 3.1: Confirmed and indicated occurences of SMS on the NCS

Source: Brekke (2021)

stage process, where each stage provides a decrease in geological uncertainty and a reduction in geographic boundaries. These stages can be categorised as

1) *regional survey*
2) *local survey*
3) *preliminary test drilling*
4) *extensive test drilling*

and are illustrated in Figure 3.2.

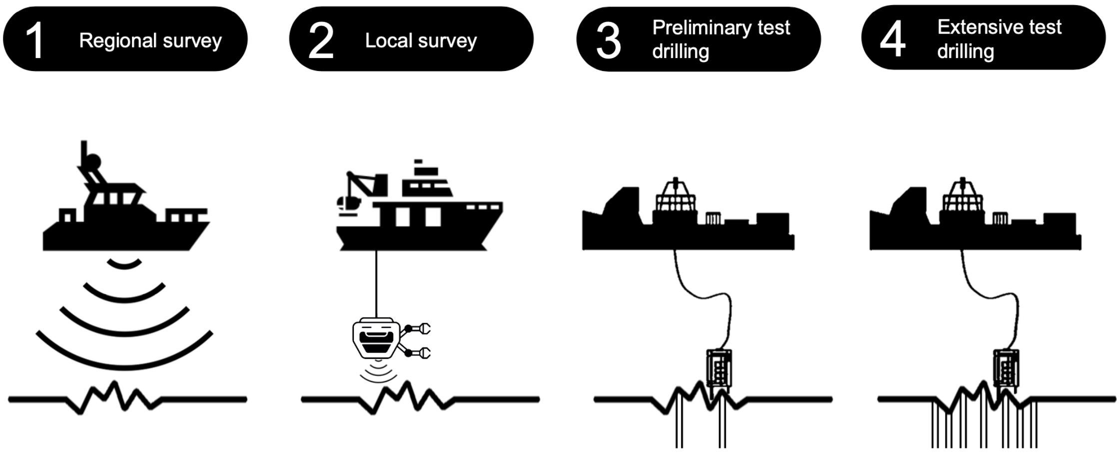


Figure 3.2: Stages in exploration for marine minerals

This categorization is in accordance with the exploration stages used in the model of Bang and Trellevik (2022), which was outlined with input from industry experts and stakeholders. This categorization is also in compliance with the exploration process that the NPD have used in their expeditions along the Mohns Ridge (NPD 2023), taken into consideration that they have not reached stage 4) *extensive test drilling* for any deposits. A similar categorization could also be deduced from explorations conducted at the TAG hydrothermal field on the Mid-Atlantic Ridge, in 2016, as part of the EU-funded Blue Mining project (Murton et al. 2019). In these explorations, indicated SMS deposits located beforehand and new ones located during the expedition were mapped using methodology in accordance with our proposed stages 2 and 3 (Murton et al.

2019). Also, in 2016 as part of the Japanese Cross-ministerial Strategic Innovation Promotion Program (SIP), a multi-stage seismic survey of the Izena Hole SMS deposit was carried out using methodology highly reminiscent of our exploration stages 1-3 (Asakawa et al. 2018).

### Stage 1) *Regional survey*

During the regional survey, one will likely survey a quite large area with a vessel that has echo-sounders or other acoustic sensors (Bang and Trellevik 2022). This is the methodology that has been used by the NPD and UiB since their very first exploration efforts in 1999 (NPD 2023). Unlike in exploration for oil and gas, the properties of the rock where marine minerals can be found may generally not allow for using seismic from the sea surface, as this method would not be able to capture SMS deposits in sufficient resolution with the current available technology (NPD 2021b). However, this is currently being researched (NPD 2021b) and in the SIP's exploration of the Izena Hole in 2016, an entirely seismic approach was used from a vessel (Asakawa et al. 2018). Also in 2016, at the TAG hydrothermal field on the Mid-Atlantic Ridge, information about the mineralogy below the maximum drilling depth was gathered by analysing seismic data from ocean bottom seismometers placed on and around SMS mounds (Murton et al. 2019). Nevertheless, using acoustic sensors to collect bathymetry (seabed topography) in search of geomorphological features that indicate the presence of SMS deposits would most likely be the initial way to proceed in this exploration stage (NPD 2021b). Thus, the regional survey will enable the explorer to identify areas of interest moving into the next phases of exploration.

### Stage 2) *Local survey*

In local survey, one will confirm that the indicated SMS deposits identified in the regional survey actually exist. A more advanced vessel, with a significant technical crew, carrying autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) will be utilised in this process (Bang and Trellevik 2022; NPD 2023; Sharma 2018). The AUVs will work on collecting high-resolution bathymetry using multibeam technology (Murton et al. 2019; NPD 2021b, 2023), meaning that acoustic sensors gather data with much higher resolution than in stage 1. This will provide the exploration crew with understanding of further needed exploration activities as well as an initial delimitation of the previously indicated SMS deposits (NPD 2021b). The ROVs will be able to collect samples of seabed rock that later can be analysed for mineral content as well as sampling the hydrothermal liquid coming from hydrothermal vents, which can indicate the properties of the deposit with regards to mineralization (NPD 2021b, 2023; Sharma 2018). In this exploration stage, deep-towed magnetics and electromagnetic methods could also be utilised in search of mineral induced anomalies on the seabed, which provide insight into mineral occurrences' horizontal extent (Hannington et al. 2010; NPD 2021b).

### Stage 3) *Preliminary test drilling* and Stage 4) *extensive test drilling*

After the local survey, the next exploration stage is to start coring or test drilling the deposits that look most promising. This exploration activity is crucial for physically confirming – or denying – the presence of exploitable minerals. Technologically, there are two main options for how this is carried out (Sharma 2018). One is using so-called coring units launched from a non-specialised vessel, that in principle are ROVs with drill rigs attached, with support from a large work-class ROV for replacement of coring tubes (Bang and Trellevik 2022; Murton et al. 2019; NPD 2021b; Sharma 2018). A different method involves using a highly specialised vessel with an on-board drilling system, but this is highly technologically complex and significantly more expensive than the other option (Sharma 2018). Therefore, the first method described here is the one further considered in this thesis. The sampled drill-cores, once analysed by geologists, provide an indication of the deposits' vertical extent and may provide a better understanding of the horizontal extent (NPD 2021b), which together gives an indication of the tonnage of ore that may exist in the deposit. Drilling for core samples is considered a necessary exploration activity as it is the activity that allows for generating resource estimates with regards to deposit specific mineralogy and ore content.

The difference between stage 3) *preliminary test drilling* and stage 4) *extensive test drilling* is the number of drill-core samples collected. Collecting core samples is a very capital intensive process. An exploration company would therefore first perform preliminary drilling, with a limited amount of drill holes, in the deposits that looked promising after the local survey, according to industry experts. The most promising deposits from this process would then again be subject to extensive test drilling, with a significantly larger amount of core samples collected from each deposit.

### 3.1.3 Extraction of marine minerals

As extraction of marine minerals not yet has been done with commercial success, the optimal designs of extraction processes and technologies are not yet agreed upon. However, a few different technologies for mining the deep seas have already been built. The Japan Oil, Gas and Metals National Corporation carried out the first pilot mining of SMS in September 2017. This was a fully integrated test with execution of extraction, fragmenting and lifting of ore from an SMS deposit at 1600 meters depth (NPD 2021b). Nautilus Minerals had a similar system built and tested on land, but they did not manage to do pilot mining before they went bankrupt (NPD 2021b). An example of a possible ore extraction process is shown in Figure 3.3.

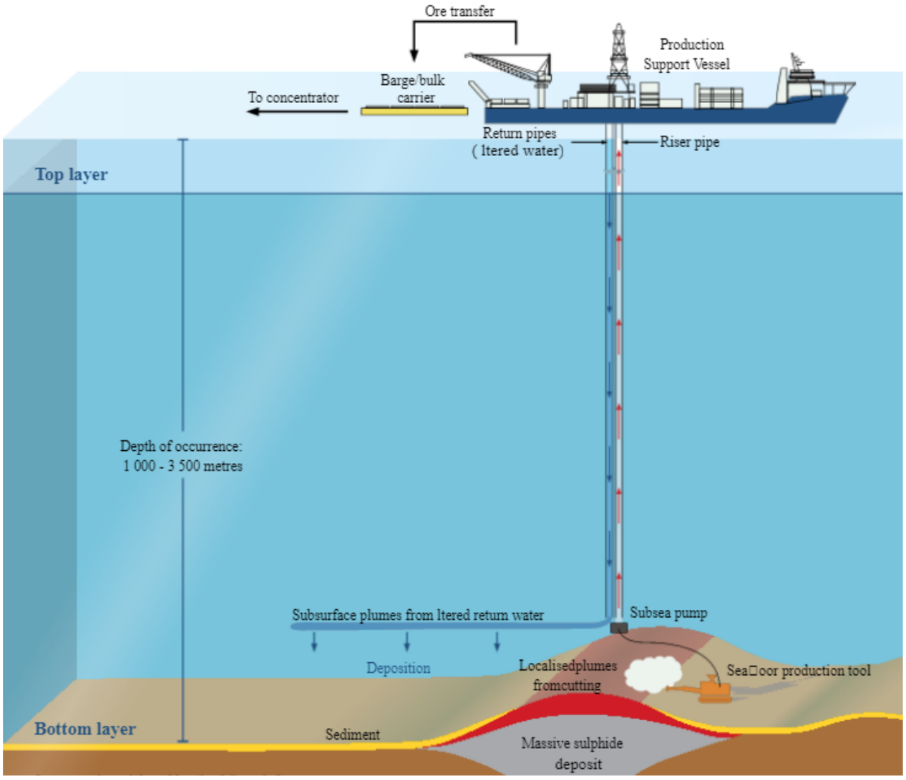


Figure 3.3: System for extraction of an SMS deposit

Source: NPD (2021b)

It is quite clear that the needed technologies for mining ore in the seabed include subsea drilling units capable of excavating ore and loading this ore into an accompanying ore-transportation system. Any methods for excavating SMS deposits would rely on mining machines would in any case use cutting and suction techniques to release the ore from the seabed and prepare the ore for surfacing (NPD 2021b). Several designs using different technologies for both vertical and horizontal excavation systems have been proposed by different companies, but the vast majority of the technologies are yet to be tested in realistic working conditions (NPD 2021b).

The ore-transportation system would likely be a riser system utilizing subsea pumps and piping that directly transfer mined ore to the surface (AMC Consultants 2018; SRK Consulting 2010), or a mechanical system that lifts the ore in some type of containers after it has been temporarily stored and accumulated in so-called buffer bins (Bang and Trellevik 2022; NPD 2021b).

Once the mined ore has risen to the surface, it will have to be received and pre-processed on some sort of platform or vessel. A large production support vessel is likely to be the first receiving end of ore at the surface (AMC Consultants 2018; Bang and Trellevik 2022; SRK Consulting 2010). This vessel could be comparable to a typical drill ship. The pre-processing done on this vessel would have to be de-watering of the ore slurry that the vessel receives. This can be done by screening, centrifuging, hydrocycloning and filtering (NPD 2021b). This way the ore is dried and excess seawater can be pumped back into the ocean, only retaining a limited amount of particles of very small size (NPD 2021b).

The last important part of the mineral extraction process can be seen as the transporting of ore to shore, so that it can be further processed and the minerals themselves can be separated from the ore. This transportation is expected to be done by barges or transport-ships (Bang and Trellevik 2022; SRK Consulting 2010), which will require ship-to-ship transfer of ore from the production support vessel. This can be done by floating hoses. This technology is almost identical to the one used by floating production storage and offloading units (FPSO) in the petroleum industry for transporting oil and gas (NPD 2021b).

## 3.2 Deep-sea mining policies on the Norwegian continental shelf

### 3.2.1 Legislation

Deep-sea mining as a commercial phenomena is immature, since no commercial mining of the minerals in the deep sea currently exist. However, many states have national legislation for mineral activities both within their jurisdiction and outside, in the so-called Area controlled by the International Seabed Authoroty (ISA) (ISA 2022b). Though, as per November 2022 the ISA's own regulations on the exploitation of mineral resources in the Area are still only a draft (ISA 2022a). This indicates that worldwide, legislation on mineral activity in the deep sea is still deficient.

#### The Seabed Minerals Act

The Norwegian legislation regarding deep-sea mining so far consists of the Seabed Minerals Act, which entered into force on 1 July 2019 (NPD 2022). The objective of this act is to "facilitate exploration for and extraction of mineral deposits on the Continental Shelf in accordance with societal objectives, in such a manner that safeguards considerations such as value creation, environment, safety, other business activity, as well as other interests." (NPD 2021a). Some central paragraphs of the Seabed Minerals Act for this thesis are summarised below.

| | |
|---|---|
| **§2-2** | The MPE is responsible for conducting impact assessments prior to opening of new areas for mineral activities, with regards to environment, as well as the expected impact on business, economic and social factors. |
| **§3-2** | A survey license neither gives exclusive rights to conduct surveys in the areas comprised by the license nor preferential rights in connection with the granting of extraction licenses. |
| **§4-1** | An extraction license gives the licensee the exclusive right to conduct surveys for and extraction of all mineral deposits in the area covered by the license. |
| **§3-1 & §4-2** | An application fee must be paid for both an exploration license and an extraction license application. The MPE issues regulations regarding the amount of the fee. |
| **§4-4** | If a licensee in an extraction license decides to extract a mineral deposit, the licensee shall submit a plan for extraction of the mineral deposit to the MPE for approval. This plan shall be adapted to the scope of the activity and contain a description of the extraction and an impact assessment. The impact assessment shall include commercial and environmental factors, such as preventive and remedial measures, |

and information about how a facility can be decommissioned upon cessation of the mineral activity.

| | |
|---|---|
| **§4-10** | The licensee under the production license becomes the owner of the minerals that are produced when they are brought up from the seabed to the sea surface. |
| **§5-1** | A licensee is obliged to ensure prudent clean-up while mineral activities are undertaken and after they have ended, and shall carry out measures as determined by the MPE as regarding clean-up and cessation. |

#### Environmental impact assessment

As stated above, the MPE is responsible for conducting environmental impact assessments (EIAs) prior to opening of new areas for mineral activities (§2-2). The report on the MPE's final assessment was published 27 October 2022. The report concludes that mineral activity related to exploration and closure will only make low impact on the environment (MPE 2022). As for mineral extraction, the report concludes that today's knowledge indicates that mitigating measures can be made for most of the impacts (MPE 2022). These conclusions make opening of the NCS for mineral activity look promising. The MPE's EIA-report was on hearing in the Storting the 27 January 2023.

In addition to the MPE's EIA prior to opening for mineral activities, mineral extraction companies will have to perform their own EIAs. As stated in the Seabed Minerals Act §4-4, an extraction licensee wanting to start extraction of a mineral deposit must submit an extraction plan including an impact assessment on commercial, but maybe more importantly environmental factors. This assessment is carried out by first doing broad-spectrum survey of the prospect area, by using numerous sensors in collecting a very large amount of baseline data on biological and ecological factors (Bang and Trellevik 2022). This should be done in parallel with all the exploration stages described in Section 3.1.2. This is the only way to set accurate baselines and to enable proper documentation on the effect that human intervention on the seabed has on the ecosystems surrounding (potential) mineral deposits (Ellefmo, personal communication). After the exploration phase, the next step of EIA is to perform pilot mining (Lesage, personal communication). During pilot mining, a deposit is mined as described in Section 3.1.3 for a limited amount of time and more data on biological and ecological factors is collected. This data is then compared to the data gathered throughout the exploration phase, to analyse what effect mining had on the ecosystem surrounding the deposit. This analysis would be the most important part of the EIA-section in the extraction plan that is submitted to the MPE for the deposit. It would be very risky for a company to avoid doing the described preparation work through the exploration stages and pilot mining, as it would not provide the company with the necessary knowledge to provide a proper EIA-section for their extraction plan. The MPE might then be likely to disapprove the plan.

### 3.2.2 Opening for exploration license applications in 2023

The MPE aims to present a white paper (Stortingsmelding) on the opening of the NCS for mineral activities in the spring of 2023 (Regjeringen 2022c). Thus, it is expected that private companies can start to apply for mineral exploration licenses in 2023. The basis for decision making on whether to open for mineral activities is the impact assessment done by the MPE as well as the input on the hearing on the Storting regarding said impact assessment, mentioned above. The area of the NCS that is covered by the opening process for mineral activities is the pink area shown in Figure 3.4. The orange area has also been considered but will not be opened for mineral activities in the first instance (Regjeringen 2022a).

According to the Norwegian Minister of Petroleum and Energy, the opening of the proposed area for mineral activities is crucial to start exploration activity and acquire further knowledge of resource potential and environmental impacts. However, he insists that the fact that the MPE's impact assessment will be on hearing in the Storting does not mean that the MPE possesses enough information to be able to approve any concrete mineral extraction projects (Regjeringen 2022c). Thus, while deep-sea mining companies wanting to operate in Norway are exposed to legal uncertainty regarding exploration licenses, the uncertainties regarding extraction licenses are far larger.

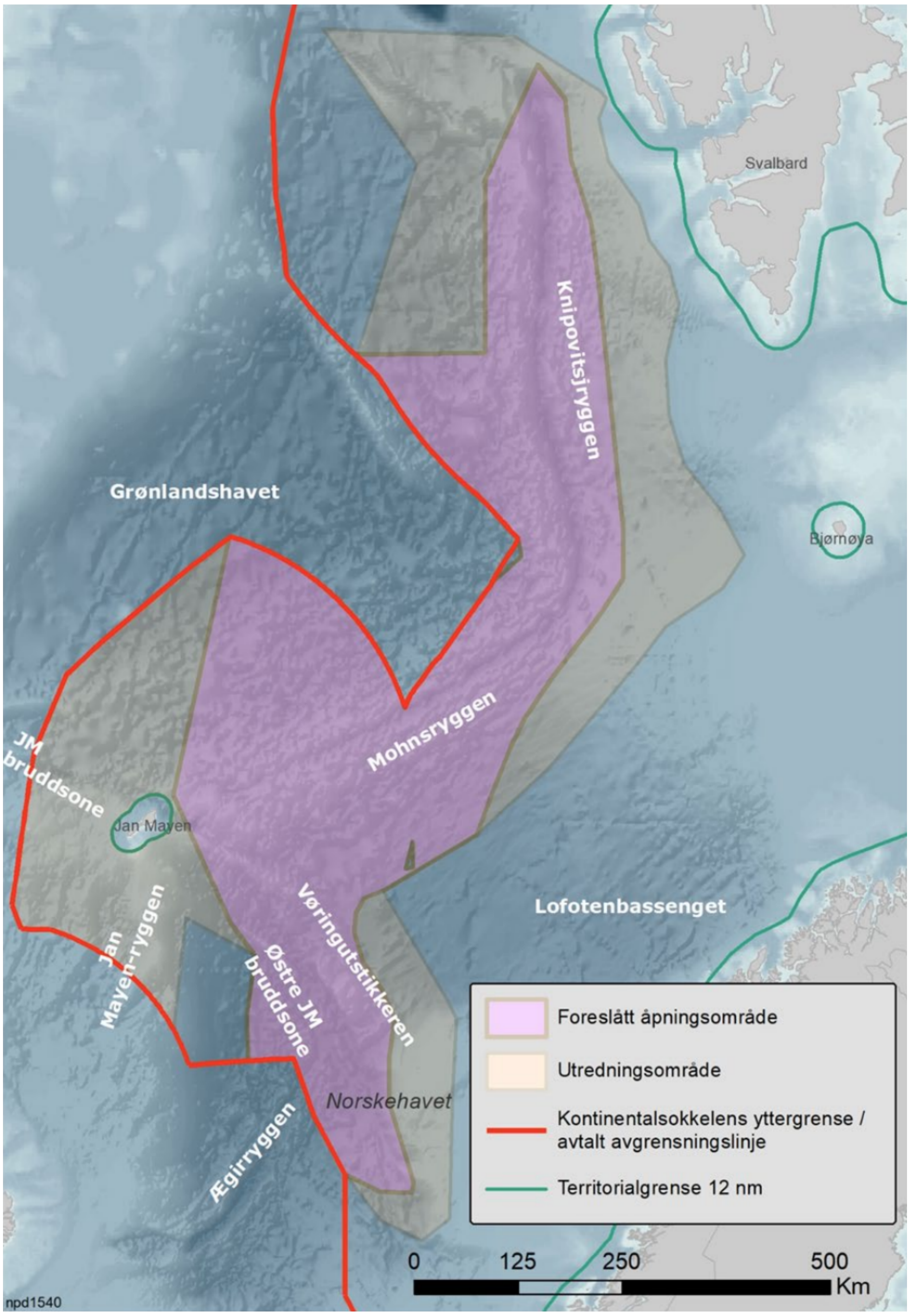


Figure 3.4: Proposed area covered by the opening process for mineral activities

Source: Regjeringen (2022a)

## 3.3 Tax regimes

In 2019, the Seabed Minerals Act was passed in Norway, as described in Section 3.2.1. In this act the issue of how the deep-sea mining industry will be taxed was not addressed (NPD 2021a). As there has not been specified any designated taxation regime for the industry, the SCT regime would apply as of today. Based on conversations with industry experts it seems likely that there will be introduced a new tax regime for deep-sea mining within the next years (Ellefmo, personal communication; Lesage, personal communication). The Norwegian Ministry of Finance has also indicated that a tax regime, reminiscent of the NPT regime could apply to deep-sea mining eventually (Regjeringen 2022b). In the sections below, we assess and explain potential tax regimes for mineral activity on the NCS, which are the SCT and the NPT regimes.

### 3.3.1 Standard corporate tax regime

Two elements regarding the SCT regime are of particular interest for a deep-sea mining company: The tax rate and the carry forward loss. The corporate tax rate, $T_c$, in Norway is set to 22% for 2022 (Regjeringen 2022d).

A carry forward loss is the benefit of paying less tax in a future year if a company records a loss in the current year. If a company made a loss of $L$ in year 0, this would be the carry forward loss obtained that year. If however in year 1 the company makes a profit $P$, where $P > L$, the total tax paid after year 1 would be $(P - L) \cdot T_c$. If $L > P$, no tax would be paid in year 1, and the new carry forward loss would be $L - P$. As becomes evident, the company has the right to write off the tax in years with profit with the carry forward loss accumulated in years with deficit.

The carry forward loss is beneficial for a company within deep-sea mining. If a company is awarded an exploration license, it is estimated that it could take as long as 10 years until the first profits will be recorded (Ellefmo, personal communication). During this period, the company would only record losses. This would result in a large accumulated carry forward loss, which could significantly reduce the amount of tax the deep-sea mining company pays the first years of mining operations.

### 3.3.2 Petroleum tax regime

In a directive on deep-sea mining, the Norwegian Ministry of Finance has suggested that the final tax regime for deep-sea mining on the NCS could have clear similarities to the current NPT regime (Regjeringen 2022b). Deep-sea mining shares several characteristics with the oil and gas industry, such as utilization of a nations finite resources and great uncertainty in the exploration phase.

The NPT regime is rather complex. In the explanation below, we have made some simplifications directed towards appreciation and depreciation regulations regarding the CAPEX investments during the extraction phase of a project.

The NPT regime may be best understood as a sequential tax regime, where a company pays tax in two steps. First a company must pay standard corporate tax. As mentioned in Section 3.3.1, the corporate tax rate, $T_c$, is 22% in Norway. However, petroleum companies operating in Norway are also subject to a special petroleum tax. The tax rate of the special petroleum tax, $T_s$, is 71.8% (PWC 2022). In the following paragraph we provide an example to clarify this.

A petroleum company has made a profit of 100. The company is first subject to the standard corporate tax. This tax will amount to $100 \cdot T_c = 100 \cdot 22\% = 22$. The company then has to pay the special petroleum tax. The tax base for the special petroleum tax is the original profit minus the deductible corporate tax: $100 - 22 = 78$. This tax base is then taxed at $T_s = 71.8\%$. This amounts to $78 \cdot T_s = 78 \cdot 71.8\% = 56$. When combining the tax paid from both the standard corporate tax and the special petroleum tax, the total tax paid is $22 + 56 = 78$. It is therefore often convenient to regard the two steps in the tax regime as one step with a 78% tax rate, as a simplification.

Two other important aspects of the NPT regime is the refund scheme in the exploration phase and the carry forward loss. If a petroleum company experiences a loss during the exploration phase within a given year, it will be refunded 71.8% of this loss the next year (PWC 2022). The refund scheme in the petroleum tax reduces the risk in the exploration phase for petroleum companies. In addition to this, there is a carry forward loss that reduces the amount of tax when a company eventually becomes profitable. How the refund scheme and carry forward loss works is best explained through an example, which is shown in Table 3.1 and further explained below.

Table 3.1: Example of the Norwegian petroleum tax

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Profit/loss | $-100$ | $-100$ | $-100$ | $-100$ | 200 | 200 | 200 | 200 |
| Refund payment | - | 71.8 | 71.8 | 71.8 | 71.8 | - | - | - |
| Carry forward loss | 100 | 200 | 300 | 400 | 200 | 0 | 0 | 0 |
| Tax reduction from carry forward loss | - | - | - | - | $-12.4$ | $-12.4$ | - | - |
| Tax on profits | - | - | - | - | 156 | 156 | 156 | 156 |
| Total tax payable | - | - | - | - | 143.6 | 143.6 | 156 | 156 |

Source: PWC (2022)

In this example we take the perspective of a petroleum company that has been awarded an exploration license. In the first four years the company completes the exploration phase. The company has a loss of 100 in each of these four years. In year 5 production starts, and from this year and onward the company makes an annual profit of 200. The company is entitled by the NPT regime to receive a refund for the losses in the exploration phase. These losses were reported in year 1 to 4. The refund for a loss in year $t$ is received in year $t + 1$. Therefore the company will receive a refund payout of 71.8 in each year from year 2 to year 5.

There will also be accumulated a carry forward loss. This increases with 100 each of the first four years. This carry forward loss will reduce the amount of tax paid when the company records its first profits. The reduced amount of tax, however, is only $78\% - 71.8\% = 6.2\%$ of the carry forward loss. In year 5 the profit is 200. Therefore 200 of the carry forward loss from year 1 to year 4 can be used to reduce tax payment this year. The total amount of tax reduction this year becomes $200 \cdot 6.2\% = 12.4$. As 200 of the carry forward loss is used in year 5, the amount of carry forward left is $400 - 200 = 200$. Therefore the same amount of tax can also be reduced for year 6.

With a profit of 200 the petroleum company is taxed $200 \cdot 78\% = 156$. Adding all together we see that the company receives a refund of 71.8 in years 2 to 5. In years 5 and 6 the total tax paid is 143.6, as the petroleum tax of 156 is reduced by 12.4 from the carry forward loss. From year 7 and onward the company has no carry forward loss to deduct the tax against, and will pay a full 156 in tax.

In the example above, the company found petroleum resources, and production could begin in year 5 with a stable profit. However it is not given that resources will be found during the exploration phase. If no resources are found, the total loss for the project in nominal values would be $400 - 400 \cdot 71.8\% = 112.8$. This is significantly lower than a loss of 400 if there was no refund scheme. This shows how the refund scheme reduces the risk of the exploration phase for petroleum companies, and thus incentivizes for activity on the NCS. Such refund schemes could also become important within deep-sea mining, as there is a large risk related to the exploration phase for marine minerals.

# 4 Methodology

In this section, we present the methodology developed in this thesis together with the solution approach used. First, we present the decision situation a corporate decision maker seeking to mine the NCS is facing. Then, we present how we model cash flows from a marine minerals project and how these are discounted and taxed to calculate the project's NPV. Next, we present the reasoning behind the non-geological and geological parameters, respectively, used in the cash flow model, as well as how the exploration process is modeled. Subsequently, we present our solution approach for the model proposed.

## 4.1 Decision situation

We consider the decision situation of a corporation seeking to commercially mine the deep sea as an operator company. We assume that the corporation will outsource the actual mineral exploration to an exploration company and extraction to a dedicated mining contractor. Also, the operator will pay a dedicated processing plant for refining of the mined ore. This means that the operator does not invest in its own exploration, mining or processing equipment. We assume that the operator company has been awarded an exploration license for one mineral activity block with a given area on the NCS. This means that we assume that mineral activity licenses follow a model similar to petroleum licenses on the NCS, where a licence may cover one ore more blocks or parts of blocks (Norwegian Petroleum 2023). This assumption is based on the beliefs of industry experts and the fact that the NPD are used to working with license blocks for the petroleum industry. We aim at quantifying the expected value of a marine minerals project corresponding to an exploration license, under a given tax regime. We assume that the operator company's objective is to maximise the value of the project by employing optimal decision making throughout different stages of the given marine minerals project. Thus, this problem can be viewed as a staged optimization problem from the perspective of the operator company.

We model the decision situation of the company as a sequential decision problem, as illustrated in Figure 4.1. We consider the four exploration stages as described in Section 3.1.2 – 1) *regional survey*, 2) *local survey*, 3) *preliminary test drilling* and 4) *extensive test drilling* – as well as the decision of whether to progress to 5) *pilot mining* and 6) *full-scale mineral extraction*, respectively, given that all four exploration stages have been undertaken. In Figure 4.1, the stages mentioned above are illustrated by blue circles. The decision gates are illustrated by rectangles. For each sequential exploration stage that is performed, the company obtains more geological information about the seabed.

Based on the gathered information the company must in advance of the next stage make a decision for each deposit respectively, on whether to progress to the next stage or to abandon the respective deposit. In practice a company might have the possibility to wait and postpone the decision of progression or abandonment at a later point in time. For the purpose of this work, and in view of computational limits, we will disregard this timing aspect of the decisions and leave an extension of our model in this regard to future research.

At each decision gate the operator company is faced with a binary decision. During the exploration phase, the company needs to decide which deposits to take to the next exploration stage and which to abandon. The company must then consider, for each identified potential deposit in its portfolio, the trade-off between the cost of further exploration, which we assume is required before any extraction of minerals can take place, and the potential revenues that may be generated if a deposit reaches the extraction phase. The decision gates corresponding to these decisions are illustrated as DG2 and DG3 in Figure 4.1. After the exploration phase is completed the company must decide whether it is worth to do pilot mining and then commence full-scale mineral extraction for each identified and fully explored deposit in its portfolio. The company must then for each deposit in its portfolio consider the trade-off between the operating costs of pilot mining and full-scale mineral extraction and the revenues that will be generated by mining the minerals in a given deposit. The corresponding decision gate to this decision is illustrated as DG4 in Figure 4.1. The outlined sequential decision problem could be interpreted as a compound European option problem

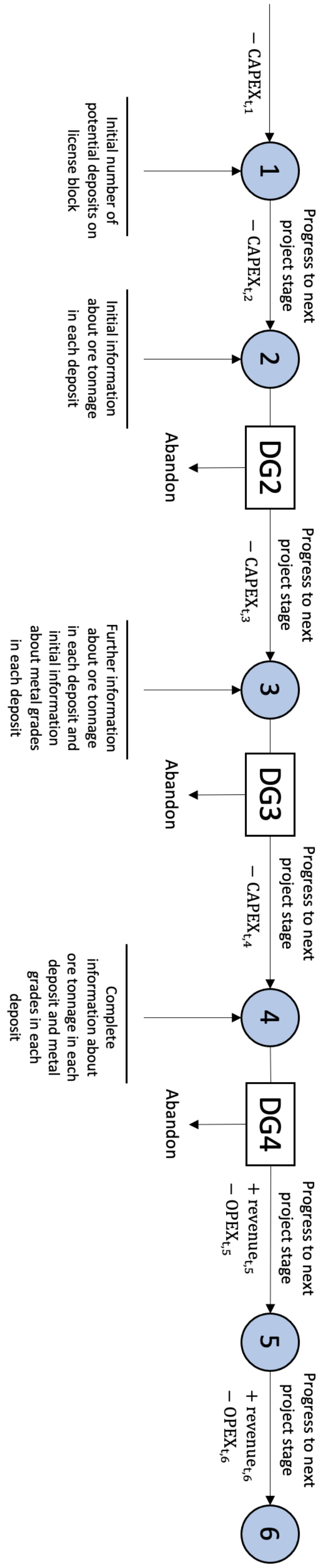


Figure 4.1: Overview of sequential decision model

of staged investment, with the corresponding exercise times at the decision gates. The decision maker holds an option for each deposit respectively, where the underlying consists of several options on whether to progress or abandon.

For computational reasons we have made a number of simplifying assumptions in modeling the decision situation. First, we assume that an operator company that has an exploration licence on a marine minerals block and embarks on exploration stage 1) *regional survey* always will undertake exploration stage 2) *local survey* as well for all the potential deposits that are initially identified during exploration stage 1. Thus, there is no decision gate between stage 1 and 2 in the modeled decision situation. Further, we assume that if a deposit is progressed from exploration stage 4) *extensive test drilling* to 5) *pilot mining*, the operator company is already determined to go ahead with stage 6) *full-scale mineral extraction* for the deposit. This means that we have not modeled a decision gate between stage 5 and stage 6.

Assumptions have also been made with regards to which stages are included in the decision situation. First, we assume that the operator company already has been awarded an exploration licence, meaning that there is no decisions being made on whether to apply for licences in the first place and bear the costs involved in that process. These costs can therefore be regarded as sunk in our model. Second, we omit to model the stage of mine closure explicitly. This last stage in a real-life project would involve clean-up and removal of equipment, and require significant CAPEX. Due to the fact that there is little information about how the specific regulation regarding mine closure would be designed we do not consider it here.

We further consider that going from exploration stage 4) *extensive test drilling* to 5) *pilot mining* and 6) *full-scale mineral extraction*, solely depends on the operator company's decision to do so and is not constrained by regulatory issues. There are two underlying assumptions here. First, we assume that having obtained an exploration license for a marine minerals block automatically gives the company the extraction license as well. This is not the case according to today's legislation, as stated in Section 3.2.1. The Seabed Minerals Act §3-2 in fact states that a survey license does not give preferential rights in connection with the granting of extraction licenses (NPD 2021a). From discussions with industry experts, however, we conclude that it is likely that a company holding the exploration licence on a block in most cases would be able to obtain the extraction licence for the block as well in the beginnings of the Norwegian marine minerals industry. Second, we assume that the application fee for these licences is negligible compared to the costs of operational activity on the NCS. However, there is currently no information available about the potential magnitude of these fees for the Norwegian marine minerals industry. Third, we assume that having obtained an extraction license for a marine minerals block automatically gives the licensee authorisation to start full-scale mineral extraction on the block after pilot mining. Thus, we assume that the pilot mining always will yield positive results for the EIA included in the operator's extraction plan, and that the operator company always will get its plan of extraction granted by the MPE. This approval is necessary to be allowed to start full-scale mining, through the Seabed Minerals Act §4-4 (see Section 3.2.1 for explanation of this). Approval of an extraction plan will not necessarily be the case in a real scenario, as the pilot mining and EIA might prove the impact of mining certain areas too vast.

Additional to the perspective of an operator company we also consider the outlined problem from a regulatory perspective, in this case the perspective of the Norwegian state. Specifically, we analyse how different tax regimes affect the optimal decisions of the operator company through a marine minerals project and to which net tax balance the respective tax regimes result in for the state. This analysis allows us to gain insight into how different tax regimes affect the incentives of a corporate decision maker to invest in a license, and how the corporate decision maker would change its decisions based on different tax regimes. What is then considered to be the optimal tax regime in eyes of the Norwegian state may vary depending on the objective of the regulator. We can account for the Norwegian state with regards to the net tax balance, and it may have as its objective to maximise the expectation of this. The regulator needs to take additional considerations in designing a tax regime, however, like the total welfare stemming from the marine minerals industry, geopolitical factors, risk appetite, etc. The regulator may also seek to incentivize mining of the largest amount of minerals possible in order to facilitate for covering the world's demand or to accelerate the energy transition the world is going through, which require growth in metal dependant industries like battery production and solar power (Rystad Energy 2020). In this thesis, we do not develop a framework to decide what is the optimal tax regime in the eyes of the regulator, given a set objective. However, the framework we develop allow us to apply different tax regimes to the decision situation of the operator company and then assess how the different tax regimes affect the net tax balance of the state as well as the share of identified potential deposits that are being mined.

## 4.2 Cash flow model

The objective of the operator company is to maximise the expected NPV of a marine minerals project on one license block through optimal decision making, under a given tax regime. The NPV is given by the sum of discounted expected cash flows of the future mineral extraction activity. The expected NPV of a project on the licence block is modeled to be maximised by the operator company through optimal, risk reducing decision making at given decision gates by abandoning deposits that are expected to yield lower discounted revenue than discounted costs if extracted. In the following we introduce the different cash flow components and define the NPV functions for a license block as a whole. We also define the functions for the state's net tax balance stemming from a project.

In the expressions formulated in this section we introduce a time scale that is dependent on which stage of a mineral project that is being performed on the license block, meaning that variables that depend on time also have a condition for project stage. Therefore, we use two subscripts, $t$ and $j$, to indicate the timing of a certain activity in a mineral project on the license block. As an example, consider the following. The standard time scale for years is $t = 1, 2, ..., T$, where $T$ indicates the end of a project on a license block, i.e. abandonment of the licence block or closure of the last mine on the licence block. What parameter values that should apply in a given year $t$ depend on what project stage $j$ is being performed in year $t$. Therefore, $j$ will take the categorical values $j = 1, 2, 3, 4, 5, 6$, indicating exploration stages 1-4 ($j = 1, ..., 4$), pilot mining ($j = 5$), and full-scale mineral extraction ($j = 6$). These categorical values reflect the sequential decision model illustrated in Figure 4.1. The subscript structure is set up in this way due to the fact that we want to allow for cases where each project stage lasts for more than a fixed amount of years. This formulation also gives us the flexibility to formulate the expressions in this section as generally as possible.

The cash flows, CF, are in total equal to gross profits, which again equal the difference between revenue and costs. In the following, we introduce the revenue and cost functions for the license block separately.

The revenue of year $t$ for a license block that is being mined is given by

$$\begin{aligned} \text{revenue}_{t,j} = \frac{d_{op,j}}{365} \cdot \omega_t \cdot \sum_m (\overline{x_{\text{grade},m}} \cdot \eta_m \cdot NF_m \cdot P_m), \\ j \in \{1, \dots, 6\}, \\ m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}. \end{aligned} \tag{4.1}$$

where $\omega_t$ is the annual production of ore at the license block in year $t$, $\overline{x_{\text{grade},m}}$ is the average metal grade of metal $m$ in the $N_{\text{extraction}}$ deposits being mined on the license block, weighted based on the relative ore tonnages of the deposits, $NF_m$ is the net smelter return for metal $m$, $\eta_m$ is the metal recovery rate of metal $m$ and $P_m$ is the obtained metal price of metal $m$. $d_{op,j}$ is the amount of days spent on operational activity per year in project stage $j$, which is different under pilot mining and under commercial mining.

The cost function is given by

$$\begin{aligned} \text{cost}_{t,j} = \text{CAPEX}_{t,j} + \text{OPEX}_{t,j}, \\ j \in \{1, \dots, 6\}, \end{aligned} \tag{4.2}$$

where $\text{CAPEX}_{t,j}$ is the total capital expenditure in year $t$ given project stage $j$, and $\text{OPEX}_{t,j}$

refers to the total operating expense in year $t$ for the operator company related to their license given project stage $j$.

The total cash flow generated by the license block for the operator company in year $t$ is denoted by $\mathrm{CF}_{t,j}$ and given by

$$\begin{aligned}\mathrm{CF}_{t,j} &= \mathrm{revenue}_{t,j} - \mathrm{cost}_{t,j} \\ &= \frac{d_{op,j}}{365} \cdot \omega_t \cdot \sum_m (\overline{x_{\mathrm{grade},m}} \cdot \eta_m \cdot NF_m \cdot P_m) - (\mathrm{OPEX}_{t,j} + \mathrm{CAPEX}_{t,j}), \\ & \qquad j \in \{1, \ldots, 6\}, \\ & \qquad m \in \{\mathrm{copper}, \mathrm{zinc}, \mathrm{gold}, \mathrm{silver}\}.\end{aligned} \tag{4.3}$$

We then express the value of an exploration license on a block, by its NPV. As we analyse the effect of different tax regimes that affect the cash flow differently in this thesis, the formulation of the NPV function depends on the tax regime. However, all formulations depend on summation over time in years $t = 1, \ldots, T$, where year $T$ is the year where the license block is abandoned by the operator.

If a license block has deposits on it that go through to full-scale mineral extraction, ore tonnage is the deciding factor for how long time (in years) constant annual production $\omega_t$ will be maintained. We call this period of time for the life of licence block (LoLB). The time $T$ when the license block no longer generates cash flows because all profitably mineable ore has been extracted occurs at $T = t_{\text{start of extraction}} + \mathrm{LoLB}$, where LoLB denotes the life of license block in years with regards to mineral extraction. LoLB is given by

$$\mathrm{LoLB} = \frac{\sum\limits_{n=1}^{N_{\mathrm{extraction}}} x_{\mathrm{tonnage},n}}{\omega_t}, \quad n \in \{1, \ldots, N_{\mathrm{extraction}}\}, \tag{4.4}$$

where $x_{\mathrm{tonnage},n}$ is the ore tonnage of deposit $n \in \{1, \ldots, N_{\mathrm{extraction}}\}$, and $N_{\mathrm{extraction}}$ deposits are being mined on the license block, such that $\sum_{n=1}^{N_{\mathrm{extraction}}} x_{\mathrm{tonnage},n}$ is the license block's total ore tonnage. $\omega_t$ is the annual production of the license block in tonnes of ore.

In the following sections we introduce the NPV expressions for the different tax regimes, respectively.

### 4.2.1 NPV under the standard corporate tax regime

For the SCT regime, described in Section 3.3.1, an operator company's NPV of a project on a license block is given by

$$\mathrm{NPV}_{\substack{\text{stand}\\\text{corp}\\\text{tax}}} = \sum_{t=1}^{T} \frac{\mathrm{CF}_{t,j} \cdot (1 - \alpha_t \cdot T_c) + \beta_t \cdot T_c}{(1+r)^t}, \tag{4.5}$$

where $T_c$ is the tax rate imposed on the gross cash flow, $\mathrm{CF}_{t,j}$. $\alpha_t$ is a binary operator that is given by

$$\alpha_t = \begin{cases} 0, & \text{for } \mathrm{CF}_{t,j} \leq 0 \\ 1, & \text{for } \mathrm{CF}_{t,j} > 0 \end{cases}, \tag{4.6}$$

and works as an indicator for when to impose tax on the cash flow, as tax is only imposed on positive cash flows. The operator $\beta_t$ indicates whether an accumulated carry forward loss exists (and therefore is applied given that the cash flow is positive) and how large the value of the basis for carry forward loss is at time $t$. $\beta_t$ is given by

$$\beta_t = \begin{cases} \mathrm{CF}_{t,j}, & \text{for } 0 < \mathrm{CF}_{t,j} \leq L_t \\ L_t, & \text{for } 0 \leq L_t < \mathrm{CF}_{t,j} \\ 0, & \text{for } \mathrm{CF}_{t,j} \leq 0 \end{cases}, \tag{4.7}$$

where $L_t$ is the accumulated carry forward loss at time $t$. The new accumulated carry forward loss for year $t+1$ is equal to $L_{t+1} = L_t - \beta_t$. $r$ is the discount rate used by the operator company.

To summarise the terms of the numerator in the right hand side of Equation (4.5), the first is the cash flow with imposed tax and the second is the tax shield from the carry forward loss.

### 4.2.2 NPV under the petroleum tax regime

For the NPT regime, described in Section 3.3.2, an operator company's NPV of a project on a licence block is given by

$$\mathrm{NPV}_{\substack{\text{pet}\\\text{tax}}} = \sum_{t=1}^{T} \left( \frac{\Big[\mathrm{CF}_{t,j} \cdot (1 - \alpha_t \cdot T_c)\Big](1 - \alpha_t \cdot T_s) + \beta_t \cdot (T_p - T_s)}{(1+r)^t} + \frac{(1 - \alpha_{t-1}) \cdot |\mathrm{CF}_{t-1,j}| \cdot T_s}{(1+r)^t} \right), \tag{4.8}$$

where $T_p$ is the total petroleum tax rate and $T_s$ is the special petroleum tax rate, as described in Section 3.3.2. $\alpha_{t-1}$ is a binary operator that is given by

$$\alpha_{t-1} = \begin{cases} 0, & \text{for } \mathrm{CF}_{t-1,j} \leq 0 \\ 1, & \text{for } \mathrm{CF}_{t-1,j} > 0 \end{cases}, \tag{4.9}$$

indicating whether refund payment is applicable, as a result of negative cash flow the previous year, or not.

To summarise the terms of the numerator in the right hand side of Equation (4.8), the first is the cash flow with imposed tax, the second is the tax shield from the carry forward loss, and the third is the refund payment for last years losses.

### 4.2.3 Net tax balance under the standard corporate tax regime

For the SCT regime, described in Section 3.3.1, the state's net tax balance of a project on a licence block is given by

$$\text{net tax balance}_{\substack{\text{stand}\\\text{corp}\\\text{tax}}} = \sum_{t=1}^{T} \frac{\mathrm{CF}_{t,j} \cdot (\alpha_t \cdot T_c) - \beta_t \cdot T_c}{(1+r)^t}. \tag{4.10}$$

To summarise the terms of the numerator in the right hand side of Equation (4.10), the first is the state's tax income from the company's positive cash flows and the second is the reduction in tax income caused by the company's tax shield.

### 4.2.4 Net tax balance under the petroleum tax regime

For the NPT regime, described in Section 3.3.2, the state's net tax balance of a project on a licence block is given by

$$\text{net tax balance}_{\substack{\text{pet}\\\text{tax}}} = \sum_{t=1}^{T} \left( \frac{\mathrm{CF}_{t,j}\Big[1 - (1 - \alpha_t \cdot T_c)(1 - \alpha_t \cdot T_s)\Big] - \beta_t \cdot (T_p - T_s)}{(1+r)^t} - \frac{(1 - \alpha_{t-1}) \cdot |\mathrm{CF}_{t-1,j}| \cdot T_s}{(1+r)^t} \right). \tag{4.11}$$

To summarise the terms of the numerator in the right hand side of Equation (4.11), the first is the state's tax income from the company's positive cash flows, the second is the reduction in tax income caused by the company's tax shield, and the third is the refund payment to the company for its losses from last year.

## 4.3 Non-geological parameters

In this section, we elaborate on the definitions of and equations behind the parameters introduced in Section 4.2 that are not explicitly geological. This includes all parameters except those describing the number of potential deposits on a license block, the ore tonnage of a deposit and the metal grade of a deposit, which we categorise as purely geological.

### 4.3.1 Annual production

Annual production of ore, $\omega_t$ is in reality highly variable. This is because the parameter depends on random events like weather conditions and unplanned equipment downtime as well as pre-known factors like choice in mining technology and differences in seabed topography between deposits. However, as no one have executed commercial deep-sea mining it is very difficult to predict how this would affect different areas of the NCS that may be opened for mineral activity. Therefore, in our model the annual production is assumed to be constant for all mined deposits in an effort of simplification.

### 4.3.2 Metal recovery rate and net smelter return

Metal recovery rate, $\eta_m$, and net smelter return, $NF_m$ are parameters that depend on metal type $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$. Both parameters are part of the revenue function in Equation (4.1) and refer to the costs, or loss of value, of ore processing.

The metal recovery rate, $\eta_m$ is the percentage at which the metal in the mined ore is extracted during initial processing in a beneficiation plant (Lesage et al. 2019). This refers to the process of crushing, grinding, gravity concentration and flotation concentration (Farjana et al. 2021). Some metal from the ore will always be lost in this processing procedure. This is for instance due to the fact that fine metal particles can bypass sieves and filters or a result of that some metal particles may still not be sufficiently separated from the gangue minerals in the separation process (Lesage et al. 2019). The minerals found in SMS deposits have different properties and thereby require different processing with different degree of loss. It is worth noting that prior to processing, a portion of the elements present in a deposit will be lost during mining (Lesage et al. 2019). However, we make the assumption that the material loss between excavation and processing is negligible, and thus we do not consider a mining recovery rate.

The net smelter return, $NF_m$, is a percentage of the value of metal $m$ in the ore, and represents the loss of value during smelting activities (Lesage et al. 2019), accounting for the smelting costs of metal concentrates. Smelting is what follows after beneficiation (Farjana et al. 2021). First, the concentrate obtained from the beneficication process undergoes a roasting process to eliminate sulfur and then smelted to produce a liquid form of the concentrate. The last step is to further purify the concentrate by electrolysis by an acid solution (Wang 2016). We assume that the net smelter return covers the whole process described above. As different metals have different properties and react differently to smelting the net smelter return rate, $NF_m$, is strongly dependent on metal type.

### 4.3.3 Metal prices

An important metal dependent parameter is prices of metals, $P_m$, for $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$. In this thesis, the prices of the relevant metals have been assumed to be constant, significantly simplifying the computational complexity of the model. For the scope of this work, only geological risk is modeled. Thus, modeling of the metal prices themselves falls outside the objectives of this thesis.

A few number of studies in the area of SMS mining have explicitly modeled metal prices as risk factors using Monte Carlo simulation to evaluate the expected value of projects over time. Among those are Andreassen and Borge (2022) who modeled the copper price using a two-factor stochastic process, using a model first proposed by Schwartz and Smith (2000). This price model allows for capturing both the mean-reversion effect and the uncertainty surrounding the equilibrium price to which prices tend to revert (Schwartz and Smith 2000).

While it evidently is possible to model metal prices, we have made the decision to use a constant price in our model. This choice is primarily driven by our focus on resource related uncertainty in this thesis, rather than market risk explicitly. Also, accurately forecasting the price trajectory of metals is a challenging task due to the involvement of numerous contributing factors. Metal prices are heavily influenced by overall economic conditions, such as gross domestic product (GDP) growth, geopolitical factors, etc. Predicting these variables with precision beyond a few years becomes increasingly challenging due to the complex and dynamic nature of the global economy. Furthermore, the metal industry involves a complex supply chain that encompasses mining, refining, and distribution. Each stage of this chain is influenced by numerous variables, including exploration discoveries, mining regulations, production capacity, and recycling trends. Additionally, the industry is susceptible to disruptive technological advancements that can significantly impact demand patterns and production methods. Because we have not modeled the uncertainty related to metal prices, we account for market risk in a simplified way. Specifically, by incorporating a premium in the discount rate, $r$.

### 4.3.4 Total survey area

Total survey area, $A_{tot,j}$, is an important parameter as it is used to calculate the CAPEX for exploration stages $j \in \{1, 2, 3, 4\}$. For exploration stage 1, $A_{tot,1}$ is the area of the license block that consists of permissive tracts. (Ellefmo and Søreide 2019) define the permissive tracts that exist along the Mohns and Knipovitch Ridge, so that this area is assumed to be already known. Only area containing potential permissive tracts would be of interest for a deep-sea mining company to explore. At exploration stage 2, $A_{tot,2}$ solely depends of the number of potential deposits discovered in stage 1. For each potential deposit that was identified in exploration stage 1 on the license block, an area of fixed size is explored. The determination of $A_{tot,3}$ and $A_{tot,4}$ is equivalent. Each deposit $n$ has an initial probability distribution for the ore tonnage, $X_{\text{grade}}$, and this distribution is updated after each stage of exploration, as later described in Section 4.5.2. However, it is possible to estimate the potential ore tonnage of a potential deposit using solely the surface expression by using a tonnage conversion factor. Such an approach has previously been used by Juliani and Ellefmo (2019). Therefore, we can sum up the expected ore tonnage from all deposits remaining in the portfolio prior to exploration stages 3 and 4 respectively, and then convert this to total deposit surface areas. Thus, $A_{tot,3}$ is the converted sum of the expected ore tonnages prior to stage 3 for all remaining deposits $n$ on the license block, resulting from the ore tonnage distributions, $X_{\text{tonnage},n}$. $A_{tot,4}$ is the converted sum of the expected ore tonnages prior to stage 4 for all remaining deposits $n$ on the license block, resulting from the ore tonnage distributions, $X_{\text{tonnage},n}$.

### 4.3.5 Days spent annually on operational activity

The days spent annually on operational activity $d_{op,j}$ depends on which project stage that is being performed on the license block. This parameter is later used for calculation of OPEX. In the exploration stages, $j = 1, ..., 4$, we have $d_{op,j} = 0$ because no mining is being performed. For pilot mining and full-scale mineral extraction, however, this is not the case. $d_{op,j}$ thus has the structure

$$d_{op,j} = \begin{cases} 0, & \text{for } j \in \{1, \ldots, 4\} \\ d_{pm} \cdot N_{\text{extraction}}, & \text{for } j = 5 \\ 365, & \text{for } j = 6 \end{cases}, \tag{4.12}$$

where $d_{pm}$ is the fixed amount of days that is spent on pilot mining one deposit and $N_{\text{extraction}}$ is the amount of deposits that are being pilot mined (and later mined full-scale) on the license block. This means that we essentially assume that each deposit during pilot mining, $j = 5$, will be mined sequentially, for the same amount of time with no down-time between deposits. During full-scale mineral extraction, $j = 6$, we assume operations every day of the year.

### 4.3.6 Costs

As described in Section 4.2, the costs involved in running a deep-sea mining operation from exploration to extraction can be split in OPEX and CAPEX. In our model, the OPEX only start to incur once the extraction of deep-sea minerals materialises. Before that, through the exploration phase, we see all costs as CAPEX. Since exploration is executed through multiple stages, with different operations in each stage, we define the CAPEX for each exploration stage individually.

The CAPEX that we assume to incur is related to each stage of the exploration process. From the Seabed Minerals Act described in Section 3.2.1, it is stated in §3-1 and §4-2 respectively that an application fee must be paid for both an exploration license and an extraction license application (NPD 2021a). However, we refrain from taking into account these costs in our calculation as there is no information released about such expenses by the Norwegian authorities yet. From the Seabed Minerals Act's §5-1 it is also evident that a licensee is obliged to ensure clean-up during and after undertaking of mineral activities. The OPEX and CAPEX of this continuous clean-up is not taken into account in our model because the scope of the clean-up process will be determined by the MPE for each unique case and is therefore difficult to generalise.

The OPEX that we account for are related to the costs arising from the operations of pilot mining and full-scale mineral extraction. The mining activities are assumed to be undertaken by a contractor, as described in Section 4.1, and the operator's OPEX are therefore equal to the fee paid to the contractor. The operator must in addition cover the costs of processing the mined ore at a dedicated processing plant.

#### CAPEX – Exploration stages 1 to 4

The CAPEX spent in each exploration stage $\text{CAPEX}_{t,j}$ can be generalised into one equation. $\text{CAPEX}_{t,j}$ is based on the number of days spent on exploration activities with a vessel in stage $j$, $d_j$, and the day rate of the corresponding vessel required for stage $j$, $C_{day,j}$. A separate cost $C_{analysis,j}$ denotes an additional cost factor, which is the cost of analysing the results from the survey performed in exploration stage $j$. The CAPEX formulation for all exploration stages is then denoted by

$$\begin{aligned}\text{CAPEX}_{t,j} &= d_j \cdot C_{day,j} + C_{analysis,j}\\ &= \big[(1+\text{EIA}) \cdot d_{survey,j} + d_{mob} + d_{demob} + d_{trans}\big] \cdot C_{day,j} + C_{analysis,j}, \\ &\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad j \in \{1, \dots, 4\}.\end{aligned} \tag{4.13}$$

Further, days spent on exploration stage $j$, $d_j$, is broken down into different components. $d_{survey,j}$ denotes the amount of days spent on survey activity in exploration stage $j$. A factor, EIA is added to this to indicate the extra time that must be spent in stage $j$ on performing biological and ecological survey in parallel with the geological exploration, as preparations work for the EIA that is required to get get an extraction plan approved by the MPE, as described in Section 3.2.1. The vessel used for exploration in each stage needs time on mobilising and demobilising, before and after going out at sea respectively. We assume that these are constant through the exploration phase and are denoted by $d_{mob}$ and $d_{demob}$. The time the vessel spends on transport from port out to the areas that are to be explored and back is denoted by $d_{trans}$.

Time spent on survey activity, $d_{survey,j}$ is calculated differently between exploration stages 1-2 and

3-4 because the cost is driven by different factors in the different stages. $d_{survey,j}$ is given by

$$d_{survey,j} = \begin{cases} \dfrac{A_{tot,j}}{A_{day,j}} = \dfrac{A_{tot,j}}{W_j \cdot v_j \cdot h_{day}}, & \text{for } j \in \{1, 2\} \\ S_{cores,j} \cdot d_{core} = S_{cores\ per\ area,j} \cdot A_{tot,j} \cdot d_{core}, & \text{for } j \in \{3, 4\} \end{cases}. \tag{4.14}$$

The way $d_{survey,j}$ is calculated for $j \in \{1, 2\}$ is inspired by the work of Bang and Trellevik (2022). For exploration stage 1 and 2, $d_{survey,j}$ is determined by the area the vessel needs to cover and the duration required to complete this task. That is because these stages solely rely on sweeping a given area with a vessel, which is explained with higher detail in Section 3.1.2. For $d_{survey,j}$, $j \in \{1, 2\}$, $A_{tot,j}$ is the total area being surveyed in stage $j$ and $A_{day,j}$ is the area the vessel is able to survey per day. This is further broken down into the survey swath, $W_j$, which is the coverage width of the surveying tools as the vessel moves along its path, as well as the vessels velocity, $v_j$, in stage $j$. $h_{day}$ denotes the amount of hours per day a vessel is able to do survey activity and is the same for stage 1 and stage 2.

For exploration stages 3 and 4, $d_{survey,j}$ is determined by the amount of core-samples being drilled and the time spent on drilling each one of them. For $d_{survey,j}$, $j \in \{3, 4\}$, $S_{cores,j}$ is the total amount of core-samples collected in stage $j$ and $d_{core}$ is the number of days it takes to drill for one core-sample. Further $S_{cores,j}$ is broken down into $S_{cores\ per\ area,j}$, which is the number of core-samples that are being collected per area unit in stage $j$ and $A_{tot,j}$ is the total area being surveyed in stage $j$.

The cost of doing analysis of results from survey performed in stage $j$, $C_{analysis,j}$, also needs to be broken down further. The only CAPEX related to analysis work accounted for in our model is that related to physical handling, shipping and analysis of the collected core samples, with a fixed cost per core sample. This means that there is no cost of analysis work in exploration stages 1 and 2, as there are no core samples to analyse in these stages. However, this cost is significant in exploration stages 3 and 4, and $C_{analysis,j}$ is denoted by

$$C_{analysis,j} = \begin{cases} 0, & \text{for } j \in \{1, 2\} \\ S_{cores\ per\ area,j} \cdot A_{tot,j} \cdot C_{core}, & \text{for } j \in \{3, 4\} \end{cases}, \tag{4.15}$$

where $S_{cores\ per\ area,j}$ is the number of core-samples that are being collected per area unit in stage $j$ and $A_{tot,j}$ is the total area being surveyed in stage $j$. $C_{core}$ is the total fixed cost per core-sample that incurs by doing analysis.

### OPEX – Mineral extraction

Mineral extraction of a deposit can properly start once a company's extraction plan for the deposit is approved by the MPE. As stated in Section 4.1, our model assumes that an operator company will outsource the mining and the processing of ore. Therefore, the operator company will pay a fixed daily fee for a mining contractor's services as well as a processing cost per tonne of ore. Thus, the OPEX can be formulated as

$$\text{OPEX}_{t,j} = d_{op,j} \cdot \Big(C_{day,contractor} + \frac{\omega_t}{365} \cdot C_{process}\Big), \tag{4.16}$$

where $d_{op,j}$ is the days spent on operational activity per year in project stage $j$, $C_{day,contractor}$ is the daily outsourcing fee paid by the operator company to the contractor that is undertaking the actual mineral excavating. $\omega_t$ is the annual production. $C_{process}$ is the ore processing cost per tonne of ore, that is paid to a processing plant that refines ore to metal extracts. We assume $C_{process}$ to be constant. In the second term on the right hand side of the equation, the yearly processing cost, $\omega_t \cdot C_{process}$, is multiplied with operational days per year in stage $j$, $d_{op,j}$, and divided with 365 to allow for cases where there is not production every day of the year.

## 4.4 Geological parameters

In this section we introduce the geological parameters used to describe a deposit and point out at which stages of the exploration process information about the specific geological parameters are obtained and explain how the geological parameters are modeled.

### 4.4.1 Modeled geological parameters

The parameters included in our modeling of deposits in a license block are based on Ellefmo and Søreide (2019). The six parameters used in our model are described in Table 4.1.

Table 4.1: Overview of geological parameters

| Geological parameter | Description | Notation |
|---|---|---|
| Potential deposits | Number of SMS deposits on a license block | $N$ |
| Ore tonnage per deposit [tonnes] | Ore tonnage contained per deposit | $x_{\text{tonnage},n}$ |
| Copper grade per deposit [%] | Relative mass of ore made up by copper | $x_{\text{grade,copper},n}$ |
| Zinc grade per deposit [%] | Relative mass of ore made up by zinc | $x_{\text{grade,zinc},n}$ |
| Gold grade per deposit [ppb] | Relative mass of ore made up by gold | $x_{\text{grade,gold},n}$ |
| Silver grade per deposit [ppm] | Relative mass of ore made up by silver | $x_{\text{grade,silver},n}$ |

We denote the general number of potential deposits on a license block as $N$, so that each potential deposit is denoted by $n \in \{1, \dots, N\}$. However, the number of potential deposits on a license block will have an initial value and then get successively lower as exploration stages are carried out, because deposits that are not expected to yield a positive NPV are abandoned at each decision gate. Therefore, we have different notation for the amount of potential deposits at different phases of a marine minerals project on a license block, referring to Figure 4.1. The initial number of potential deposits on a license block, that we adopt from a scaled-down version of the probability distributions of Ellefmo and Søreide (2019) (described in detail in Section 5.2.1), is denoted as $N_{\text{DG2}}$. This is the number of potential deposits that are considered for progression or abandonment at decision gate 2 by the operator. This is sampled from a log-normally distributed random variable, as elaborated on in Section 4.5.1. The assumption that the number of potential deposits follows a log-normal probability distribution is in line with the scientific standard for SMS deposits (Ellefmo and Søreide 2019). $N_{\text{DG3}}$ and $N_{\text{DG4}}$ are correspondingly the number of potential deposits considered in decision gates 3 and 4 respectively, as some deposits are sequentially abandoned at the decision gates. At last, $N_{\text{extraction}}$ is the number of deposits that pass through all decision gates and that are extracted in stages 5 and 6.

The ore tonnage parameter describes how many metric tonnes of mineable ore an SMS accumulation on the modeled licence block contains. The parameter for ore tonnage per deposit $n$, $x_{\text{tonnage},n}$, is sampled from a random variable $X_{\text{tonnage}}$, that is log-normally distributed. The metal grade parameter describes the share of an SMS accumulation on the modeled license block that consist of metal $m$ by mass. Each deposit $n$ on the license block has its own metal grade, $x_{\text{grade},m,n}$, for each metal $m$, that is sampled from the random variables $X_{\text{grade},m}$, that is log-normally distributed. Both the ore tonnage and the metal grades are random parameters assumed to follow log-normal distributions, which is in line with the scientific standard for SMS deposits (Ellefmo and Søreide 2019; Hannington et al. 2010). The mean and standard deviation of the random variables $X_{\text{grade},m}$ vary dependent on metal type $m$.

### 4.4.2 Introduction to the information obtained at each exploration stage

The company performing the exploration phase will obtain geological data of the seabed with each stage performed. In the following we will elaborate on which type of information we model to be obtained at each stage, as illustrated in Figure 4.2.

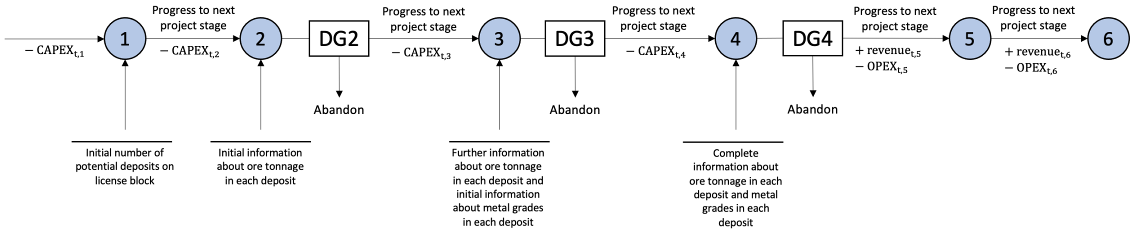


Figure 4.2: Information obtained at each exploration stage

**Stage 1)** ***Regional survey***

In a regional survey a vessel with acoustic sensors is used to scan the seabed, as described in Section 3.1.2. The acquired sensor data – when interpreted by geoscientists – can be used to estimate the number of potential deposits within a license block. This is because the acquired data on the seabed topography

According to industry experts it is challenging to estimate the size of a deposit based on acoustic data from a vessel, and this data does not give information about ore tonnage and metal grade of a potential deposit (Ellefmo, personal communication; Lesage, personal communication). The output from a regional survey is therefore the initial number of potential deposits within the license block area, $N_{\text{DG2}}$.

**Stage 2)** ***Local survey***

A local survey mainly consists of scanning the seabed more closely by using AUVs and ROVs, but may also include deep-towed magnetics and electromagnetic methods as described in Section 3.1.2. Regardless, the data obtained in stage 2 is more granular than the data from stage 1. Based on the local survey data it is possible to estimate how large the surface area of each deposit $n$ might be, and thus get an estimate of the ore tonnage, $X_{\text{tonnage},n}$ of the deposit. This is done by using a conversion factor between deposit surface area and ore tonnage (Juliani and Ellefmo 2019). However, and it is important to stress, there is still uncertainty left regarding the ore tonnage of each deposit. The outcome of a local survey is therefore modeled as an updated probability distribution for the final value of the ore tonnage for each deposit, with a shifted mean and a reduced variance.

**Stage 3)** ***Preliminary test drilling***

In stage 3 of exploration, preliminary test drilling of the $N_{\text{DG3}}$ potential deposits that remain in the portfolio is performed. The data received from this exploration stage gives further information on the ore tonnage, $X_{\text{tonnage},n}$ per deposit $n$ as well as information on metal grade, $X_{\text{grade},m,n}$, of metal $m$ per deposit $n$. Metal grade refers to the concentration of the metals $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$. However, as previously stressed, there is still uncertainty regarding the actual values of these geological parameters. Therefore, we model the outcome of exploration stage 3 as updated probability distributions for the values of ore tonnage, $X_{\text{tonnage},n}$, and metal grades $X_{\text{grade},m,n}$ of deposit $n$, with shifted means and a reduced variances.

**Stage 4)** ***Extensive test drilling***

In stage 4 of exploration, extensive test drilling is conducted for the $N_{\text{DG4}}$ deposits that yielded promising results in the preliminary test drilling and thus remain in the portfolio. This stage consists of an extensive amount of core drilling to reduce the uncertainty of deposit $n$'s ore tonnage, $X_{\text{tonnage},n}$, and metal grades, $X_{\text{grade},m,n}$ by providing even more detailed information on these geological parameters. After this exploration stage there will in reality still be some uncertainty regarding the final values of the geological parameters, however significantly reduced compared to the uncertainty before the exploration phase. In our modeling, though, we assume that all uncertainty regarding ore tonnage and metal grades for each of the portfolio's remaining $N_{\mathrm{DG4}}$ deposits is eliminated in exploration stage 4.

## 4.5 Modeling of geological parameters and exploration

In this section we explain how the geological parameters, ore tonnage and metal grades, are modeled and how the exploration stages are tied to this modeling. First, we introduce the modeling of the information that is gained through different exploration stages. Then, we explain how uncertainty regarding deposits' ore tonnage and metal grades is modeled to be successively reduced for each stage throughout the exploration phase. Then, we describe the simulation approach that is used to decide in each decision gate which potential deposits to select to progress to the next exploration stage and which should be abandoned.

### 4.5.1 Modeling of information gain throughout exploration stages

Information about the ore tonnage and metal grades of a deposit $n$ is gathered through multiple steps of exploration. In exploration stage 1) *regional survey*, the amount of potential deposits on a licence block, $N_{\mathrm{DG2}}$ is identified. $N_{\mathrm{DG2}}$ is the number of deposits that are considered for progression to the next exploration stage at decision gate 2. $N_{\mathrm{DG2}}$ is sampled from a log-normal distribution denoted by

$$I_{\text{deposits},1} \sim \text{lognormal}(\mu_{\text{deposits},1},\ \sigma_{\text{deposits},1}) \tag{4.17}$$

Through exploration activities in stage 2) *local survey*, stage 3) *preliminary test drilling* and stage 4) *extensive test drilling* information about the ore tonnage is gathered for each of the $N$ deposits that remain unabandoned by the company in the respective stage. $N$, the number of deposits considered, will vary from each decision gate as more and more deposits likely are abandoned through the exploration phase. The information gathered about ore tonnage in exploration stage $j$ of deposit $n$ is denoted as

$$\begin{aligned} &i_{\text{tonnage},n,j}, \\ n &\in \{1,\dots,N\}, \\ j &\in \{2,3,4\}. \end{aligned}$$

For each deposit, this information is sampled from the non-deposit specific log-normally distributed random variables $I_{\text{tonnage},j}$, and we assume that $I_{\text{tonnage},j}$, $j \in \{2,3,4\}$ are independent of each other. We aim to adopt Ellefmo and Søreide's (2019) original probability distributions for geological parameters on the NCS through contributions from the information gained in each exploration stage (described in detail in Section 5.2). This is in order for the problem to be modeled as sequential, as explained in Section 4.1, where the information gain from exploration activity happens in sequential stages. For ore tonnage, we do this by assigning relative weights, $w_{\text{tonnage},j}$, to Ellefmo and Søreide's (2019) original ore tonnage probability distribution function parameters, $\sigma_{\text{tonnage,original}}$ and $\mu_{\text{tonnage,original}}$. These relative weights indicate the relative knowledge gain from each individual exploration stage. Thus, the log-normally distributed random variables for information gathered about ore tonnage in stage $j$ are denoted by

$$\begin{aligned} I_{\text{tonnage},j} &\sim \text{lognormal}(\mu_{\text{tonnage},j}, \sigma_{\text{tonnage},j}) \\ &= \text{lognormal}\left(w_{\text{tonnage},j} \cdot \mu_{\text{tonnage,original}},\ \sqrt{w_{\text{tonnage},j} \cdot \sigma^2_{\text{tonnage,original}}}\right), \\ &\qquad j \in \{2,3,4\}, \\ &\qquad \sum_j w_{\text{tonnage},j} = 1. \end{aligned} \tag{4.18}$$

Information about the metal grades of the metals that a deposit $n$ is assumed to contain, is gathered through exploration activities in stages 3 and 4. The information gathered in exploration stage $j$ about the grade of metal $m$ for deposit $n$ is denoted by

$$\begin{aligned} &i_{\text{grade},m,n,j}, \\ m \in \{&\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}, \\ n \in \{&1, \ldots, N\}, \\ j \in \{&3, 4\}. \end{aligned}$$

For each deposit, this information is sampled from the non-deposit specific log-normally distributed random variables $I_{\text{grade},m,j}$, and we assume that $I_{\text{grade},m,j}$, $j \in \{3, 4\}$ are independent of each other. For metal grades, we adopt a scaled-down version of Ellefmo and Søreide's (2019) original probability distributions (described in detail in Section 5.2.3) by assigning relative weights, $w_{\text{grade},m,j}$, to their original metal grade probability distribution function parameters, $\sigma_{\text{grade,original},m}$ and $\mu_{\text{grade,original},m}$ respectively. Thus, the log-normally distributed random variables for information gathered about metal grade of metal $m$ in stage $j$ are denoted by

$$\begin{aligned} I_{\text{grade},m,j} &\sim \text{lognormal}(\mu_{\text{grade},m,j}, \sigma_{\text{grade},m,j}), \\ &= \text{lognormal}\left(w_{\text{grade},m,j} \cdot \mu_{\text{grade,original},m},\ \sqrt{w_{\text{grade},m,j} \cdot \sigma^2_{\text{grade,original},m}}\right), \\ &\qquad m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}, \\ &\qquad j \in \{3, 4\}, \\ &\qquad \sum_j w_{\text{grade},m,j} = 1. \end{aligned} \tag{4.19}$$

As information is gathered through multiple stages, we model the ore tonnage as a product of the information gathered in exploration stages 2, 3, and 4, and the metal grades as a product of information gathered in exploration stages 3 and 4.

Thus, the ore tonnage of each deposit, $X_{\text{tonnage}}$, is modeled as a log-normally distributed random variable that is composed of the product of the independent log-normally distributed random variables $I_{\text{tonnage},j}$, and can be denoted by

$$\begin{aligned} X_{\text{tonnage}} &= I_{\text{tonnage},2} \cdot I_{\text{tonnage},3} \cdot I_{\text{tonnage},4}, \\ &\sim \text{lognormal}\Big(\mu_{\text{tonnage},2} + \mu_{\text{tonnage},3} + \mu_{\text{tonnage},4}, \\ &\qquad \sqrt{\sigma^2_{\text{tonnage},2} + \sigma^2_{\text{tonnage},3} + \sigma^2_{\text{tonnage},4}}\Big) \\ &\sim \text{lognormal}\left(\mu_{\text{tonnage,original}},\ \sigma_{\text{tonnage,original}}\right). \end{aligned} \tag{4.20}$$

This means that the random variable $X_{\text{tonnage}}$ is log-normally distributed with mean and variance of

$$\text{E}[X_{\text{tonnage}}] = e^{\mu_{\text{tonnage},2} + \mu_{\text{tonnage},3} + \mu_{\text{tonnage},4} + \frac{1}{2}(\sigma^2_{\text{tonnage},2} + \sigma^2_{\text{tonnage},3} + \sigma^2_{\text{tonnage},4})}, \tag{4.21}$$

$$\begin{aligned} \text{Var}[X_{\text{tonnage}}] &= \text{Var}[I_{\text{tonnage},2}] \cdot \text{Var}[I_{\text{tonnage},3}] \cdot \text{Var}[I_{\text{tonnage},4}] \\ &= \text{E}[(I_{\text{tonnage},2} \cdot I_{\text{tonnage},3} \cdot I_{\text{tonnage},4})^2] - \text{E}[I_{\text{tonnage},2} \cdot I_{\text{tonnage},3} \cdot I_{\text{tonnage},4}]^2 \\ &= \text{E}[I^2_{\text{tonnage},2}] \cdot \text{E}[I^2_{\text{tonnage},3}] \cdot \text{E}[I^2_{\text{tonnage},4}] \\ &\quad - \text{E}[I_{\text{tonnage},2}]^2 \cdot \text{E}[I_{\text{tonnage},3}]^2 \cdot \text{E}[I_{\text{tonnage},4}]^2 \\ &= \left(e^{2\mu_{\text{tonnage},2} + 2\sigma^2_{\text{tonnage},2}} - 1\right) \cdot e^{2\mu_{\text{tonnage},3} + 2\mu_{\text{tonnage},4} + \sigma^2_{\text{tonnage},3} + \sigma^2_{\text{tonnage},4}} \\ &\quad + \left(e^{2\mu_{\text{tonnage},3} + 2\sigma^2_{\text{tonnage},3}} - 1\right) \cdot e^{2\mu_{\text{tonnage},2} + 2\mu_{\text{tonnage},4} + \sigma^2_{\text{tonnage},2} + \sigma^2_{\text{tonnage},4}} \\ &\quad + \left(e^{2\mu_{\text{tonnage},4} + 2\sigma^2_{\text{tonnage},4}} - 1\right) \cdot e^{2\mu_{\text{tonnage},2} + 2\mu_{\text{tonnage},3} + \sigma^2_{\text{tonnage},2} + \sigma^2_{\text{tonnage},3}} \\ &\quad - e^{2\mu_{\text{tonnage},2} + 2\mu_{\text{tonnage},3} + 2\mu_{\text{tonnage},4} + \sigma^2_{\text{tonnage},2} + \sigma^2_{\text{tonnage},3} + \sigma^2_{\text{tonnage},4}}, \end{aligned} \tag{4.22}$$

respectively.

For each of the exploration stages, $j = \{2, 3, 4\}$, we draw samples from the probability distributions denoted by $I_{\text{tonnage},j}$. The resulting composed sample for ore tonnage of deposit $n$, $x_{\text{tonnage},n}$, is then equal to

$$\begin{aligned} x_{\text{tonnage},n} = i_{\text{tonnage},n,2} \cdot i_{\text{tonnage},n,3} \cdot i_{\text{tonnage},n,4}, \\ n \in \{1, \dots, N\}. \end{aligned} \tag{4.23}$$

In the same way as for ore tonnage, also the metal grades for each deposit, $X_{\text{grade},m}$ are log-normally distributed random variables that are products of the independent log-normally distributed random variables $I_{\text{grade},m,j}$, which are denoted by

$$\begin{aligned} X_{\text{grade},m} &= I_{\text{grade},m,3} \cdot I_{\text{grade},m,4} \\ &\sim \text{lognormal}\left(\mu_{\text{grade},m,3} + \mu_{\text{grade},m,4},\ \sqrt{\sigma^2_{\text{grade},m,3} + \sigma^2_{\text{grade},m,4}}\right) \\ &\sim \text{lognormal}\left(\mu_{\text{grade,original},m},\ \sigma_{\text{grade,original},m}\right), \\ &\qquad m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}. \end{aligned} \tag{4.24}$$

This means that the random variables $X_{\text{grade},m}$ are log-normally distributed with means and variances of

$$\text{E}[X_{\text{grade},m}] = e^{\mu_{\text{grade},m,3} + \mu_{\text{grade},m,4} + \frac{1}{2}(+\sigma^2_{\text{grade},m,3} + \sigma^2_{\text{grade},m,4})}, \tag{4.25}$$

$$\text{Var}[X_{\text{grade},m}] = (e^{\sigma^2_{\text{grade},m,3} + \sigma^2_{\text{grade},m,4}} - 1) \cdot e^{2\mu_{\text{grade},m,3} + 2\mu_{\text{grade},m,4} + \sigma^2_{\text{grade},m,3} + \sigma^2_{\text{grade},m,4}}, \tag{4.26}$$

respectively.

For each of the exploration stages, $j = \{3, 4\}$, we draw samples from the probability distributions denoted by $I_{\text{grade},m,j}$. The resulting composed samples for the metal grades of deposit $n$, $x_{\text{grade},m,n}$, are then equal to

$$\begin{aligned} x_{\text{grade},m,n} = i_{\text{grade},m,n,3} \cdot i_{\text{grade},m,n,4}, \\ m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}, \\ n \in \{1, \dots, N\}. \end{aligned} \tag{4.27}$$

### 4.5.2 Effect of increased amount of available information through the exploration phase

A company's reason for undertaking further exploration activities on already identified deposits is to gain information - and reduce uncertainty - about the deposits' geological character. In statistical terms, the information gains from exploration activity appears as possible shifts in means and reductions in variances of geological parameters that follow probability distributions.

In our model, we do get shifts in means and reductions in variances of the ore tonnage and metal grades of deposits through each completion of an exploration activity. This can be illustrated with a starting point in Equation (4.20) and Equation (4.24). When only exploration stage 1) *regional survey* has been undertaken, $X_{\text{tonnage}}$ from Equation (4.20) and $X_{\text{grade},m}$ from Equation (4.24) are the distribution functions of ore tonnage and metal grade respectively for all the $N_{\text{DG2}}$ potential deposits located, with means and variances from Equation (4.21), Equation (4.22) and Equation (4.25), Equation (4.26) respectively.

#### Stage 2) *Local survey*

When exploration stage 2) *local survey* has been undertaken, initial information is gathered about the ore tonnage for each of the $N_{\text{DG2}}$ potential deposits. For the purpose of our modeling this means that we sample a unique scalar, $i_{\text{tonnage},n,2}$, from the distribution function $I_{\text{tonnage},2}$ for each deposit. Therewith, the log-normally distributed random variable for ore tonnage, for each deposit respectively, is updated to

$$\begin{aligned} X_{\text{tonnage},n} = i_{\text{tonnage},n,2} \cdot I_{\text{tonnage},3} \cdot I_{\text{tonnage},4}, \\ n \in \{1, \ldots, N_{\text{DG2}}\}. \end{aligned} \tag{4.28}$$

The fact that the random factor $I_{\text{tonnage},2}$ is now replaced with the sample $i_{\text{tonnage},n,2}$ results in the following change of the probability distribution of $X_{\text{tonnage},n}$. The mean shifts upwards or downwards by a factor of $i_{\text{tonnage},n,2} \cdot e^{-(\mu_{\text{tonnage},2} + \frac{1}{2}\sigma^2_{\text{tonnage},2})}$ while the variance of the ore tonnage of deposit $n$ is reduced. The updated mean and variance are then given by

$$\mathrm{E}[X_{\text{tonnage},n}] = i_{\text{tonnage},n,2} \cdot e^{\mu_{\text{tonnage},3} + \mu_{\text{tonnage},4} + \frac{1}{2}(\sigma^2_{\text{tonnage},3} + \sigma^2_{\text{tonnage},4})}, \tag{4.29}$$

$$\begin{aligned} \mathrm{Var}[X_{\text{tonnage},n}] = i^2_{\text{tonnage},n,2} \cdot (e^{\sigma^2_{\text{tonnage},3}} - 1) \cdot (e^{\sigma^2_{\text{tonnage},4}} - 1) \\ \cdot e^{2\mu_{\text{tonnage},3} + 2\mu_{\text{tonnage},4} + \sigma^2_{\text{tonnage},3} + \sigma^2_{\text{tonnage},4}}, \end{aligned} \tag{4.30}$$

respectively.

Exploration stage 2) *local survey* does not provide information about metal grades, and therefore the statistical moments of $X_{\text{grade},m}$ stays the same as before this exploration stage.

### Stage 3) *Preliminary test drilling*

Upon completion of exploration stage 3) *preliminary test drilling* more detailed information about ore tonnage as well as initial information about metal grades for the $N_{\text{DG3}}$ deposits that remained after decision gate 2 is available. For the purpose of our modeling this means that we, for each deposit, sample a unique scalar, $i_{\text{tonnage},n,3}$, from the probability distribution function $I_{\text{tonnage},3}$, as well as the scalars $i_{\text{grade},m,n,3}$ for $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$, from the probability distribution functions $I_{\text{grade},m,3}$ for $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$. Therewith, the log-normally distributed random variable for ore tonnage, for each deposit respectively, is updated to

$$\begin{aligned} X_{\text{tonnage},n} = i_{\text{tonnage},n,2} \cdot i_{\text{tonnage},n,3} \cdot I_{\text{tonnage},4}, \\ n \in \{1, \ldots, N_{\text{DG3}}\}. \end{aligned} \tag{4.31}$$

The fact that the random factor $I_{\text{tonnage},3}$ is now replaced with the sample $i_{\text{tonnage},n,3}$ results in the following change of the probability distribution of $X_{\text{tonnage},n}$. The mean further shifts upwards or downwards by a factor of $i_{\text{tonnage},n,3} \cdot e^{-(\mu_{\text{tonnage},3} + \frac{1}{2}\sigma^2_{\text{tonnage},3})}$ while the variance of the ore tonnage of deposit $n$ is reduced. The updated mean and variance are then given by

$$\mathrm{E}[X_{\text{tonnage},n}] = i_{\text{tonnage},n,2} \cdot i_{\text{tonnage},n,3} \cdot e^{\mu_{\text{tonnage},4} + \frac{1}{2}\sigma^2_{\text{tonnage},4}}, \tag{4.32}$$

$$\mathrm{Var}[X_{\text{tonnage},n}] = i^2_{\text{tonnage},n,2} \cdot i^2_{\text{tonnage},n,3} \cdot (e^{\sigma^2_{\text{tonnage},4}} - 1) \cdot e^{2\mu_{\text{tonnage},4} + \sigma^2_{\text{tonnage},4}}, \tag{4.33}$$

respectively.

The log-normally distributed random variables for metal grades, for each deposit respectively, is updated to

$$\begin{aligned} X_{\text{grade},m,n} = i_{\text{grade},m,n,3} \cdot I_{\text{grade},m,4}, \\ m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}, \\ n \in \{1, \ldots, N_{\text{DG3}}\}. \end{aligned} \tag{4.34}$$

The fact that the random factor $I_{\text{grade},m,3}$ is now replaced with the sample $i_{\text{grade},m,n,3}$ results in the following change of the probability distributions of $X_{\text{grade},m,n}$. The means shift upwards or downwards by a factor of $i_{\text{grade},m,n,3} \cdot e^{-(\mu_{\text{grade},m,3} + \frac{1}{2}\sigma^2_{\text{grade},m,3})}$ while the variances of the metal grades of deposit $n$ are reduced. The updated means and variances are then given by Equation (4.25) and Equation (4.26), to

$$\mathrm{E}[X_{\text{grade},m,n}] = i_{\text{grade},m,n,3} \cdot e^{\mu_{\text{grade},m,4} + \frac{1}{2}\sigma^2_{\text{grade},m,4}}, \tag{4.35}$$

$$\mathrm{Var}[X_{\text{grade},m,n}] = i^2_{\text{grade},m,n,3} \cdot (e^{\sigma^2_{\text{grade},m,4}} - 1) \cdot e^{2\mu_{\text{grade},m,4} + \sigma^2_{\text{grade},m,4}}, \tag{4.36}$$

respectively.

**Stage 4)** ***Extensive test drilling***

For the $N_{\mathrm{DG4}}$ deposits that remain in the portfolio after decision gate 3, more detailed information about both ore tonnage and metal grade is provided during exploration stage 4) *extensive test drilling*. Upon completion of this exploration stage we assume that all information about the remaining $N_{\mathrm{DG4}}$ deposits is known, meaning that we are completely certain about the exact ore tonnage and metal grades of these deposits. For the purpose of our modeling this means that we, for each deposit, sample a unique scalar $i_{\mathrm{tonnage},n,4}$ from the distribution function $I_{\mathrm{tonnage},4}$, as well as the scalars $i_{\mathrm{grade},m,n,4}$ for $m \in \{\mathrm{copper}, \mathrm{zinc}, \mathrm{gold}, \mathrm{silver}\}$ from the distribution functions $I_{\mathrm{grade},m,4}$ for $m \in \{\mathrm{copper}, \mathrm{zinc}, \mathrm{gold}, \mathrm{silver}\}$. Therewith, the log-normally distributed random variable for ore tonnage, for each deposit respectively, is updated to

$$\begin{aligned} X_{\mathrm{tonnage},n} = x_{\mathrm{tonnage},n} = i_{\mathrm{tonnage},n,2} \cdot i_{\mathrm{tonnage},n,3} \cdot i_{\mathrm{tonnage},n,4}&, \\ n \in \{1, \ldots, N_{\mathrm{DG4}}\}&, \end{aligned} \tag{4.37}$$

while the log-normally distributed random variables for metal grades, for each deposit respectively, are updated to

$$\begin{aligned} X_{\mathrm{grade},m,n} = x_{\mathrm{grade},m,n} = i_{\mathrm{grade},m,n,3} \cdot i_{\mathrm{grade},m,n,4}&, \\ m \in \{\mathrm{copper}, \mathrm{zinc}, \mathrm{gold}, \mathrm{silver}\}&, \\ n \in \{1, \ldots, N_{\mathrm{DG4}}\}&. \end{aligned} \tag{4.38}$$

Now, we have the scalar $i_{\mathrm{tonnage},n,4}$, as a factor in $X_{\mathrm{tonnage},n}$, as opposed to the log-normally distributed random variable $I_{\mathrm{tonnage},4}$, and we have the scalar $i_{\mathrm{grade},m,n,4}$ as a factor in $X_{\mathrm{grade},m,n}$, as opposed to the log-normally distributed random variable $I_{\mathrm{grade},m,4}$. We now have scalars only as factors in the expressions for $X_{\mathrm{tonnage},n}$ and $X_{\mathrm{grade},m,n}$. Thus, these log-normally distributed random variables now have definitive values and a variance that is reduced to zero.

## 4.6 Solution approach to decision making at decision gates

At each decision gate, the operator decides whether to progress a deposit to the next stage or to abandon it. This decision must be taken for all the $N$ potential deposits in the portfolio, and at decision gates 2 and 3 it is based on limited knowledge of the geological parameters of the deposits. The decision rule for whether to progress a deposit to the next exploration stage or not, is based on the expected NPV of exploiting the given deposit that is calculated using simulations when the decision maker does not have complete information. We simulate the information that might be gained through future exploration and use the resulting values of ore tonnage and metal grades for deposits to calculate the NPVs. Figure 4.3 and Figure 4.4 provide illustrations of the simulation structure and the decision rules along the different decision gates. Below we elaborate on the simulation procedure in more detail.

In our solution approach, there are two main steps of importance. The first is that of simulating our way forwards in time through exploration stages that may have not been performed yet. This is done to obtain values of geological parameters that not yet have definitive values, indeed because the exploration activities that would reveal these values may not have been performed yet. The second is the step of propagating backwards in time through a tree structure where each node represents an outcome of mentioned simulated information. This is done in order to arrive at the expected optimal decision, taken with incomplete information, at a present decision gate. These two principles is the foundation of our solution approach, which is clear from the sections below.

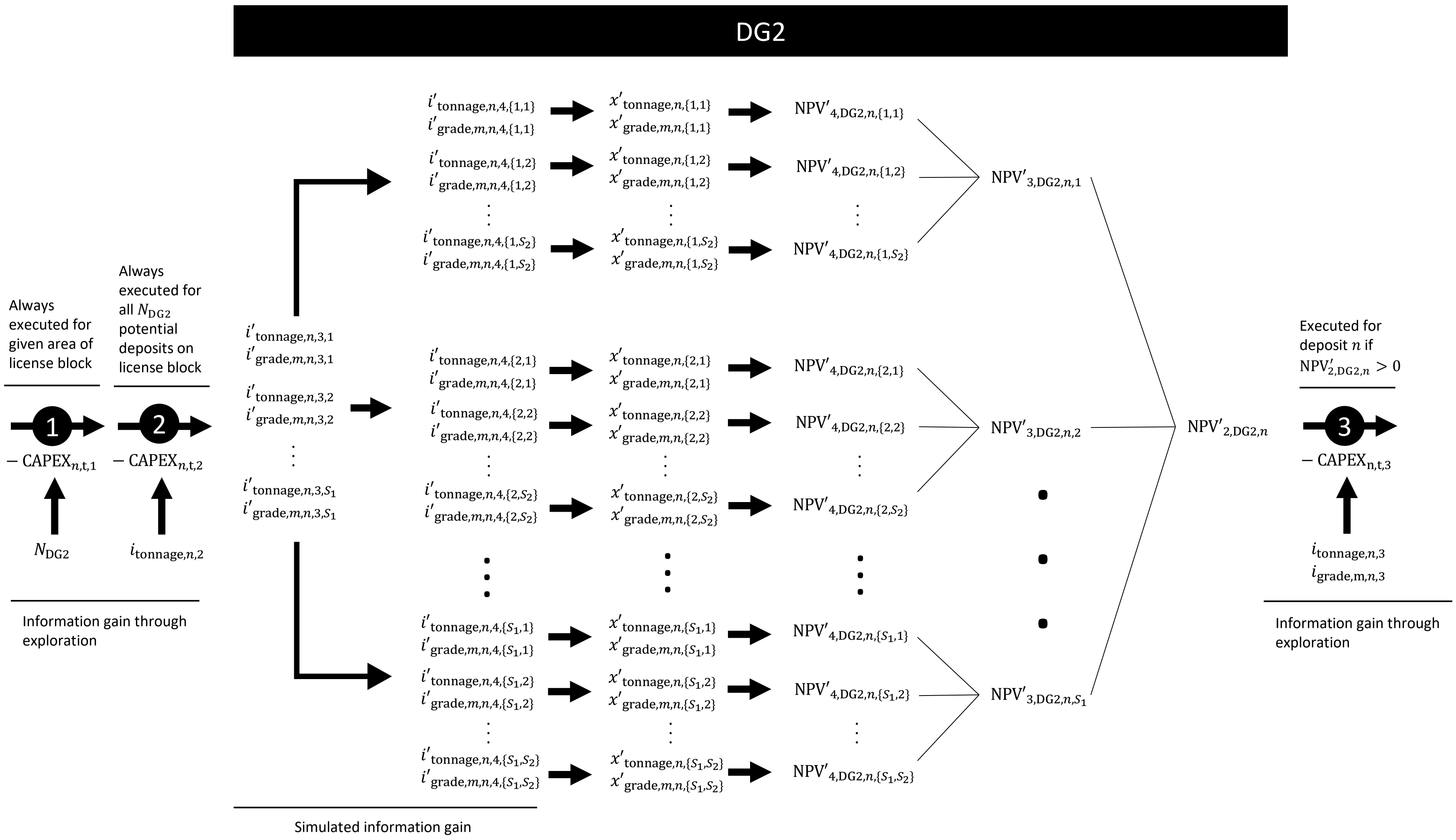


Figure 4.3: Simulation structure of decision gate 2

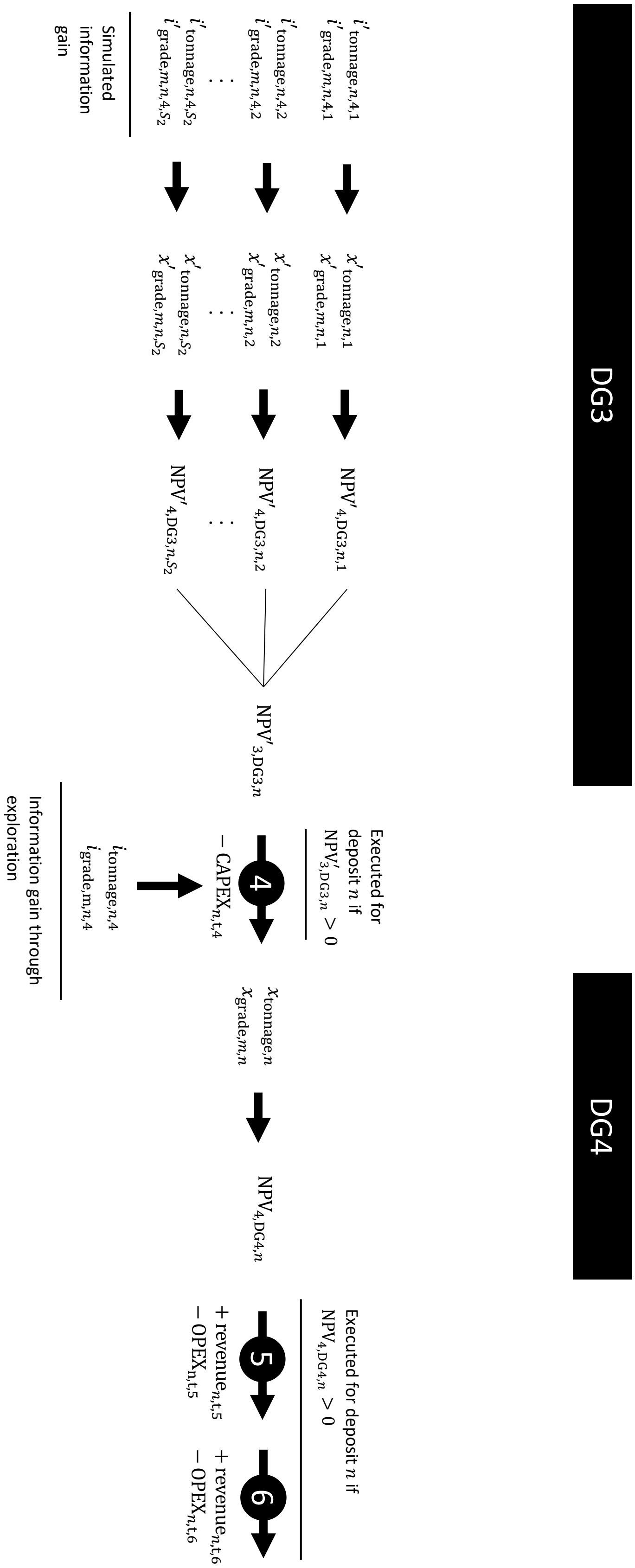


Figure 4.4: Simulation structure of decision gates 3 and 4

### 4.6.1 Decision gate 2

When the corporate decision maker is facing decision gate 2, it has to determine whether to undertake exploration stage 3 for each deposit $n \in \{1, \dots, N_{\text{DG2}}\}$ that were located in exploration stage 1) *regional survey*, respectively. Doing so will give additional information about ore tonnage and initial information about metal grades, but comes at the cost of $\text{CAPEX}_{n,t,2}$, for each deposit respectively. At the point in time of decision gate 2, exploration stages 1) *regional survey* and 2) *local survey* have been performed, and thus, the initial number of potential deposits on the licence block, $N_{\text{DG2}}$, and initial information about ore tonnage, $i_{\text{tonnage},n,2}$ for each of the $n \in \{1, \dots, N_{\text{DG2}}\}$ deposits are known. In the case of our modeling, $N_{\text{DG2}}$ and $i_{\text{tonnage},n,2}$ are sampled from the following probability distributions respectively:

$$\begin{aligned} N_{\text{DG2}} &\text{ sampled from } I_{\text{deposits},1} \sim \text{lognormal}(\mu_{\text{deposits},1}, \sigma_{\text{deposits},1}), \\ i_{\text{tonnage},n,2} &\text{ sampled from } I_{\text{tonnage},2} \sim \text{lognormal}(\mu_{\text{tonnage},2}, \sigma_{\text{tonnage},2}). \end{aligned}$$

The decision rule for whether to progress a deposit to the next exploration stage or not, is based on the expected NPV of exploiting the given deposit. This expected NPV is at decision gate 2 calculated by propagating backwards in time through a tree structure created by simulating possible future scenarios. If the expected NPV of exploiting a deposit after having performed all exploration stages is positive, perceived from decision gate 2, the deposit is progressed to exploration stage 3. However, when the decision maker is facing decision gate 2, it does not have information about what is unveiled in exploration stages 3 and 4, as they have yet not been performed. In terms of our modeling, this means that the parameters $i_{\text{tonnage},n,j}$ and $i_{\text{grade},m,n,j}$, for $n \in \{1, \dots, N_{\text{DG2}}\}$, $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$, $j \in \{3, 4\}$ are unknown, because they have not yet been sampled from the random variables $I_{\text{tonnage},j}$ and $I_{\text{grade},m,j}$ respectively. Therefore we simulate the future values of these parameters, by doing a simulation sampling from the respective distribution functions of $I_{\text{tonnage},j}$ and $I_{\text{grade},m,j}$, in order to be able to get values of the ore tonnage, $x_{\text{tonnage},n}$, from Equation (4.23), and values of the metal grades, $x_{\text{grade},m,n}$ from Equation (4.27). These values will again form a tree structure of possible future scenarios and allow us to calculate the cash flows and thus the expected NPV of exploiting each of the $N_{\text{DG2}}$ deposits under different tax regimes, with basis in Equation (4.3) - Equation (4.9), by propagating backwards in time through the mentioned tree structure.

In exploration stage 3 the decision maker obtains further information about the ore tonnage in a deposit, in addition to initial information about the grade of copper, zinc, gold and silver. To simulate the information obtained in stage 3, we run $S_1$ simulations for each of the $N_{\text{DG2}}$ potential deposits, representing $S_1$ potential outcomes of completing exploration stage 3 for each potential deposit respectively. For ore tonnage, we denote the samples from the distribution function of $I_{\text{tonnage},3}$ in the simulated scenarios as $i'_{\text{tonnage},n,3,s_1}$ for $n \in \{1, \dots, N_{\text{DG2}}\}$, $s_1 \in \{1, \dots, S_1\}$, where 3 denotes that the information comes from stage 3. For the metal grades, we denote the samples from the distribution functions of $I_{\text{grade},m,3}$ in the simulated scenarios as $i'_{\text{grade},m,n,3,s_1}$ for $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$, $n \in \{1, \dots, N_{\text{DG2}}\}$, $s_1 \in \{1, \dots, S_1\}$. The mark, $'$, is included to indicate that the information obtained is only from simulations and not from actual physical progress in exploration to the next stage. To summarize, in order to simulate the future information obtained in exploration stage 3 when facing decision gate 2, to then again be able to later propagate backwards in time and calculate the expected NPV of exploiting each deposit $n$, we sample the following values from the following probability distribution functions:

$$\begin{aligned} i'_{\text{tonnage},n,3,s_1} &\text{ sampled from } I_{\text{tonnage},3} \sim \text{lognormal}(\mu_{\text{tonnage},3}, \sigma_{\text{tonnage},3}), \\ i'_{\text{grade,copper},n,3,s_1} &\text{ sampled from } I_{\text{grade,copper},3} \sim \text{lognormal}(\mu_{\text{grade,copper},3}, \sigma_{\text{grade,copper},3}), \\ i'_{\text{grade,zinc},n,3,s_1} &\text{ sampled from } I_{\text{grade,zinc},3} \sim \text{lognormal}(\mu_{\text{grade,zinc},3}, \sigma_{\text{grade,zinc},3}), \\ i'_{\text{grade,gold},n,3,s_1} &\text{ sampled from } I_{\text{grade,gold},3} \sim \text{lognormal}(\mu_{\text{grade,gold},3}, \sigma_{\text{grade,gold},3}), \\ i'_{\text{grade,silver},n,3,s_1} &\text{ sampled from } I_{\text{grade,silver},3} \sim \text{lognormal}(\mu_{\text{grade,silver},3}, \sigma_{\text{grade,silver},3}). \end{aligned}$$

In exploration stage 4, the decision maker once again obtains information about the ore tonnage in a deposit, in addition to the grade of metals. To simulate the information obtained in stage 4, we make $S_2$ simulations on top of the already made $S_1$ simulations for each of the $n$ deposits. This then represents $S_2$ potential outcomes of completing stage 4 for each of the $S_1$ potential outcomes of completing stage 3.

For ore tonnage, we denote the samples from the distribution function $I_{\text{tonnage},4}$ in the simulated scenarios as $i'_{\text{tonnage},n,4,\{s_1,s_2\}}$ for $n \in \{1,\dots,N_{\text{DG2}}\}$, $s_1 \in \{1,\dots,S_1\}$, $s_2 \in \{1,\dots,S_2\}$, where 4 denotes that the information comes from stage 4. For the metal grades, we denote the samples from the distribution functions $I_{\text{grade},m,4}$ in the simulated scenarios as $i'_{\text{grade},m,n,4,\{s_1,s_2\}}$ for $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$, $n \in \{1,\dots,N_{\text{DG2}}\}$, $s_1 \in \{1,\dots,S_1\}$, $s_2 \in \{1,\dots,S_2\}$. To summarize, in order to simulate the future information obtained in exploration stage 4 when facing decision gate 2, to then again be able to later propagate backwards in time and calculate the expected NPV of exploiting each deposit $n$, we sample the following values from the following probability distribution functions:

$$\begin{aligned}
i'_{\text{tonnage},n,4,\{s_1,s_2\}} &\text{ sampled from } I_{\text{tonnage},4} \sim \text{lognormal}(\mu_{\text{tonnage},4}, \sigma_{\text{tonnage},4}),\\
i'_{\text{grade,copper},n,4,\{s_1,s_2\}} &\text{ sampled from } I_{\text{grade,copper},4} \sim \text{lognormal}(\mu_{\text{grade,copper},4}, \sigma_{\text{grade,copper},4}),\\
i'_{\text{grade,zinc},n,4,\{s_1,s_2\}} &\text{ sampled from } I_{\text{grade,zinc},4} \sim \text{lognormal}(\mu_{\text{grade,zinc},4}, \sigma_{\text{grade,zinc},4}),\\
i'_{\text{grade,gold},n,4,\{s_1,s_2\}} &\text{ sampled from } I_{\text{grade,gold},4} \sim \text{lognormal}(\mu_{\text{grade,gold},4}, \sigma_{\text{grade,gold},4}),\\
i'_{\text{grade,silver},n,4,\{s_1,s_2\}} &\text{ sampled from } I_{\text{grade,silver},4} \sim \text{lognormal}(\mu_{\text{grade,silver},4}, \sigma_{\text{grade,silver},4}).
\end{aligned}$$

We have now simulated possible outcomes of the information obtained in both exploration stage 3 and exploration stage 4. These simulated outcomes are the basis of how the decision maker makes its decision on which deposits to progress and which to abandon at decision gate 2. This is because we are propagating backwards in time to decision gate 2 from the point in time where stage 4 is simulated to be completed through the point in time where stage 3 is simulated to be completed. Through simulations of exploration stages 3 and 4 we have constructed a total of $S_1 \cdot S_2$ nodes for each deposit respectively. These nodes represent $S_1 \cdot S_2$ different outcomes of the information that is obtained through all exploration of the given deposit, after stage 4 has been conducted. The nodes are denoted by $\{s_1, s_2\}$, $s_1 \in \{1,\dots,S_1\}$, $s_2 \in \{1,\dots,S_2\}$. At the node $\{s_1, s_2\}$ we thus have information from stage 3, represented in $s_1$, and information from stage 4, represented in $s_2$. Based on the totality of this information we can calculate a simulated value of the ore tonnage, $x'_{\text{tonnage},n,\{s_1,s_2\}}$, and the metal grades, $x'_{\text{grade},m,n,\{s_1,s_2\}}$, for a given node $\{s_1, s_2\}$.

The ore tonnage of deposit $n$ for a given node $\{s_1, s_2\}$ simulated forward in time from the perspective of decision gate 2 is given by

$$\begin{aligned}
x'_{\text{tonnage},n,\{s_1,s_2\}} = i_{\text{tonnage},n,2} \cdot i'_{\text{tonnage},n,3,s_1} \cdot i'_{\text{tonnage},n,4,\{s_1,s_2\}},&\\
n \in \{1,\dots,N_{\text{DG2}}\},&\\
s_1 \in \{1,\dots,S_1\},&\\
s_2 \in \{1,\dots,S_2\}.&
\end{aligned} \tag{4.39}$$

The metal grade of metal $m$ in deposit $n$ for a given node $\{s_1, s_2\}$ simulated forward in time from the perspective of decision gate 2 is given by

$$\begin{aligned}
x'_{\text{grade},m,n,\{s_1,s_2\}} = i'_{\text{grade},m,n,3,s_1} \cdot i'_{\text{grade},m,n,4,\{s_1,s_2\}},&\\
m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\},&\\
n \in \{1,\dots,N_{\text{DG2}}\},&\\
s_1 \in \{1,\dots,S_1\},&\\
s_2 \in \{1,\dots,S_2\}.&
\end{aligned} \tag{4.40}$$

Based on these parameters it is possible to calculate the cash flow, and thus also the NPV, after stage 4 has been conducted (in simulations). To calculate the cash flow for each year $t$ after stage 4 for each node $\{s_1, s_2\}$, we can use the following equation, which is the single-deposit equivalent to Equation (4.3).

$$\begin{aligned}\mathrm{CF}'_{n,t,j,\{s_1,s_2\}} &= \mathrm{revenue}'_{n,t,j,\{s_1,s_2\}} - \mathrm{cost}_{n,t,j} \\ &= \frac{d_{op,j}}{365} \cdot \omega_t \cdot \sum_m (x'_{\mathrm{grade},m,n,\{s_1,s_2\}} \cdot \eta_m \cdot NF_m \cdot P_m) \\ &\quad - (\mathrm{OPEX}_{n,t,j} + \mathrm{CAPEX}_{n,t,j}), \\ &\qquad m \in \{\text{copper, zinc, gold, silver}\}, \\ &\qquad n \in \{1, \dots, N_{\mathrm{DG2}}\}, \\ &\qquad s_1 \in \{1, \dots, S_1\}, \\ &\qquad s_2 \in \{1, \dots, S_2\}.\end{aligned} \tag{4.41}$$

The cash flow that is obtained can be used to calculate the NPV corresponding to each node $\{s_1, s_2\}$ based on the simulated scenarios. The NPV for each node $\{s_1, s_2\}$ after stage 4, from the perspective of decision gate 2, is denoted as $\mathrm{NPV}'_{4,\mathrm{DG2},n,\{s_1,s_2\}}$. Since the NPV depends on the given tax regime, different equations for the NPV need to be used for different regimes. Because of the dynamic programming approach in our modeling, we have a max-condition in the following equations. If simulations show that the taxed and discounted cash flows generated from mining a deposit would be negative, we assume that the operator would choose not to mine the given deposit. Thus, no further costs would incur which makes the NPV from that point in time zero in reality, making a non-negativity necessary to reflect the reality of decision making. Therewith, for the standard corporate tax regime, the petroleum tax regime and the PIS tax regime, the NPV for the scenario in node $\{s_1, s_2\}$, after conducting stage 4, is respectively

$$\mathrm{NPV}'_{\substack{\text{stand}\\\text{corp}\\\text{tax}},4,\mathrm{DG2},n,\{s_1,s_2\}} = \max\left(\sum_{t=t_{\substack{\text{start of}\\\text{extraction}}}}^{T} \frac{\mathrm{CF}'_{n,t,j,\{s_1,s_2\}} \cdot (1 - \alpha_t \cdot T_c) + \beta_t \cdot T_c}{(1+r)^t},\ 0\right), \tag{4.42}$$

$$\begin{aligned}&\mathrm{NPV}'_{\substack{\text{pet}\\\text{tax}},4,\mathrm{DG2},n,\{s_1,s_2\}} \\ &= \max\left(\sum_{t=t_{\substack{\text{start of}\\\text{extraction}}}}^{T} \left(\frac{\left[\mathrm{CF}'_{n,t,j,\{s_1,s_2\}} \cdot (1 - \alpha_t \cdot T_c)\right](1 - \alpha_t \cdot T_s) + \beta_t \cdot (T_p - T_s)}{(1+r)^t}\right.\right. \\ &\qquad\qquad \left.\left. + \frac{(1 - \alpha_{t-1}) \cdot |\mathrm{CF}'_{n,t-1,j,\{s_1,s_2\}}| \cdot T_s}{(1+r)^t}\right),\ 0\right),\end{aligned} \tag{4.43}$$

where $T$ is given by

$$T = t_{\text{start of extraction}} + \frac{x'_{\mathrm{tonnage},n,\{s_1,s_2\}}}{\omega_t}. \tag{4.44}$$

We have now obtained an NPV for each of the $S_1 \cdot S_2$ nodes after stage 4. These NPVs can be used to propagate backwards to make a decision at decision gate 2. $S_1$ simulations of the outcome of stage 3 are made, and each of the $S_1$ outcomes have an additional $S_2$ outcomes of stage 4. This means that for a given simulation of stage 3, for example $s_1 = 1$, we have $S_2$ nodes that span out from this one simulation, $\{1,1\}, \{1,2\}, \dots, \{1, S_2\}$. Based on the NPV of these nodes and the CAPEX required to reach these nodes, we can decide whether an investor who had completed stage 3 and obtained the information that was given in $s_1 = 1$ would continue to perform stage 4. This is decided by using the $k$-th percentile method. This means we sort the values of $\mathrm{NPV}_{4,\mathrm{DG2},n,\{1,s_2\}}$. The value that is the basis for the decision is the one which corresponds to having $k\%$ of the $S_2$ observations being larger than itself. In our model P75 is the decision criteria, meaning that the $\mathrm{NPV}_{4,\mathrm{DG2},n,\{1,s_2\}}$-value used in the decision is valued such that 75% of the $\mathrm{NPV}_{4,\mathrm{DG2},n,\{1,s_2\}}$-values are larger than it. This decision criteria is set because the industry experts we have consulted expect that investors in the deep-sea mining industry are relatively risk-averse. We denote the P75 value of $\mathrm{NPV}_{4,\mathrm{DG2},n,\{s_1,s_2\}}$ as $\mathrm{P75}\left(\mathrm{NPV}_{4,\mathrm{DG2},n,\{s_1,s_2\}}\right)$.

Also here, the dynamic programming approach in our modeling involves a max-condition with a constraint that ensures that the calculated resulting NPV in the simulations never becomes a negative value. This is needed because we assume that if performing the next exploration stage for a deposit is expected to yield a negative NPV using the P75 criteria and accounting for the cost of performing the given exploration stage, the operator would choose not to perform the exploration stage and thus, making no further costs incur. Therewith, the expected NPV that is propagated backwards from the simulated point in time (after completion of exploration stage 4) to the other simulated point in time (after completion of exploration stage 3) is for the standard corporate tax regime and for the PIS tax regime

$$\text{NPV}'_{\substack{\text{stand}\\ \text{corp}\\ \text{tax}},3,\text{DG3},n,s_1} = \max\left( \frac{\text{P75}\left(\text{NPV}'_{\substack{\text{stand}\\ \text{corp}\\ \text{tax}},4,\text{DG2},n,\{s_1,s_2\}}\right)}{(1+r)^t} - \text{CAPEX}_{n,t,4},\ 0 \right) \tag{4.45}$$

The decision rule is rather similar for the petroleum tax regime, however it is necessary to include the refund received from the refund scheme. A company will receive a refund of $T_s$ of the exploration costs spent in stage 4. However this refund is received one year later than the incurring exploration cost, and the refund must therefore be discounted one year, here expressed by $t$ for the purpose of generalization, by the discount factor $r$. This gives the following equation.

$$\begin{multline} \text{NPV}'_{\substack{\text{pet}\\ \text{tax}},3,\text{DG2},n,s_1} = \max\left( \frac{\text{P75}\left(\text{NPV}'_{\substack{\text{pet}\\ \text{tax}},4,\text{DG2},n,\{s_1,s_2\}}\right)}{(1+r)^t} \right. \\ \left. - \text{CAPEX}_{n,t,4} + \frac{\text{CAPEX}_{n,t,4} \cdot T_s}{(1+r)^t},\ 0 \right) \tag{4.46} \end{multline}$$

The values of $\text{NPV}'_{3,\text{DG2},n,s_1}$ gives us $S_1$ simulated values of the NPV after stage 3 is conducted. To decide on whether to progress in decision gate 2 or to abandon, we use these values. For the company to arrive at stage 3 from stage 2 they would need to invest CAPEX, and one must also discount the time value of money. For the petroleum tax regime, the received refund $T_s$ of the exploration costs spent in stage 3 must also be accounted for. To arrive at the NPV perceived at decision gate 2 then, and thus decide if one should abandon or progress a deposit, we use the following equations respectively.

$$\text{NPV}'_{\substack{\text{stand}\\ \text{corp}\\ \text{tax}},2,\text{DG2},n} = \max\left( \frac{\text{P75}\left(\text{NPV}'_{\substack{\text{stand}\\ \text{corp}\\ \text{tax}},3,\text{DG2},n,s_1}\right)}{(1+r)^t} - \text{CAPEX}_{n,t,3},\ 0 \right) \tag{4.47}$$

$$\begin{multline} \text{NPV}'_{\substack{\text{pet}\\ \text{tax}},2,\text{DG2},n} = \max\left( \frac{\text{P75}\left(\text{NPV}'_{\substack{\text{pet}\\ \text{tax}},3,\text{DG2},n,s_1}\right)}{(1+r)^t} \right. \\ \left. - \text{CAPEX}_{n,t,3} + \frac{\text{CAPEX}_{n,t,3} \cdot T_s}{(1+r)^t},\ 0 \right) \tag{4.48} \end{multline}$$

If $\text{NPV}'_{2,\text{DG2},n}$ is larger than zero, the potential deposit $n$ has a positive expected NPV. In this case the company would choose to progress to the next stage. Otherwise, the company would choose to abandon the deposit. Thus, the $n$-parameter which stores the deposits that are expected to yield positive NPVs is updated from $n \in \{1, \ldots, N_{\mathrm{DG2}}\}$ to $n \in \{1, \ldots, N_{\mathrm{DG3}}\}$.

### 4.6.2 Decision gate 3

When the corporate decision maker is facing decision gate 3, it has to determine whether to undertake exploration stage 4 for each deposit $n \in \{1, \ldots, N_{\mathrm{DG3}}\}$ that remain in the portfolio, respectively. Doing so will give additional and complete information about both ore tonnage and metal grades but comes at the cost of $\mathrm{CAPEX}_{n,t,4}$ for each deposit respectively. At the point in time of decision gate 3, exploration stages 1) *regional survey* and 2) *local survey*, and 3) *preliminary test drilling* have been completed. Thus, initial information about ore tonnage, $i_{\mathrm{tonnage},n,2}$ for each of the $n \in \{1, \ldots, N_{\mathrm{DG3}}\}$ deposits are known just as in decision gate 2. However, we now also have certain information $i_{\mathrm{tonnage},n,3}$ and $i_{\mathrm{grade},m,n,3}$ for $n \in \{1, \ldots, N_{\mathrm{DG3}}\}$, $m \in \{\mathrm{copper}, \mathrm{zinc}, \mathrm{gold}, \mathrm{silver}\}$, respectively sampled from the following probability distributions.

$$\begin{aligned}
i_{\mathrm{tonnage},n,3} &\text{ sampled from } I_{\mathrm{tonnage},3} \sim \mathrm{lognormal}(\mu_{\mathrm{tonnage},3}, \sigma_{\mathrm{tonnage},3}),\\
i_{\mathrm{grade,copper},n,3} &\text{ sampled from } I_{\mathrm{grade,copper},3} \sim \mathrm{lognormal}(\mu_{\mathrm{grade,copper},3}, \sigma_{\mathrm{grade,copper},3}),\\
i_{\mathrm{grade,zinc},n,3} &\text{ sampled from } I_{\mathrm{grade,zinc},3} \sim \mathrm{lognormal}(\mu_{\mathrm{grade,zinc},3}, \sigma_{\mathrm{grade,zinc},3}),\\
i_{\mathrm{grade,gold},n,3} &\text{ sampled from } I_{\mathrm{grade,gold},3} \sim \mathrm{lognormal}(\mu_{\mathrm{grade,gold},3}, \sigma_{\mathrm{grade,gold},3}),\\
i_{\mathrm{grade,silver},n,3} &\text{ sampled from } I_{\mathrm{grade,silver},3} \sim \mathrm{lognormal}(\mu_{\mathrm{grade,silver},3}, \sigma_{\mathrm{grade,silver},3}).
\end{aligned}$$

Still, the decision rule for whether to progress a deposit to the next exploration stage or not, is based on the expected NPV of exploiting the given deposit. This expected NPV is at decision gate 3, just as at decision gate 2, calculated by propagating backwards in time through a tree structure created by simulating possible future scenarios. If the expected NPV of exploiting a deposit after having performed all exploration stages is positive, perceived from decision gate 3, the deposit is progressed to exploration stage 4. However, when the decision maker is facing decision gate 3, it does not have information about what is unveiled in exploration stage 4. In terms of our modeling, this means that the parameters $i_{\mathrm{tonnage},n,4}$, $i_{\mathrm{grade},m,n,4}$, for $n \in \{1, \ldots, N_{\mathrm{DG3}}\}$, $m \in \{\mathrm{copper}, \mathrm{zinc}, \mathrm{gold}, \mathrm{silver}\}$, are not known, because they have not yet been sampled from the random variables $I_{\mathrm{tonnage},4}$ and $I_{\mathrm{grade},m,4}$ respectively. Therefore we simulate the future values of these parameters by doing a simulation sampling from the respective distribution functions of $I_{\mathrm{tonnage},4}$ and $I_{\mathrm{grade},m,4}$, in order to be able to get values of the ore tonnage, $x_{\mathrm{tonnage},n}$, from Equation (4.23), and values of the metal grades, $x_{\mathrm{grade},m,n}$ from Equation (4.27). These values will again form a tree structure of possible future scenarios and allow us to calculate the cash flows and thus the expected NPV of exploiting each of the $N_{\mathrm{DG3}}$ deposits under different tax regimes, with basis in Equation (4.3) - Equation (4.9), by propagating backwards in time through the mentioned tree structure.

In exploration stage 4, the decision maker obtains further information about the ore tonnage in a deposit, in addition to the grade of copper, zinc, gold and silver. Just like when faced with decision gate 2, we once again simulate the information obtained in stage 4, by making $S_2$ simulations for each of the $N_{\mathrm{DG3}}$ deposits, representing $S_2$ potential outcomes of completing exploration stage 4 for each deposit respectively. For ore tonnage, we denote the samples from the distribution function of $I_{\mathrm{tonnage},4}$ in the simulated scenarios as $i'_{\mathrm{tonnage},n,4,s_2}$ for $n \in \{1, \ldots, N_{\mathrm{DG3}}\}$, $s_2 \in \{1, \ldots, S_2\}$, where 4 denotes that the information comes from stage 4. For the metal grades, we denote the samples from the distribution functions of $I_{\mathrm{grade},m,4}$ in the simulated scenarios as $i'_{\mathrm{grade},m,n,4,s_2}$ for $m \in \{\mathrm{copper}, \mathrm{zinc}, \mathrm{gold}, \mathrm{silver}\}$, $n \in \{1, \ldots, N_{\mathrm{DG3}}\}$, $s_2 \in \{1, \ldots, S_2\}$. To summarize, in order to simulate the future information obtained in exploration stage 4 when facing decision gate 3, to then again be able to propagate backwards and calculate the expected NPV of exploiting each deposit $n$, we sample the following values from the following probability distribution functions:

$$\begin{aligned}
i'_{\mathrm{tonnage},n,4,s_2} &\text{ sampled from } I_{\mathrm{tonnage},4} \sim \mathrm{lognormal}(\mu_{\mathrm{tonnage},4}, \sigma_{\mathrm{tonnage},4}),\\
i'_{\mathrm{grade,copper},n,4,s_2} &\text{ sampled from } I_{\mathrm{grade,copper},4} \sim \mathrm{lognormal}(\mu_{\mathrm{grade,copper},4}, \sigma_{\mathrm{grade,copper},4}),\\
i'_{\mathrm{grade,zinc},n,4,s_2} &\text{ sampled from } I_{\mathrm{grade,zinc},4} \sim \mathrm{lognormal}(\mu_{\mathrm{grade,zinc},4}, \sigma_{\mathrm{grade,zinc},4}),\\
i'_{\mathrm{grade,gold},n,4,s_2} &\text{ sampled from } I_{\mathrm{grade,gold},4} \sim \mathrm{lognormal}(\mu_{\mathrm{grade,gold},4}, \sigma_{\mathrm{grade,gold},4}),\\
i'_{\mathrm{grade,silver},n,4,s_2} &\text{ sampled from } I_{\mathrm{grade,silver},4} \sim \mathrm{lognormal}(\mu_{\mathrm{grade,silver},4}, \sigma_{\mathrm{grade,silver},4}).
\end{aligned}$$

Having simulated the possible outcomes of information obtained in stage 4, we can use this in combination with all known information to make a decision at decision gate 3. This is because we are propagating backwards in time to decision gate 3 from the point in time where stage 4 is simulated to be completed. Through simulations of exploration stage 4 we have constructed a total of $S_2$ nodes for each deposit respectively. These nodes represent $S_2$ different outcomes of the information that is obtained through all exploration of a given deposit, after stage 4 has been conducted. These nodes are denoted by $s_2 \in \{1, \ldots, S_2\}$. At the node $s_2$ we thus have one simulated outcome of the information gathered exploration stage 4. Based on this information we can calculate a simulated value of the ore tonnage, $x'_{\text{tonnage},n,s_2}$, and metal grades $x'_{\text{grade},m,n,s_2}$ for a given node $s_2$.

The ore tonnage of deposit $n$ for a given node $s_2$ simulated forward in time from the perspective of decision gate 3 is given by

$$\begin{aligned} x'_{\text{tonnage},n,s_2} = i_{\text{tonnage},n,2} \cdot i_{\text{tonnage},n,3} \cdot i'_{\text{tonnage},n,4,s_2}, \\ n \in \{1, \ldots, N_{\text{DG3}}\}, \\ s_2 \in \{1, \ldots, S_2\}. \end{aligned} \tag{4.49}$$

The metal grade of metal $m$ in deposit $n$ for a given node $s_2$ from the perspective of decision gate 3 is given by

$$\begin{aligned} x'_{\text{grade},m,n,s_2} = i_{\text{grade},m,n,3} \cdot i'_{\text{grade},m,n,4,s_2}, \\ m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}, \\ n \in \{1, \ldots, N_{\text{DG3}}\}, \\ s_2 \in \{1, \ldots, S_2\}. \end{aligned} \tag{4.50}$$

Based on these parameters it is possible to calculate the cash flow, and thus also the NPV, after stage 4 has been conducted (in simulations). To calculate the cash flow for each year $t$ after stage 4 for each node $s_2$, we can use the following equation:

$$\begin{aligned} \text{CF}'_{n,t,j,s_2} &= \text{revenue}'_{n,t,j,s_2} - \text{cost}_{n,t,j} \\ &= \frac{d_{op,j}}{365} \cdot \omega_t \cdot \sum_m (x'_{\text{grade},m,n,s_2} \cdot \eta_m \cdot NF_m \cdot P_m) - (\text{OPEX}_{n,t,j} + \text{CAPEX}_{n,t,j}), \\ &\qquad m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}, \\ &\qquad n \in \{1, \ldots, N_{\text{DG3}}\}, \\ &\qquad s_2 \in \{1, \ldots, S_2\}. \end{aligned} \tag{4.51}$$

The cash flow that is obtained can be used to calculate the NPV that corresponds to each node $s_2$ based on the simulated scenarios. The NPV for each node $s_2$ after stage 4, from the perspective of decision gate 3, is denoted as $\text{NPV}'_{4,\text{DG3},n,s_2}$. Since the NPV depends on the given tax regime, different equations for the NPV need to be used for different regimes. Again, we apply a max-condition, following the dynamic programming approach in our modeling. For the standard corporate tax regime, the petroleum tax regime and the PIS tax regime, the NPV for the scenario in node $s_2$, after conducting stage 4 is respectively

$$\text{NPV}'_{\substack{\text{stand} \\ \text{corp} \\ \text{tax}},4,\text{DG3},n,s_2} = \max\left( \sum_{t=t_{\substack{\text{start of} \\ \text{extraction}}}}^{T} \frac{\text{CF}'_{n,t,j,s_2} \cdot (1 - \alpha_t \cdot T_c) + \beta_t \cdot T_c}{(1+r)^t},\ 0 \right), \tag{4.52}$$

$$
\begin{aligned}
&\mathrm{NPV}'_{\substack{\text{pet}\\\text{tax}},4,\mathrm{DG3},n,s_2} = \\
&\max\left( \sum_{t=t_{\substack{\text{start of}\\\text{extraction}}}}^{T} \left( \frac{\Big[\mathrm{CF}'_{n,t,j,s_2}\cdot(1-\alpha_t\cdot T_c)\Big](1-\alpha_t\cdot T_s)+\beta_t\cdot(T_p-T_s)}{(1+r)^t} \right.\right. \\
&\qquad\qquad \left.\left. + \frac{(1-\alpha_{t-1})\cdot|\mathrm{CF}'_{n,t-1,j,s_2}|\cdot T_s}{(1+r)^t} \right),\ 0 \right),
\end{aligned}
\tag{4.53}
$$

where $T$ is given by

$$
T = t_{\text{start of extraction}} + \frac{x'_{\text{tonnage},n,s_2}}{\omega_t}.
\tag{4.54}
$$

We have now obtained an NPV for each of the $S_2$ nodes after stage 4. These NPVs can be used to propagate backwards to make a decision at decision gate 3. We now only need to propagate one step backwards, compared to two when we were at decision gate 2. Still, we use the same $k$-th percentile method and dynamic programming approach as in that scenario. Therewith, the expected NPV that is propagated backwards in time from the simulated point in time (after completion of exploration stage 4) to the point in time of decision gate 3 is for the different tax regimes respectively given by

$$
\mathrm{NPV}'_{\substack{\text{stand}\\\text{corp}\\\text{tax}},3,\mathrm{DG3},n} = \max\left( \frac{\mathrm{P75}\left(\mathrm{NPV}'_{\substack{\text{stand}\\\text{corp}\\\text{tax}},4,\mathrm{DG3},n,s_2}\right)}{(1+r)^t} - \mathrm{CAPEX}_{n,t,4},\ 0 \right)
\tag{4.55}
$$

$$
\begin{aligned}
\mathrm{NPV}'_{\substack{\text{pet}\\\text{tax}},3,\mathrm{DG3},n} = \max&\left( \frac{\mathrm{P75}\left(\mathrm{NPV}'_{\substack{\text{pet}\\\text{tax}},4,\mathrm{DG3},n,s_2}\right)}{(1+r)^t} \right. \\
&\qquad \left. - \mathrm{CAPEX}_{n,t,4} + \frac{\mathrm{CAPEX}_{n,t,4}\cdot T_s}{(1+r)^t},\ 0 \right)
\end{aligned}
\tag{4.56}
$$

If $\mathrm{NPV}'_{3,\mathrm{DG3},n}$ is larger than zero, the potential deposit $n$ has a positive expected NPV. In this case the company would choose to progress to the next stage. Otherwise, the company would choose to abandon the deposit. Thus, the $n$-parameter which stores the deposits that have potential of yielding positive NPVs is updated from $n \in \{1,\ldots,N_{\mathrm{DG3}}\}$ to $n \in \{1,\ldots,N_{\mathrm{DG4}}\}$.

### 4.6.3 Decision gate 4

When the corporate decision maker is facing decision gate 4, it has to determine whether to undertake the mineral exploiting stages 5) *pilot mining* and 6) *full-scale mineral extraction* for each deposit $n \in \{1,\ldots,N_{\mathrm{DG4}}\}$ that remains in the portfolio, respectively. Thus, when making this decision, all exploration has been carried out for all of the $n \in \{1,\ldots,N_{\mathrm{DG4}}\}$ potential deposits. Therewith, all information possible to gather through exploration for the deposits has been obtained and the decision maker is assumed to have complete information about the geological parameters of each deposit. This information regards the ore tonnage of each deposit, $i_{\text{tonnage},n,j}$ for $j \in \{2,3,4\}$, and the metal grades of each deposit, $i_{\text{grade},m,n,j}$ for $m \in \{\text{copper},\text{zinc},\text{gold},\text{silver}\}$, $j \in \{3,4\}$. The newly obtained certain information is $i_{\text{tonnage},n,4}$ and $i_{\text{grade},m,n,4}$. All other values have been gathered previously, through earlier exploration. The newly gathered certain information, $i_{\text{tonnage},n,4}$ and $i_{\text{grade},m,n,4}$, are sampled from the following probability distributions respectively:

$$\begin{aligned}
i_{\text{tonnage},n,4} &\text{ sampled from } I_{\text{tonnage},4} \sim \text{lognormal}(\mu_{\text{tonnage},4}, \sigma_{\text{tonnage},4}),\\
i_{\text{grade,copper},n,4} &\text{ sampled from } I_{\text{grade,copper},4} \sim \text{lognormal}(\mu_{\text{grade,copper},4}, \sigma_{\text{grade,copper},4}),\\
i_{\text{grade,zinc},n,4} &\text{ sampled from } I_{\text{grade,zinc},4} \sim \text{lognormal}(\mu_{\text{grade,zinc},4}, \sigma_{\text{grade,zinc},4}),\\
i_{\text{grade,gold},n,4} &\text{ sampled from } I_{\text{grade,gold},4} \sim \text{lognormal}(\mu_{\text{grade,gold},4}, \sigma_{\text{grade,gold},4}),\\
i_{\text{grade,silver},n,4} &\text{ sampled from } I_{\text{grade,silver},4} \sim \text{lognormal}(\mu_{\text{grade,silver},4}, \sigma_{\text{grade,silver},4}).
\end{aligned}$$

Since the operator now has certain information for each deposit $n$, we do not need to use simulations to calculate the cash flows that may be generated from exploitation of a given deposit and the associated NPV. A deposit $n$ is now progressed to stage 5) *pilot mining* and stage 6) *full-scale mineral extraction* if the NPV of doing so, calculated with certain parameters only, is positive. The cash flows and associated NPVs of the $N_{\text{DG4}}$ deposits are calculated with basis in Equation (4.3) - Equation (4.9).

The ore tonnage of deposit $n$, $x_{\text{tonnage},n}$, now depend on the known values $i_{\text{tonnage},n,2}$, $i_{\text{tonnage},n,3}$ and $i_{\text{tonnage},n,4}$. The metal grades for deposit $n$, $x_{\text{grade},m,n}$, for $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$, now depend on the known values $i_{\text{grade},m,n,3}$ and $i_{\text{grade},m,n,4}$. This is the scenario portrayed in Equation (4.23) and Equation (4.27).

The cash flow generated by exploiting deposit $n$ in year $t$ can now simply be calculated with the certain values mentioned above, as

$$\begin{aligned}
\text{CF}_{n,t,j} &= \text{revenue}_{n,t,j} - \text{cost}_{n,t,j}\\
&= \frac{d_{op,j}}{365} \cdot \omega_t \cdot \sum_m (x_{\text{grade},m,n} \cdot \eta_m \cdot NF_m \cdot P_m) - (\text{OPEX}_{n,t,j} + \text{CAPEX}_{n,t,j}),\\
&\qquad\qquad m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\},\\
&\qquad\qquad n \in \{1, \dots, N_{\text{DG4}}\}.
\end{aligned} \tag{4.57}$$

The NPV of each deposit can then be calculated by inserting the cash flows into the following NPV equations, for different tax regimes.

$$\text{NPV}_{\substack{\text{stand}\\\text{corp}\\\text{tax}},4,\text{DG4},n} = \max\left(\sum_{t=t_{\substack{\text{start of}\\\text{extraction}}}}^{T} \frac{\text{CF}_{n,t,j} \cdot (1-\alpha_t \cdot T_c) + \beta_t \cdot T_c}{(1+r)^t},\ 0\right), \tag{4.58}$$

$$\begin{aligned}
&\text{NPV}_{\substack{\text{pet}\\\text{tax}},4,\text{DG4},n} =\\
&\max\left(\sum_{t=t_{\substack{\text{start of}\\\text{extraction}}}}^{T} \left(\frac{\Big[\text{CF}_{n,t,j} \cdot (1-\alpha_t \cdot T_c)\Big](1-\alpha_t \cdot T_s) + \beta_t \cdot (T_p - T_s)}{(1+r)^t}\right.\right.\\
&\qquad\left.\left.\frac{+(1-\alpha_{t-1}) \cdot |\text{CF}_{n,t-1,j}| \cdot T_s}{(1+r)^t}\right),\ 0\right),
\end{aligned} \tag{4.59}$$

where $T$ is given by

$$T = t_{\text{start of extraction}} + \frac{x_{\text{tonnage},n}}{\omega_t}. \tag{4.60}$$

If $\text{NPV}_{4,\text{DG4},n}$ is larger than zero, deposit $n$ has a positive certain NPV. In this case the company would choose to progress to the next stages, which are 5) *pilot mining* and 6) *full-scale mineral extraction*. Otherwise, the company would choose to abandon the deposit. Thus, the $n$ parameter which stores the deposits that have potential of yielding positive NPVs is updated from $n \in \{1, \dots, N_{\text{DG4}}\}$ to $n \in \{1, \dots, N_{\text{extraction}}\}$.

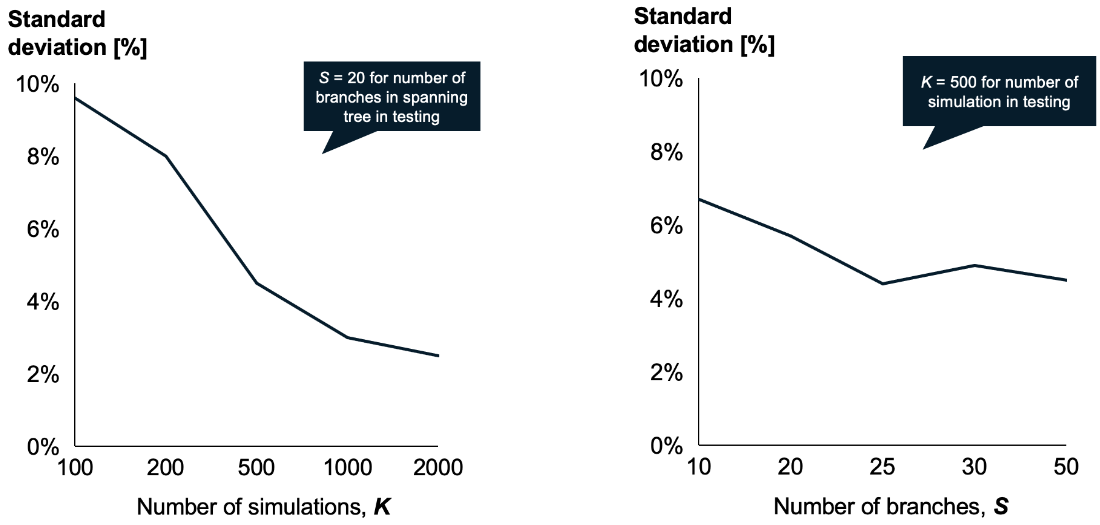
## 4.7 Number of simulations and branches in spanning tree

At decision gates 2 and 3, the decision to proceed or abandon a deposit is contingent upon the evaluation of $S_1$ and $S_2$ simulated scenarios, represented as branches in a spanning tree. The complete process illustrated in Figure 4.3 and Figure 4.4 is simulated $K$ times for the simulations' given total portfolio of deposits, and the resulting $K$ outcomes inform the computation of the expected NPV for both the company and the state with respect to a particular license.

The model critically relies on both the quantity of branches, $S_1$ and $S_2$, as well as the number of simulations, $K$. Therefore, it is imperative to select reasonable values for these parameters. Increasing the number of branches and simulations would enhance the model's robustness. However, a significant rise in computational expense would accompany this. The computational expense escalates linearly with the number of simulations $K$ and with the square of the number of branches $S_1$ and $S_2$. In the rest of this section $S_1$ and $S_2$ are set equal and referred to as $S$ for the purpose of clarity and ease of understanding.

We adopted an empirical approach to determine optimal values that would ensure the model's robustness in generating trustworthy managerial insights, while simultaneously controlling computational expenses.

Empirical testing was initiated by conducting two different tests. Firstly, the number of simulations, $K$, were varied whilst keeping number of branches in the spanning tree, $S$, constant. Secondly, numbers of branches in the spanning tree, $S$, were varied whilst keeping the number of simulations, $K$, constant. The objective was to see how the standard deviation of the outcome of the model, the expected NPV, changed by varying the parameters. The results are presented in Figure 4.5 below.



(a) Standard deviation of project NPV as a function of number of simulations, $K$

(b) Standard deviation of project NPV as a function of number of branches, $S$

Figure 4.5: Standard deviation of project NPV for varying number of branches, $S$, and simulations, $K$, using high metal grades

Figure 4.5 shows the standard deviation measured in percentage of the expected NPV for a varying numbers of branches, $S$, and simulations, $K$. The results suggests that there exists a clear relationship between the standard deviation of the average NPV and the number of simulations, $K$. As number of simulations, $K$, is increased, the standard deviation decreases. This is in line with expectations. This result indicates that increasing the number of simulations can lead to a more stable and reliable output from the model.

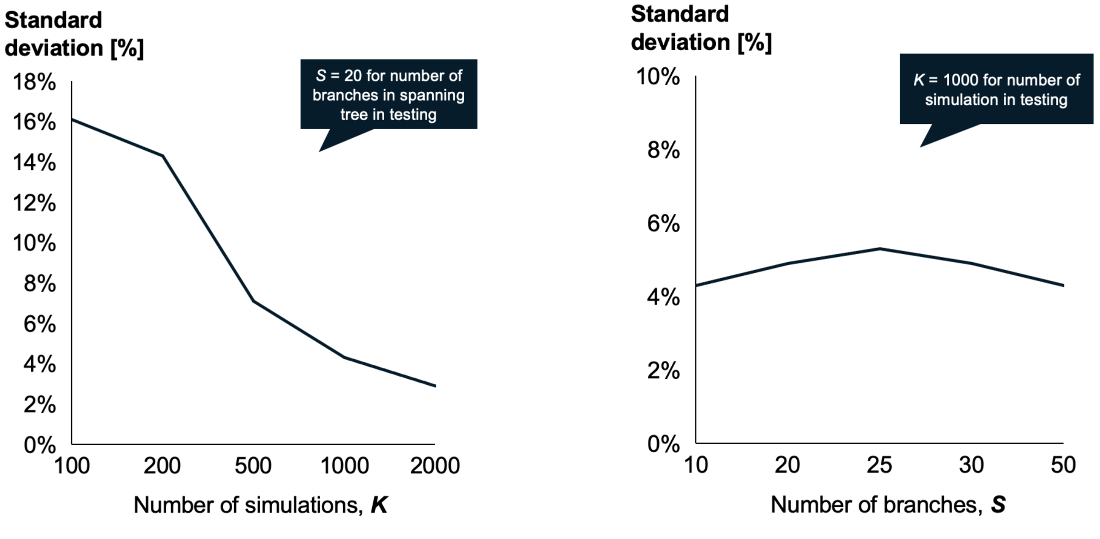
The relationship between the number of branches in the spanning tree, $S$, and the standard deviation of the expected NPV outcome appears to be relatively weak. However, it is possible that some model inputs in this specific simulation, such as metal grade distributions, may have influenced the outcomes of the experiments. If the metal grades are sufficiently high, the simulated scenario at each branch will consistently yield positive results. If all branches yields a positive scenario, increasing the number of branches in the spanning tree will not make a difference in the decision making(as the deposit will be progressed anyways).

In the simulations used for obtaining the results in Figure 4.5 the metal grades of Ellefmo and Søreide (2019) are used. These metal grades are shown in Table 5.12.

To increase the understanding and gain deeper insights into the optimal parameter values, we conduct a subsequent test selecting significantly lower metal grade distributions. The metal grade distributions of Lesage et al. (2019) were used. These metal grades are presented in Table 5.11. In this experiment, we again vary the number of branches in the spanning tree, $S$, while maintaining a constant number of simulations, $K$. Conversely, we also varied the number of simulations, $K$ while keeping the number of branches, $S$, constant.

For low metal grade the results showed a standard deviation of approximately 0% across all cases. This is because at these metal grade levels, no potential deposits are progressed to mineral extraction. This result offers valuable insight into an aspect of our model with regards to robustness, as it demonstrates that the model consistently generates reliable outputs for input values that are too low for mineral extraction to make economical sense. This enhances the degree of confidence that can be placed in the model's output. However the results does not enhance the understanding of the optimal choice of number of simulations, $K$, or number of branches in the spanning trees, $S$.

Tests have been conducted with relatively high and low metal grade distributions. Due to the certainty of outcome (high probability for progressing a deposit with high metal grades and high probability of abandoning a deposit with low metal grades), the necessary numbers of branches in the spanning tree to ensure a robust model may have been underestimated. To determine the necessary number of branches, we adjust the metal grade distributions such that approximately 50% of the potential deposits are progressed for mineral extraction, whilst the remaining 50% of the potential deposits are abandoned during the exploration phase. The number of branches, $S$, is varied while keeping the number of simulations, $K$, constant, and vice versa. The results of these tests are illustrated in Figure 4.6 below.



(a) Standard deviation of project NPV as a function of number of simulations, $K$

(b) Standard deviation of project NPV as a function of number of branches, $S$

Figure 4.6: Standard deviation of project NPV for varying number of branches, $S$, and simulations, $K$, using intermediate metal grades

Figure 4.6 shows the standard deviation measured in percentage of the expected NPV for a varying numbers of branches, $S$, and simulations, $K$. The results presented make it evident that there is a significant reduction in standard deviation when increasing the number of simulations, $K$. For instance, increasing the number of simulations from $K = 100$ to $K = 2000$ results in a decrease of the standard deviation measured in percentage of expected NPV from 16% to 3%. However, the results presented in Figure 4.6 demonstrate that even for middle metal grades case, there appears to be a limited effect on the standard deviation of the NPV from varying the number of branches, $S$.

Further tests were conducted to gain better understanding of why the number of branches, $S$, seem to have limited impact on the robustness of the model. The limited effect of the number of branches, $S$, can be explained by how decisions are made at the decision gates, by comparing the P75 metric as decision rule used in our model to an average NPV rule. Using the the P75 metric, a deposit is progressed if the P75 of the NPV´s from the $S$ simulated branches is larger than the CAPEX of performing the following stage adjusted for tax reimbursement. With the average NPV rule, a deposit would be progressed to the next stage if the average NPV calculated from the $S$ simulated branches is larger than the CAPEX of performing the following stage adjusted for tax reimbursement. There are significant differences between the P75 metric as decision rule and the average NPV rule when model parameters are sampled from log-normal distributions. To show this, the log-normal distribution with the largest variance in our proposed model, ore tonnage of individual deposits, $X_{\text{tonnage}}$, was selected for testing. This log-normally distributed random variable has an expected value of 930 and a standard deviation of 3630. We varied the number of samples taken from this variable, denoted as $Q$, and calculated both the the average and the P75 from these $Q$ samples. This process was repeated 100 000 times for each specified value of $Q$, allowing for an assessment of the standard deviation for both the average and the P75 at different values of $Q$. The number of samples, $Q$, will in this case be similar to the number of branches, $S$ in the model. In this test, the average and P75 is calculated for $Q$ samples of the selected log-normal random variable. In our proposed model the P75 is calculated based on $S$ branches, where each branch have a associated NPV obtained from simulation. Figure 4.7 below illustrates the results.

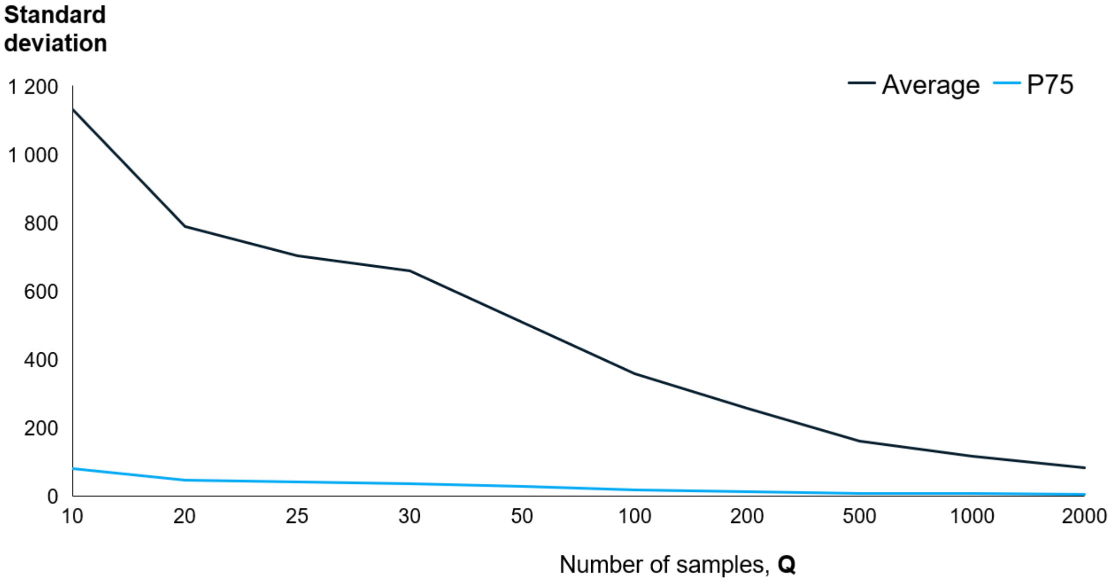


Figure 4.7: Standard deviation for the average and P75 from varying number of samples, $Q$.

Figure 4.7 shows how the standard deviation decreases with increasing number of samples calculating both the average and the P75. The figure shows a notable difference between using the P75 and the average. Notably, the standard deviation of the calculated P75 with only 10 samples is equivalent to the standard deviation of the average using using 2000 samples. This is driven by the fact some that log-normal distributions have extreme cases that yield very high values. These extreme values are incorporated into the average, and they will therefore affect the outcome metric.

When calculating the P75, the values of the extreme high cases does not affect the outcome metric.

By utilizing 50 samples for the P75-rule, we obtained a standard deviation of $\sim 25$. This is relativity low when considering that we are drawing from a log-normal distribution with an average of 930 and a standard deviation of 3630. The low standard deviation provides us with a high level of confidence in the P75 outcome at 50 samples. Therefore, we can trust the P75 result at this sample size with a relatively high degree of certainty.

After conducting the tests, we have decided to select $K = 2000$ and $S = 50$. Increasing the number of simulations generally results in a lower standard deviation, but the marginal benefit gradually diminishes. Additionally, increasing the number of simulations also leads to increased computational expense. Therefore, we have determined that $K = 2000$ provides an appropriate balance between low standard deviation of the NPV and computational manageability.

Selecting $S = 50$ for the number of branches strikes a balance between two opposing considerations. On one hand, our simulations have shown that the number of branches does not have a significant impact on the standard deviation, and therefore a lower number of branches could be selected to reduce computational costs. On the other hand, setting $S = 50$ rather than lower values makes the output from the model more reliable. Throughout the testing process, we engaged in discussions with mathematics professors, who emphasized the significance of having a minimum of 30 samples to replicate behavior that follows a normal distribution. By setting the value of $K$ to 50, we exceed this threshold, whilst also ensuring that the computational costs remains manageable.

It is an inevitable reality that models will always exhibit some degree of uncertainty and variance. While we acknowledge that increasing both $K$ and $S$ would result in further reductions in standard deviation in the NPV, the primary aim of our model is to highlight managerial insights and explore changes in behavior across different tax regimes and parameter sensitivities. We are confident that the model, with its selected values for $K$ and $S$, is robust enough to support reliable and insightful managerial decision making.

# 5 Data

In this section, we present all utilised data and parameter values assigned to the parameters described in Section 4.

## 5.1 Non-geological parameter values

In this section we present the parameter values assigned to the parameters discussed in Section 4.3 in our case study.

### 5.1.1 Annual production

Annual production of ore on the license block, denoted $\omega_t$, is difficult to accurately estimate. As commercial deep-sea mining is yet to take place, the technologies involved in this are not yet tested with commercial mining volumes and unforeseen down-time is likely to occur. Various deposits will have different characteristics that affect annual production rate. On top of that, external factors like weather could play a role in this and vary year to year, location to location.

The best current estimates for annual production of SMS deposits may be those made for Nautilus Mineral's planned mining of Solwara 1 by SRK Consulting (2010). The average production rate for the Solwara 1, from the set production schedule, was 1.35 million tonnes of ore per year excluding site initiation and shut-down, but taking into account the mining equipment's predicted outage, downtime and idling as well as delays (SRK Consulting 2010). The weather conditions in the arctics, where SMS deposits are likely to be found on the NCS, are rougher than those in the Bismarck Sea outside Papaua New Guinea, where Solwara 1 is located. However, Frimanslund's (2016) estimate of annual production of the Loki's Castle deposit on the Mohns Ridge is 1.3 million tonnes, with a similar production system as planned for Solwara 1 and taking into account downtime from wating-on-weather and maintenance. Frimanslund's (2016) estimate is to a large degree based on the Solwara 1 schedule. Thus, we assume an annual production rate of 1.3 million tonnes as a baseline in this thesis.

### 5.1.2 Net smelter return and metal recovery rate

Net smelter return and metal recovery rate per metal, denoted $NF_m$ and $\eta_m$ respectively, are values that we obtain from Wellmer et al. (2008). These values describe processing of ore from terrestrial mining, but they have earlier been used by Lesage et al. (2019) for deep-sea mining purposes, as it is assumed that mined ore from the seabed has similar properties to ore mined terrestrially. The net smelter return and metal recovery rates for copper, zinc, silver and gold from Wellmer et al. (2008) are reproduced in Table 5.1.

Table 5.1: Metal recovery rate and net smelter return

| Metal $m$ | Metal recovery rate, $\eta_m$ | Net smelter return, $NF_m$ |
|---|---|---|
| Copper (Cu) | 90% | 65% |
| Zinc (Zn) | 90% | 50% |
| Gold (Au) | 80% | 95% |
| Silver (Ag) | 80% | 95% |

Source: Wellmer et al. (2008)

### 5.1.3 Metal prices

The metal price, $P_m$, for each of the four metals that are modeled in this thesis is fixed as approximately the spot rates at the start of April 2023 (IndexMundi 2023). This is a simplification, as metal prices in reality are highly varying. The considered commodity prices for copper, zinc, gold and silver are given in Table 5.2. The purpose of rounding the metal prices is to avoid misleading readers with a false impression of precision regarding these values.

Table 5.2: Metal prices

| Metal $m$ | Commodity price, $P_m$ |
|---|---:|
| Copper (Cu) | 9 000 USD/tonne |
| Zinc (Zn) | 3 000 USD/tonne |
| Gold (Au) | 60 000 000 USD/tonne |
| Silver (Ag) | 750 000 USD/tonne |

### 5.1.4 Timing of model stages

We assume that the time spent on each exploration stage and the time between final exploration and full-scale mineral extraction is constant. The time for each stage is listed in Table 5.3 and is based on the work of Bang and Trellevik (2022) as well as input from industry experts.

Table 5.3: Timing of modeled stages

| Stage $j$ | Time stage takes [years] | Time index, $t$, of stage's start [year] |
|---|:---:|:---:|
| 1) *Regional survey* | 1 | 1 |
| 2) *Local survey* | 1 | 2 |
| 3) *Preliminary test drilling* | 1 | 3 |
| 4) *Extensive test drilling* | 1 | 4 |
| 5) *Pilot mining* | 1 | 5 |
| 6) *Mineral extraction* | LoLB | 6 |

Every stage leading up to 6) *full-scale mineral extraction* is set to last for one year in our model. Even though the actual operational activity that is performed in a stage not necessarily would last one year, each stage is modeled to be performed within one year. This is to allow for the fact that data gathered in exploration must be analysed, which takes additional time after the operations themselves. Also, it is unlikely that exploration activity will be undertaken during the winter months, when the weather in the Arctic is at its roughest (Ellfmo, personal communication) which makes one year per stage a reasonable estimate, according to industry experts.

### 5.1.5 CAPEX

As is evident from Section 4.3.6, there are multiple parameters that go into the CAPEX functions for the different exploration stages. First, we will explain the values of the parameters that are shared between all stages of exploration, both those that are constant over all exploration stages and those that are exploration stage-dependent. Then we will explain the values of the parameters that are unique for the different exploration stages.

The vessel day rate $C_{day,j}$ is also an exploration stage-dependent parameter that is used through all exploration stages. The day rate for exploration stages 1 and 2 are set in accordance with the work of Bang and Trellevik (2022), to 82 500 USD and 140 000 USD respectively. The the day rate for stages 3 and 4 are set at twice the amount for stage 2, 280 000 USD after consultation with industry expert Lesage (personal communication). The increase in day rates for stage 3 and 4 compared to stage 2 is a result of the types of vessels needed for these stages. The day rates are summarised in Table 5.4.

We have decided to model the EIA-factor, EIA, as an exploration stage-independent parameter that is added on top of the exploration time itself in all exploration stages. It accounts for the extra time spent on performing EIA related activities in parallel with exploration activities. Industry experts disagree on the appropriate value of this premium. Both a fixed premium of maximum 20% for all exploration stages and a linearly increasing premium of 20% in stage 1 and 50% in stage 4 have been recommended as appropriate. However, for the base case parameter values, we have decided to set a fixed EIA of 20% for all stages, $j \in \{1, 2, 3, 4\}$, as stated in Table 5.4.

The exploration stage-independent parameters for days spent on mobilisation, demobilisation and transport, $d_{mob}$, $d_{demob}$ and $d_{trans}$ are estimations that have been made in accordance with Lesage (personal communication). We assume that a vessel in all exploration stages spend two days in mobilisation before going out at sea, making $d_{mob} = 2$. When returning, we assume that the vessel spends one day in demobilisation, making $d_{demob} = 1$. We assume that Bergen is a probable base port, and therefore starting point for an exploration mission. From Bergen to the area where the Mohns and Knipovich Ridge are located it takes approximately three days with vessel transport (Lesage, personal communication). The vessel also needs to get back from the survey area, which takes approximately the same amount of time, making the total transport time six days, $d_{trans} = 6$. This is also summarised in Table 5.4.

Table 5.4: Values of CAPEX parameters for exploration stages 1-4

| Stage $j$ | $C_{day,j}$ [USD] | EIA [-] | $d_{mob}$ [days] | $d_{mob}$ [days] | $d_{trans}$ [days] |
|---|---|---|---|---|---|
| 1) *Regional survey* | 82 500 | 0.20 | 2 | 1 | 6 |
| 2) *Local survey* | 140 000 | 0.20 | 2 | 1 | 6 |
| 3) *Preliminary test drilling* | 280 000 | 0.20 | 2 | 1 | 6 |
| 4) *Extensive test drilling* | 280 000 | 0.20 | 2 | 1 | 6 |

### Exploration stages 1 and 2

The parameter values stated in this section are the ones explaining the amount of days a vessel spends on survey activity in exploration stages 1 and 2, $d_{survey,j}$ from Equation (4.14). The total area to be covered by survey, $A_{tot,j}$ is in exploration stage 1 the area of the assigned license block with permissive tract, as described in Section 5.2.1, which is updated to stage 2 through the mechanism also described in Section 5.2.1. However, for the survey swath, $W_j$, the velocity of survey vessel, $v_j$ and the number of operative hours per day, $h_{day}$, we use the same values as (Bang and Trellevik 2022). These are given in Table 5.5. The swath and vessel speed are greater in exploration stage 1 than stage 2 because of the different level of detail in the data gathered and the different equipment required in the two exploration stages, as described in Section 3.1.2.

Table 5.5: Values of CAPEX parameters unique for exploration stages 1-2

| Stage $j$ | $W_j$ [km] | $v_j$ [km/h] | $h_{day}$ [h/day] |
|---|---|---|---|
| 1) *Regional survey* | 2.222 | 3.704 | 18 |
| 2) *Local survey* | 0.926 | 1.852 | 18 |

### Exploration stages 3 and 4

The parameter values stated in this section are the ones explaining the amount of days a vessel spends on survey activity in exploration stages 3 and 4, $d_{survey,j}$ from Equation (4.15). The total area to be covered by survey, $A_{tot,j}$ is in exploration stages 3 and 4 set in accordance with the mechanism described in Section 5.2.2. The number of core-samples collected per area unit however, $S_{cores\ per\ area,j}$, is set such that in a deposit one would have a grid of one drill hole per $20 \times 20$ meters after having gone through exploration stage 4. This would be realistic according to Lesage (personal communication), though deposit dependant in reality. This corresponds to a total number of core-samples of 2500 per km$^2$ of deposit. Lesage (personal communication) estimates that one would drill for 20% of the total amount of holes in exploration stage 3. This means that for exploration stage 3 we drill for 500 core-samples per km$^2$ and for exploration stage 4 we drill for 2000 core-samples per km$^2$. Thus, we assume $S_{cores\ per\ area,3} = 500$ [cores/km$^2$] and $S_{cores\ per\ area,4} = 2000$ [cores/km$^2$]. Further, we assume that during exploration activity one core-sample is collected per day on average. This was estimated by Ellefmo (personal communication) to be realistic during both exploration stage 3 and 4 with the currently available technology. Therefore, we use a constant $d_{core} = 1$ [day/core].

To add on the cost of analysing the core-samples we have added a parameter $C_{analysis,j}$ to the CAPEX, which depends on the same area and cores per area as described above, as seen in Equation (4.15). However we have also added an analysis cost per core, $C_{core}$ which is the total cost involved with analysing one core-sample. This is set to 10 000 USD as a fixed average per core for both exploration stage 3 and 4 after consulting with Lesage (personal communication), making $C_{core} = 10\ 000$ [USD/core].

### 5.1.6 OPEX

The OPEX depends on the daily outsourcing fee paid to the mining operator as well as the per tonne cost of processing and refining the mined ore into metal concentrates, as described in Section 4.3.6.

The daily outsourcing fee is set with the estimated daily operating cost in Nautilus Minerals' Solwara 1 project as a baseline. This is found in SRK Consulting (2010) and is replicated in Table 5.6.

Table 5.6: OPEX summary for the Solwara 1 project

| Description | Total daily cost [USD] |
|---|---:|
| Production support vessel | 144 796 |
| Seafloor mining equipment | 20 130 |
| Workclass ROV's | 20 910 |
| Riser and lift system | 23 184 |
| Support services | 15 235 |
| Barging | 12 964 |
| Sub-total operating costs | 236 949 |
| Contingency (10%) | 23 695 |
| Total operating costs | 260 644 |

As mentioned, these are the OPEX estimates for the Solwara 1 project, but are not necessarily representable for a mining operation on the NCS. This is because the arctic conditions likely would result in higher costs along all cost items, and the far distance from nearest port likely would result in high logistical costs (Ellefmo, personal communication). In addition, the estimates in Table 5.6 are only the costs of operations themselves. Nautilus Minerals' business model was to invest in its own mining equipment and run the mining operation itself (SRK Consulting 2010), resulting in high CAPEX but a lower OPEX. However, in our model we assume that we outsource the mining operation to a contractor, and the contractor would obviously require a premium above their operations costs. All this taken into consideration, we set the daily daily outsourcing fee paid to the mining operator per deposit, $C_{day,contractor}$, to 350 000 USD/day. The same assumption has earlier been made by Andreassen and Borge (2022) based on consultation with industry experts.

The value of the ore processing cost per tonne, $C_{process}$, we use is the same that is used in Lesage et al.'s (2019) model. Thus, the processing cost for ore is 19.47 USD/tonne.

### 5.1.7 Days spent annually on operational activity

The number of days spent per year on operational activity, is dependent on whether the mineral project on the license block is in the pilot mining stage the full-scale mineral extraction stage. This is evident from Equation (4.12). Under pilot mining, a deposit needs to be mined for approximately 2 months according to industry experts, making the amount of days spent on pilot mining per deposit $d_{pm} = \frac{2}{12} \cdot 365 \approx 61$. The number of extracted deposits, $N_{\text{extraction}}$, is determined in the model's solution mechanism, described in Section 4.6. As is evident from Equation (4.12), we assume that under full-scale mineral extraction the operation runs 365 days per year. Down-time is therefore incorporated in the annual production parameter, $\omega_t$, which takes waiting-on-weather and maintenance into account.

### 5.1.8 Discount rate

The discount rate that the operator company would require in a marine mineral mining project is set to 15%. This required rate of return is set based on consultation with industry experts. The required rate of return is based on the average rate of return employed in terrestrial mining, adjusted for industry specific differences between terrestrial and deep-sea mining, as well as parameter modeling choices.

In the realm of terrestrial mining, the average discount rate typically falls within the range of 7-8% (Ovalle 2020). However, there are several compelling reasons supporting a higher discount rate in the context of deep-sea mining. Primarily, deep-sea mining entails a notable amount of technological risks that surpasses that of traditional terrestrial mining. The mining techniques and technologies employed in terrestrial mining are proven and known, resulting in a a greater level of reliability. Naturally, unproven deep-sea mining technologies carry a significantly higher degree of technological risk. Secondly, there exists a substantial political risk associated with exploring and extracting resources from the seabed. In the case of terrestrial mining, where numerous similar operations have been undertaken before, the risks pertaining to permits and grants are comparatively lower due to established processes. However, deep-sea mining operates in a domain where legislation is still evolving, introducing greater uncertainties and political risks. As deep-sea mining is a relatively novel industry, there is currently no universally accepted approach for explicitly integrating these technological and political risks into a model, to the best of our knowledge. Consequently, it becomes imperative to employ a higher risk premium for deep-sea mining projects compared to terrestrial mining to account for the technological and political risk.

Large corporations in the terrestrial mining sector typically incorporate explicit modeling of risks associated with specific parameters in their models. In our proposed model, we explicitly consider geological risks, such as metal grade and ore tonnage. However, we do not explicitly incorporate risks associated with metal prices, day rates utilised for calculating OPEX and CAPEX, as well as other relevant factors in our model. The value of these parameters are set constant throughout the model. To address that these risks are not modeled explicitly, we increase the risk premium in the required rate of return.

Based on the average rate of return within terrestrial mining, adjusted for industry specific differences between terrestrial and deep-sea mining, as well as parameter modeling choices, we arrive at a rate of return at 15%. This rate also resonates with rate of returns applied within similar work within deep-sea mining. In the work of for example Bang and Trellevik (2022) there is used a discount rate of 10%. However, more of the risk relating to metal prices and other dynamic parameters are incorporated into the model of Bang and Trellevik (2022) compared to the model presented in this thesis. When considering these differences in modeling approaches, we find ourselves approximately aligned in terms of the discount rate.

### 5.1.9 Tax rates

The tax rates applied to the different tax regimes modeled in Equation (4.5) and Equation (4.8) are summarised in Table 5.7.

Table 5.7: Tax rates

| Parameter | Rate | Description |
|---|---|---|
| $T_c$ | 22% | Standard corporate tax rate in Norway |
| $T_p$ | 78% | Total petroleum tax rate in Norway (simplified) |
| $T_s$ | 71,8% | Special petroleum tax rate in Norway |

The total petroleum tax rate is simplified as described in Section 3.3.2.

## 5.2 Geological parameter values

In this section the probability distributions of the geological parameters discussed in Section 4.4 will be presented. All distributions are log-normally distributed.

### 5.2.1 Initial number of potential deposits

The initial number of potential deposits, $N_{\text{DG2}}$ within the license block is obtained in the first stage of the exploration model. A probability distribution for the number of potential deposits is obtained from Ellefmo and Søreide (2019) and reproduced in Table 5.8.

Table 5.8: Distribution of number of potential deposits from Mohns and Knipovich Ridge

| | Mode | Mean | Std | F100 | F95 | F90 | F75 | F50 | F25 | F20 | F10 | F5 | F0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of deposits | 80 | 155 | 112 | 1 | 32 | 45 | 75 | 125 | 205 | 228 | 308 | 382 | 594 |

Source: Ellefmo and Søreide (2019)

The probability distribution of Table 5.8 applies to a total area of 11 389 km$^2$ of the permissive tracts of Mohns and Knipovich Ridge. In this thesis, we make the assumption that the probability distribution of potential deposits per area within the modeled exploration license will closely resemble that of the Mohns and Knipovich Ridge. However, in our model the license areas are assumed to be smaller than 11 389 km$^2$, and the whole license area granted will not be permissive tracts. We have assumed that the area of a license block is 1000 km$^2$, and that 50% of the area is permissive tracts after consultation with industry experts. This results in a relevant area for exploration of 500 km$^2$. An area of 500 km$^2$ has the following probability distribution for the initial number of potential deposits:

Table 5.9: Distribution of number of potential deposits for example license block

| | Mode | Mean | Std | F100 | F95 | F90 | F75 | F50 | F25 | F20 | F10 | F5 | F0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of deposits | 3.6 | 6.8 | 4.9 | 0 | 1.9 | 2.4 | 3.5 | 5.5 | 8.5 | 9.5 | 12.5 | 16 | 30 |

The number of potential deposits must be an integer in the model proposed in this thesis. To arrive at an integer the number obtained from the distribution described in Table 5.9 is rounded to the nearest integer. The resulting probability for each number of potential deposits is shown as a histogram in Figure 5.1.

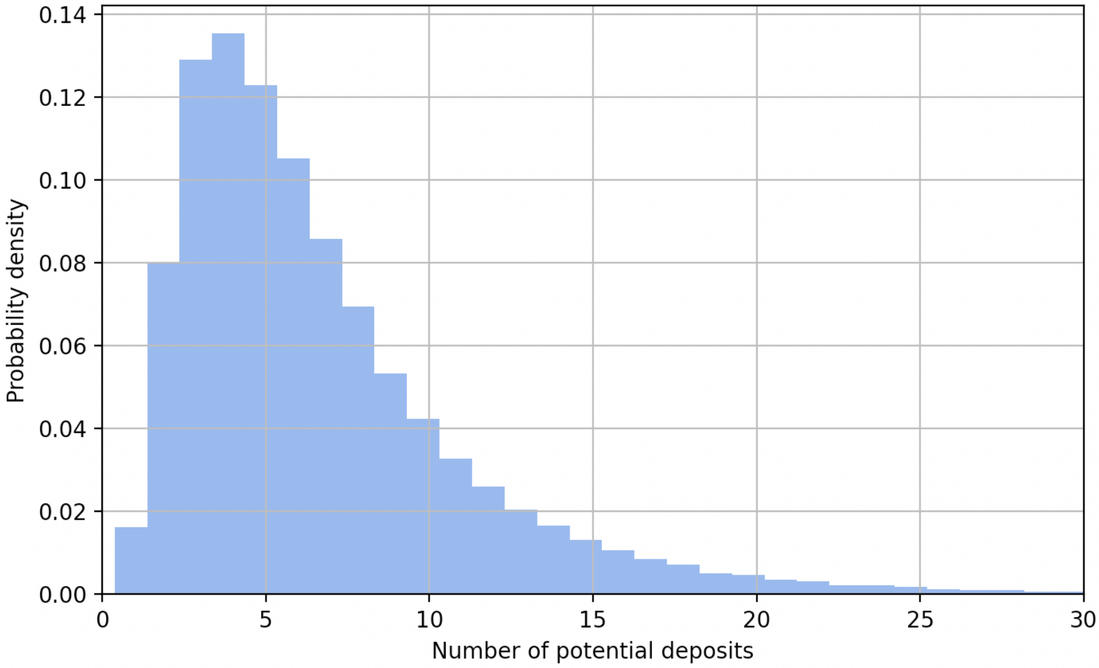


Figure 5.1: Distribution of number of potential deposits

### 5.2.2 Ore tonnage per deposit

The distribution of ore tonnage for a potential deposit is given by Ellefmo and Søreide (2019). This distribution is obtained for the permissive tracts of the Mohns and Knipovich Ridge, and we apply this distribution to our model in this thesis. The distribution is given in Table 5.10.

Table 5.10: Distribution of ore tonnage per deposit

| | Mode | Mean | Std | F100 | F95 | F90 | F75 | F50 | F25 | F20 | F10 | F5 | F0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ore tonnage [kt] | 2 | 855.4 | 3053 | 1.7 | 2.8 | 4.5 | 4.5 | 15 | 73 | 383 | 1643 | 3824 | 23 856 |

Source: Ellefmo and Søreide (2019)

In some parts of the proposed model the surface area of a deposit is necessary (e.g. calculating the area for test drilling in exploration stages 3 and 4. To obtain the surface area the ore tonnage is used in combination with a converting factor. This converting factor is 27.7 tonnes/m$^2$ and proposed by Juliani and Ellefmo (2019). By dividing the ore tonnage by the converting factor, one arrives at the area of a deposit.

### 5.2.3 Metal grades

The metal grades in SMS deposits on the NCS are subject to significant uncertainty. Multiple estimates of these grades exist, and it is evident that the various estimates differ considerably.

One estimate of probability distributions for metal grades can be retrieved from Lesage et al. (2019). In the paper of Lesage et al. (2019) the ore tonnage of a deposit has been decomposed into three different segments: Cu-rich, Zn-rich and Si-rich. Each of these three segments have their own probability distributions for the grades of copper, zinc, gold and silver. In this thesis we do not separate the ore from a deposit into different segments. Therefore the relative weights of each segment (13.3% Cu-rich, 12.1% Zn-rich and 74.6% Si-rich) have been used together with the metal grade distributions for each segment to arrive at metal grade distributions for the unsegmented ore. This gives the following metal grade distributions:

Table 5.11: Metal grades estimates from Lesage et al. (2019)

| Metal | Mode | Mean | Standard deviation |
|---|---|---|---|
| Cu | 1.93% | 2.41% | 0.98% |
| Zn | 0.07% | 0.25% | 0.29% |
| Ag | 223 ppb | 291 ppb | 128 ppb |
| Au | 3.7 ppm | 6.8 ppm | 4.8 ppm |

Ellefmo and Søreide (2019) present a different estimate of metal grades in SMS deposits on the NCS. The following probability distributions are presented in this work:

Table 5.12: Metal grades estimates from Ellefmo and Søreide (2019)

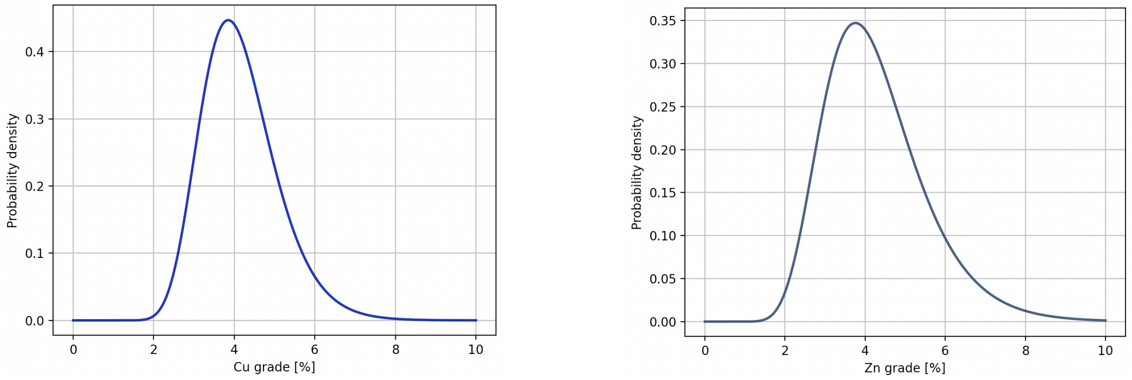
| Metal | Mode | Mean | Standard deviation |
|---|---|---|---|
| Cu | 5.45% | 5.90% | 1.35% |
| Zn | 5.74% | 6.08% | 1.82% |
| Ag | 670 ppb | 1580 ppb | 1910 ppb |
| Au | 76.7 ppm | 90.9 ppm | 44.1 ppm |

As can be observed, there is a significant difference between the grades presented by Lesage et al. (2019) and Ellefmo and Søreide (2019). As we have observed both a low and a high estimate of metal grades in SMS deposits on the NCS from the literature, we found it appropriate to use a middle grade for our base case. The metal grades we apply to our base case are obtained by using Ellefmo and Søreide (2019) as the starting point. However, we multiply the input parameter $\mu_{grade,m}$, $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$, for the log-normally distributed metal grades proposed by Ellefmo and Søreide (2019) with 0.8. The $\sigma_{grade,m}$, $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$, values for the metal grade distributions are kept equal to the original distribution of Ellefmo and Søreide (2019). This gives the following metal grade distributions that we apply to our base case:

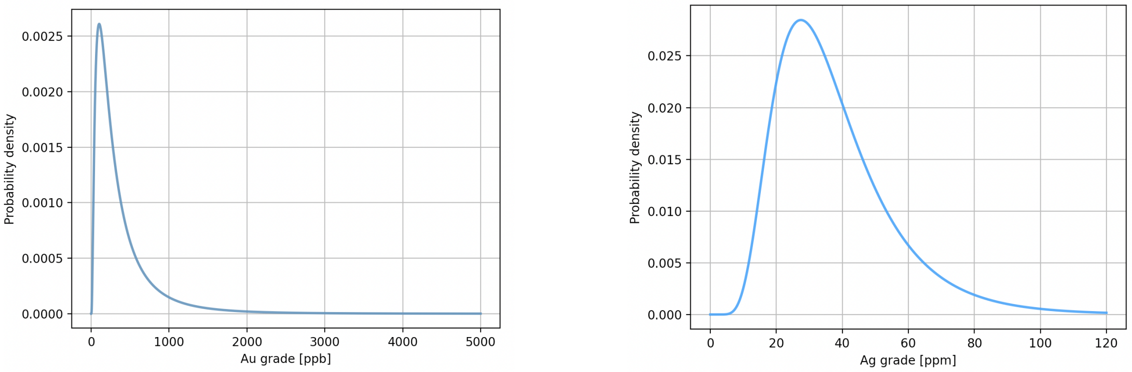
Table 5.13: Metal grades used as base case

| Metal | Mode | Mean | Standard deviation |
|---|---|---|---|
| Cu | 3.85% | 4.16% | 0.95% |
| Zn | 3.76% | 4.27% | 1.28% |
| Ag | 103 ppb | 396 ppb | 478 ppb |
| Au | 27.4 ppm | 37.6 ppm | 18.2 ppm |

The metal grade distributions used for the base case in this thesis are illustrated in Figure 5.2.



(a) Copper grade distribution (b) Zinc grade distribution



(c) Gold grade distribution (d) Silver grade distribution

Figure 5.2: Metal grade distributions

## 5.3 Reduction of variance for geological parameters throughout the exploration process

The geological probability distributions that are given in Table 5.9 and Table 5.12 are probabilities of the final outcome before any stages of the exploration is conducted. As explained in Section 4.4, the uncertainty of the final values decreases when information is obtained throughout the exploration process, which is modeled as a decrease in variance for the probability distributions. In Table 5.14 we have summarised the percentage of the original variance that is removed at each stage. The overview is shown for every relevant geological parameter.

Table 5.14: Variance reduction for geological parameters through the exploration phase

| Parameter | Stage 1 weight | Stage 2 weight $w_{\text{tonnage},2}$ | Stage 3 weights $w_{\text{tonnage},3}$ $w_{\text{grade},m,3}$ | Stage 4 weights $w_{\text{tonnage},4}$ $w_{\text{grade},m,4}$ |
|---|---|---|---|---|
| Initial number of potential deposits | 100% | - | - | - |
| Ore tonnage per deposit | - | 50% | 15% | 35% |
| Copper grade | - | - | 30% | 70% |
| Zinc grade | - | - | 30% | 70% |
| Gold grade | - | - | 30% | 70% |
| Silver grade | - | - | 30% | 70% |

The percentage of variance decreased for each stage completed is based on conversations with industry experts. It is however important to stress that there is great uncertainty regarding these numbers, and they should only be viewed as estimates.

# 6 Results and discussion

In this section we present and discuss the results when applying the methodology presented above. We consider the different tax regimes presented in Section 3.3: the standard corporate tax (SCT), Norwegian petroleum tax regime (NPT) and three variants of the NPT with different tax and refund rates.

In a directive published by the Norwegian Ministry of Finance, it is suggested that the tax regime for deep-sea mining on the Norwegian Continental Shelf (NCS) could be modeled after the existing tax regime for the petroleum industry (Regjeringen 2022b). This also resonates with the impression of industry experts, who anticipate that a new tax regime with similarities to the petroleum tax regime could be proposed in the near future. However, some experts argue that the total tax rate of 78% in the petroleum tax regime is too high for deep-sea mining, as projects can potentially struggle to become profitable if taxes are too high. We have therefore conducted simulations for variations of the Norwegian petroleum tax regime with lower tax rates (and thus also lower refund rates). This provides insight on how tax and refund rates might affect the decision making and profitability of corporations, and the expected tax income for the state.

Table 6.1 provides an overview of the different tax regimes considered. The abbreviations presented in Table 6.1 are used throughout the rest of this thesis.

Table 6.1: Abbreviations for tax regimes

| Abbreviation | Tax regime |
|---|---|
| SCT | Standard corporate tax |
| NPT | Norwegian petroleum tax regime (78% total tax and 71.8% refund) |
| 60-55 PT | Norwegian petroleum tax regime with 60% total tax and 55% refund |
| 45-40 PT | Norwegian petroleum tax regime with 45% total tax and 40% refund |
| 30-25 PT | Norwegian petroleum tax regime with 30% total tax and 25% refund |

To ensure better understanding for readers, we would like to repeat the information regarding the refund rate in the petroleum tax regime, presented in Section 3.3.2. If an operator company experiences a loss, $L$, in a given year, $Y$, the company is eligible to receive a payment of $L * T_s$ in the following year, $Y + 1$. Here, $T_s$ represents the refund rate. When an operator company engages in exploration activities, it typically generates minimal revenue in that specific year, resulting in all exploration costs contributing to a loss. However, with the implementation of a refund rate, parts of the exploration costs will be reimbursed to the operator company the following year.

In the following we will present results from the perspectives of both the operator company and state. For the operator company we consider the net present value of a license block. For the state we consider the net expected tax balance of a license block, which is the sum of tax revenues received by the state, subtracted by the refunds disbursed to companies for their exploration activities, discounted at the designated discount rate.

## 6.1 Base case

In the following section the results for the base case considering the different tax regimes are presented for both the operator company and for the Norwegian state.

The expected NPV for the operator company and expected net tax balance for the state for each tax regime are presented in Figure 6.1. Figure 6.1 shows that the operator company attains its maximum expected NPV of 115.8 million USD under the 30-25 PT. The SCT and 45-40 PT also results in relatively high expected NPV for the operator company, amounting to 94.9 and 84.3 million USD, respectively. The operator company obtains the lowest expected average NPV under the NPT, with an average of 8.7 million USD. The NPT regime has a high tax rate, which appears to reduce the incentives for exploration and extraction, despite the presence of a high refund rate

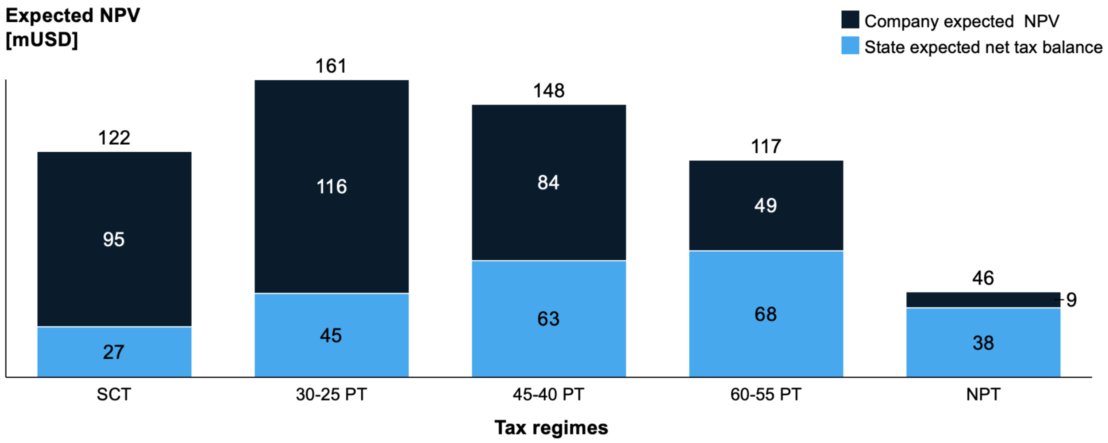


Figure 6.1: Expected NPV for operator company and net tax balance for state for the different tax regimes

that de-risks the exploration phase.

As presented in Figure 6.1, the state achieves the highest expected net tax balance at 60-55 PT and 45-40 PT, amounting to 68.4 and 63.2 million USD, respectively. The relatively high tax rates in 60-55 PT and 45-40 PT appear to secure the state a large share of the value creation from mineral extraction. As shown in Figure 6.1, the expected net tax balance is lower for the tax regimes with the lowest taxes, i.e. SCT and 30-25 PT. The expected net tax balance for the state at SCT and 30-25 PT are 27.2 and 45.3 million USD, respectively. Although lower refund rates at these tax regimes compared to 45-40 PT and 60-55 PT reduces expenditure on covering parts of the operator companies' exploration costs, the lower tax rates results in a lower share of mineral extraction profits accruing to the state. Under the NPT regime, the state obtains a relatively high portion of the profits when deposits are mined; however, the expected tax net balance is lower than for 45-40 PT and 60-55 PT. The reason for that is that due to the high taxes, the project is expected to be less profitable for the company and therefore, fewer potential deposits are taken to the mineral extraction stage. This is illustrated in Figure 6.2.

Figure 6.2 exhibits the proportion of prospective mineral deposits that translate into mineral extraction for the different tax regimes. Among the tax regimes examined, the 30-25 PT and 45-40 PT correspond to the highest percentage of deposits mined at 49% and 44%, respectively. At SCT, 39% of potential deposits are mined. The SCT has lower tax than 30-25 PT and 45-40 PT, but still results in lower percentage of deposits mined. This suggests the 0% refund rate in the SCT makes the operator company less willing to conduct exploration compared to when it is partly refunded. At the 60-55 PT and NPT tax regimes the percentage of deposits mined are 36% and 17%, respectively. The lower mining percentage rates compared to 30-25 PT and 45-40 PT suggests that the higher tax rates makes it less attractive with exploration and extraction, despite higher refund rates. Higher tax rates reduce the value accruing to the operator company from mineral extraction. It appears that with high tax rates, the potential profit is not large enough to justify the risky and costly exploration steps for a relatively large share of potential deposits.

In Figure 6.1 the total combined expected NPV for the operator company and state is included. The maximum combined expected NPV is obtained at 30-25 PT with 161.1 million USD. However, at the 30-25 PT tax regime the state ends up with a lower expected net tax balance compared to the tax regimes with higher tax and refund rates. We believe the state would like to ensure that the tax revenue from mineral extraction is high, but also ensure that the operator companies have enough incentive to perform exploration and extraction. Considering both the state and operator companies interests, the 45-40 PT tax regime seem to be satisfactory for both parts.

Based on the findings presented in Figure 6.1 we see that there appears to exist a trade-off relationship between the tax rate and the refund rate for both operator company and state. The highest expected NPV is not obtained at the SCT at the lowest tax rate, but rather at 30-25 PT. It appears that increasing the refund rate some times is worth the simultaneous increase in tax rate for the operator company. The highest expected net tax balance for the state is not obtained at NPT with the highest tax, but rather at 60-55 PT. This suggests that the state must be aware of the trade-off relationship that exist for both the operator companies and the state when deciding on the tax regime.

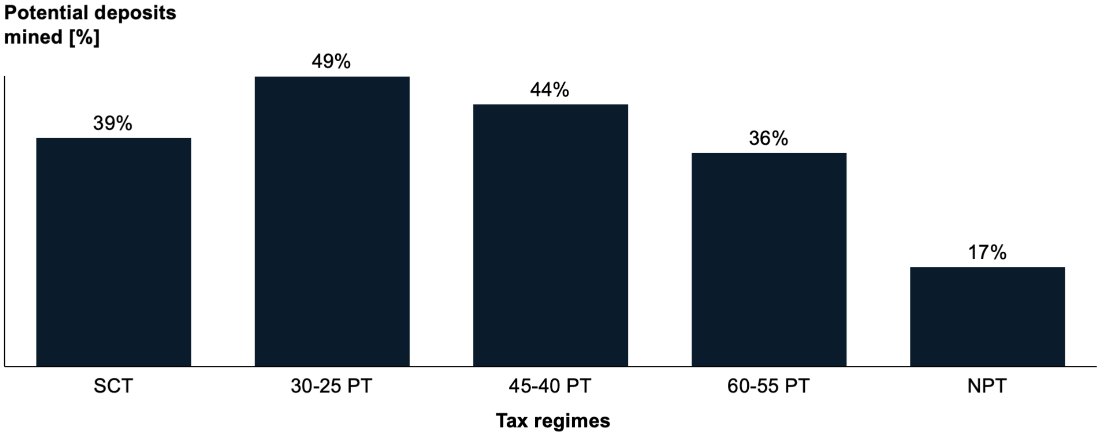


Figure 6.2: Percentage of potential deposits mined at different tax regimes at base case

So far we have only presented the results related to the expected NPV and expected net tax balance. However, this measure does not provide a complete picture and gives limited insight about the risk profile for either the company or state. To address this we now present box plots illustrating the whole distribution of the resulting NPV and net tax balance. This provides insight on the risk associated with the different tax regimes. To facilitate reader comprehension of the information conveyed by box plots, we prepare the results of three cases in terms of probability distributions and compare the visualisations to box plots.

In Figure 6.3 we present the probability distributions for three different cases: a low case, a base case and a high case. The lines included in the probability distribution plot indicate the mean for each of the distributions, respectively. Below the probability distributions are the three corresponding box plots that illustrate the same three distributions. Box plots display distributions through quartiles, the median and max/min-values. The edges of the box indicate the first and third quartile, while the middle line shows the median. The whiskers represent the minimum and maximum value.

By looking at Figure 6.3 we see how a probability distribution compares to a box plot. The high case (indicated by green) has the highest median, which is shown by both the high case probability distribution laying most to the right and the high case median in the box plot being highest. The larger interquartile range of the high case box plot compared to the low case is reflected in the probability distribution, which shows that the high case probability distribution is spread out over a wider range. Furthermore, the leftward-tending median line within the interquartile boxes indicates that the represented data is skewed to the right, as is evident in Figure 6.3.

Figure 6.4 shows the box plots for the expected NPV for the operator company and the expected net tax balance for the state at the different tax regimes for the base case.

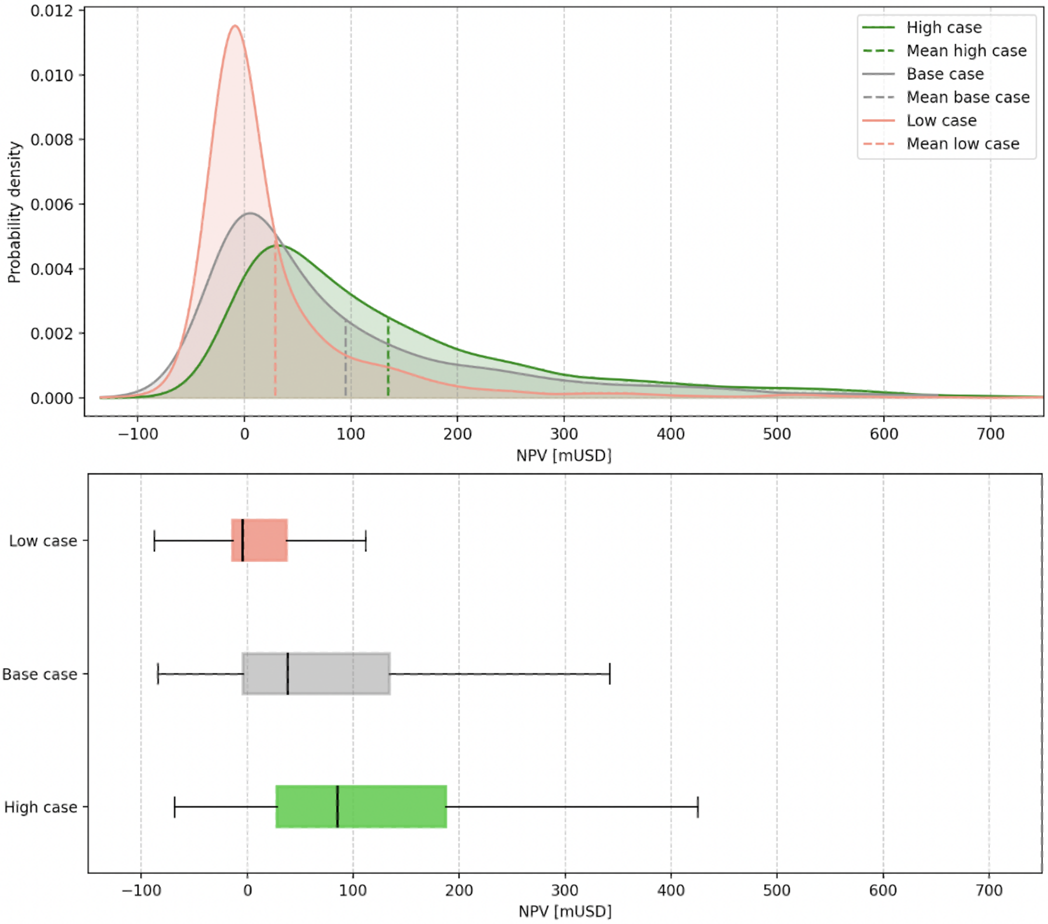
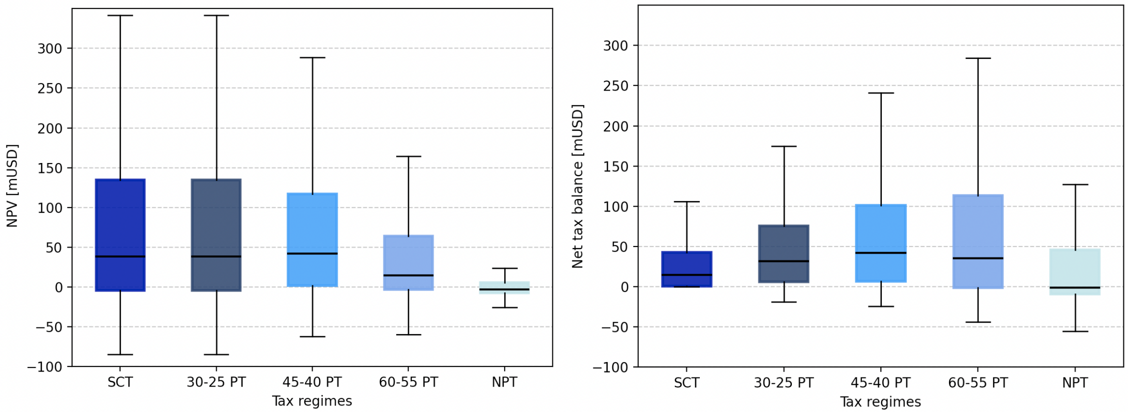


Figure 6.3: Results for three selected cases presented as probability distribution (upper plot) and box plots (lower plot)



(a) Company (b) State

Figure 6.4: Base case for operator company and state

For the operator company the interquartile ranges of the box plots are largest for SCT and 30-25 PT, the tax regimes corresponding to a relatively low tax rate and a low refund rate. It is at these tax regimes that the operator company see the highest positive outcomes, but also the lowest negative outcomes. The interquartile ranges, minimum value and maximum value all reduce for the operator company as the tax rate and refund rate increases gradually along the selected tax regimes. This highlights that SCT and 30-25 PT results in the highest uncertainty regarding the outcome for the operator company, whilst higher tax and refund reduces the uncertainty of the outcome. The interquartile range of the box plot representing the NPT is slim. This appears to be due to the finding that the NPT results in the fewest number of deposits mined, as mentioned above and illustrated in Figure 6.2. Fewer deposits mined results in lower uncertainty regarding the outcome. The SCT, 30-25 PT and 45-40 PT are quite similar, however SCT and 30-25 PT exhibit more upside potential while exhibiting slightly more downside risk than the 45-40 PT.

Figure 6.4 also provides insights for the risk profile of the state. As the tax rate and refund rate is gradually increased from SCT to 60-55 PT, we observe that the interquartile range expands, the maximum outcome increases and the minimum outcome decreases. This suggests that the higher tax rate allows for greater participation of the state of the value creation when profitable deposits are mined. However, it also suggests larger negative outcomes when potential deposits are not mined, as the state must still cover parts of the exploration costs. It also highlights that a higher tax and refund rate results in more uncertainty regarding the outcome. At NPT we observe a lower interquartile range, maximum outcome and median than for 60-55 PT. Despite the higher tax rate leading to relatively high tax revenue for profitable deposits, relatively few deposits are mined at NPT, as shown in Figure 6.2. For the NPT the refund rate is relatively high, resulting in the most negative outcomes (when exploration is conducted, but no extraction is performed). 60-55 appear to be the best tax regime for the state in terms of net tax balance, as it has the largest upside potential, while remaining within the same range of downside risk as the 30-25 PT and 45-40 PT. Considering only the risk perspective, the SCT present the tax regime that contains the least risk for the state.

Table 6.2 and Table 6.3 provides additional insights to the risk profile of the operator company and state. Table 6.2 states the probabilities of the outcome being positive or negative for the operator company, and the expected NPV given that the outcome is positive or negative. As can be seen in Table 6.2, the largest expected NPV when negative occurs at SCT, at $-14.9$ million USD. The expected NPV when negative decreases as the refund rate is increased, and the lowest expected NPV when negative occurs at NPT with $-6.9$ million USD. However the probability of a negative outcome is significantly higher at NPT at 66.9% compared to 29.1% at SCT. The expected NPV when positive is higher for the tax regimes with relatively lower tax, the SCT and 30-25 PT, compared to the tax regimes with higher tax and refund rate. The SCT results in an expected 139.8 million USD when positive compared to 40.3 million USD for the NPT. These results confirm that the tax regimes with relatively low tax rate and refund rate results in larger range of possible outcoms for the operator company.

Table 6.2: Results for operator company at base case

| | STC | 30-25 PT | 45-40 PT | 60-55 PT | NPT |
|---|---|---|---|---|---|
| Total simulations | 2000 | 2000 | 2000 | 2000 | 2000 |
| Simulations with positive NPV | 71.0% | 80.6% | 76.3% | 66.3% | 33.1% |
| Expected NPV when positive [$10^6$ USD] | 139.8 | 146.6 | 113.2 | 78.0 | 40.3 |
| Simulations with negative NPV | 29.1% | 19.4% | 23.75% | 33.7% | 66.9% |
| Expected NPV when negative [$10^6$ USD] | $-14.9$ | $-12.1$ | $-8.5$ | $-7.8$ | $-6.9$ |
| Deposits mined | 38.6% | 49.0% | 44.3% | 36.1% | 16.8% |

The results presented in Table 6.3 indicate a clear relationship between the tax and refund rate and the risk profile of the state. As the tax and refund rate increases, the expected net tax balance when negative increases. The net tax balance when negative is 0 for SCT (no refunds), and decreases to $-10.6$ million USD for NPT. This highlights that increasing the refund rate leads to larger negative outcomes. The probability of an outcome being negative for the state also increases gradually as the tax and refund rate increases. On the other hand, the expected net tax balance when positive is significantly higher for the three tax regimes with the highest tax rates (45-40 PT, 60-55 PT and NPT) compared to the tax regimes with lower tax rate (SCT and 30-25 PT). These results are in line with the results presented in Figure 6.4, that when tax rate and refund rate is increased, this increases the range of possible outcomes for the state.

Table 6.3: Results for state at base case

| | STC | 30-25 PT | 45-40 PT | 60-55 PT | NPT |
|---|---|---|---|---|---|
| Total simulations | 2000 | 2000 | 2000 | 2000 | 2000 |
| Simulations with positive expected net tax balance | 77.2% | 84.2% | 81.2% | 73.8% | 47.8% |
| Expected net tax balance when positive [$10^6$ USD] | 35.3 | 54.4 | 78.5 | 94.9 | 90.2 |
| Simulations with negative expected net tax balance | 0.0% | 15.9% | 18.5% | 26.2% | 52.3% |
| Expected net tax balance when negative [$10^6$ USD] | - | $-3.1$ | $-4.2$ | $-6.5$ | $-10.6$ |
| Simulations with zero expected net tax balance | 22.8% | 0.0% | 0.0% | 0.0% | 0.0% |

## 6.2 Sensitivity analysis

In the following we perform a sensitivity analysis with respect to key parameters. The selected parameters are the metal prices, the CAPEX in the exploration phase, the OPEX in the mining phase, the ore tonnage per square meter of seabed surface area, the annual production of ore, the discount rate, and the EIA factor for additional time spent on EIA during operational activities in the exploration phase. These parameters are chosen for the sensitivity analysis because we regard these among the most uncertain and critical parameters for the decision making of the operator company. In Table 6.4 we present the considered parameter ranges in the sensitivity analysis for the respective parameters.

Table 6.4: Parameter values for sensitivity analysis

| Parameter | Notation | Considered range | Base case value |
|---|---|---|---|
| Metal prices | $P_m$ | ± 30% | See Table 5.2 |
| CAPEX | $C_{day,j}$ and $C_{core}$ (Equation (4.15)) | ± 30% | See Table 5.4 and 10 000 USD/core |
| OPEX | $C_{day,contractor}$ and $C_{process}$ | ± 25% | 350 000 USD/day and 19.47 USD/tonne |
| Ore tonnage per $\mathrm{m}^2$ | - | ± 25% | 27.7 tonnes/$\mathrm{m}^2$ |
| Annual production | $\omega_t$ | ± 0.3 Mt | 1.3 Mt |
| Discount rate | $r$ | ± 3 pp | 15% |
| EIA factor | EIA | ± 10 pp | 20% |

For metal prices we consider a range of ±30%. We deem this reasonable as a 30% decrease in copper price from our base case value of 9000 USD/tonne roughly corresponds with the general copper price level of the last couple of years prior to Covid-19. Also, a 30% increase in copper price from our base case value approximately corresponds with Goldman Sachs' average price forecast for 2024 (Gluyas 2022). Copper is by far the most significant metal in our model. For CAPEX in the exploration phase we consider a range of ±30%. This range was deemed sensible by the industry experts that we have consulted. Over the last years we observed high volatility in vessel prices for other maritime operations. Due to the volatility we do not believe that fluctuations of ±30% over time are unlikely. For OPEX, a ±25% range is considered. For the daily contractor fee, $C_{day,contractor}$, this sensitivity corresponds with the sensitivity analysis of previous work by Andreassen and Borge (2022), where a similar cash flow function as ours is presented. Setting ±25% for the ore tonnage per $m^2$ was done in accordance with industry experts who highlighted the uncertainty of this geological parameter, and how important it may prove to be for the profitability of projects. Annual production, $\omega_t$, has a minimum and maximum of 1 and 1.6 million tonnes of ore as this lies within the ranges that the industry experts we consulted deemed reasonable. It also represents a slightly larger variation than the estimated annual production of the Solwara 1 project, which laid between 1.1 and 1.5 million tonnes of ore (SRK Consulting 2010). A discount rate, $r$, of 12-18% was deemed a reasonable range by the industry experts we consulted The average discount used in terrestrial mining lies between 7-8% (Ovalle 2020). For deep-sea mining there is however more technological and political risk, so investors would likely require a higher expected return. There are also risks that have not been modeled explicitly in the proposed model (for example metal prices being held constant over time). The range of 12 - 18% is therefore set to reflect the increased technological and political risk compared to terrestrial mining, in addition to the estimated range of risk premium pertaining to risk factors that we have not modeled explicitly. The EIA-factors represents the extra time spent on EIA preparations work in different exploration stages. An increase and reduction of 10 percentage points was deemed reasonable by industry experts. It is however worth noting that there is large uncertainty related to how much additional costs the EIA will represent, and industry experts we have talked with differ on their estimates.

### 6.2.1 Operator company

In the following section we examine how the sensitivities affect the profitability and decision making of the operator company.

Table 6.5 lists the expected NPV for the operator company at the different tax regimes for the different sensitivities. In order to visualise how sensitivities impacts the resulting expected NPV, we illustrate the results of Table 6.5 in Figure 6.5. In Figure 6.5, the expected NPV is presented for the selected tax regimes at the selected sensitivities. Each tax regime is represented by a distinct color, and the sensitivities are arranged based on their impact. Each sensitivity is represented by a marker. Dotted lines are drawn between the markers, but it is important to highlight that these lines do not depict continuous development. Rather, they are included to provide readers with a clearer understanding of the trends in the performance of different tax regimes as the impact of selected sensitivities change.

Table 6.5: Expected NPV for operator company at different sensitivities for the different tax regimes [in million USD]

| Parameter | Change | STC | 30-25 PT | 45-40 PT | 60-55 PT | NPT |
|---|---|---|---|---|---|---|
| Base case | - | 94.9 | 115.8 | 84.3 | 49.0 | 8.7 |
| Metal prices | +30% | 264.3 | 281.0 | 221.6 | 156.5 | 79.9 |
| | −30% | −2.6 | −3.9 | −2.5 | −1.4 | −0.9 |
| CAPEX | +30% | 20.3 | 44.7 | 29.4 | 10.3 | −2.8 |
| | −30% | 188.3 | 177.5 | 134.8 | 104.0 | 51.0 |
| OPEX | +25% | 49.7 | 63.4 | 44.5 | 25.6 | −1.0 |
| | −25% | 148.8 | 161.1 | 120.0 | 85.3 | 23.5 |
| Ore tonnage per $m^2$ | +25% | 146.4 | 151.3 | 116.5 | 83.8 | 28.8 |
| | −25% | 26.0 | 48.9 | 30.4 | 6.5 | −2.3 |
| Annual production | +300 kt | 152.6 | 169.5 | 121.2 | 80.2 | 23.8 |
| | −300 kt | 29.8 | 49.5 | 29.5 | 14.7 | −2.0 |
| Discount rate | +3 pp | 65.7 | 81.0 | 55.2 | 30.3 | 0.4 |
| | −3 pp | 144.0 | 162.0 | 120.0 | 92.5 | 22.0 |
| EIA factor | +10 pp | 77.6 | 91.9 | 67.4 | 42.4 | 2.3 |
| | −10 pp | 123.3 | 127.9 | 99.0 | 64.4 | 17.0 |

From Figure 6.5 we can make several observations. First, we can identify which parameters that appear to have the largest effect on the expected NPV. It is important to highlight that the comparisons between the different sensitivities are relative, as all parameters are not increased by the same percentage or amount (for example ±25

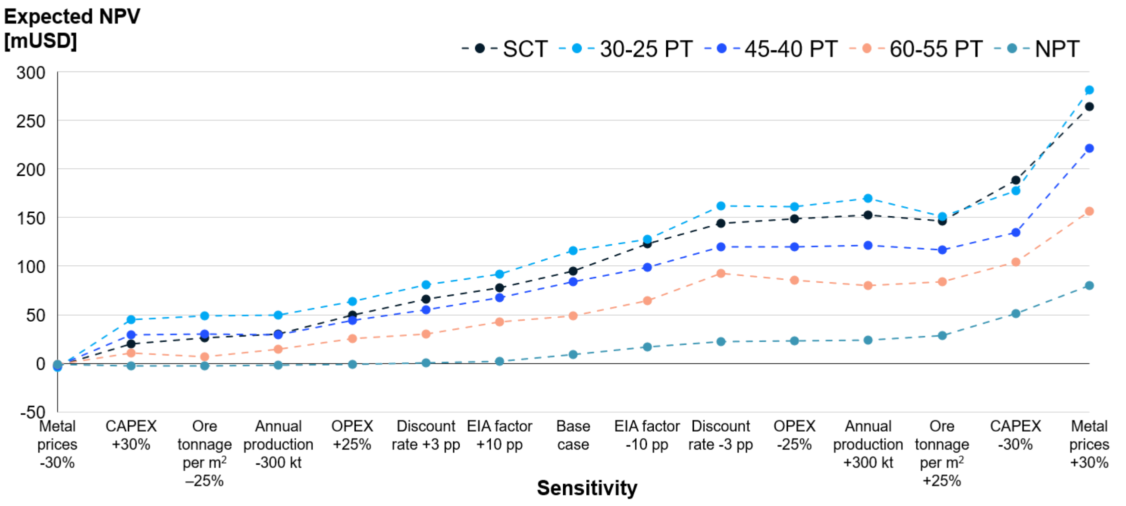


Figure 6.5: Expected NPV for operator company for selected sensitivities and different tax regimes, respectively

Figure 6.5 also illustrates that in cases where sensitivities are economically favorable for the operator company, tax regimes with relatively lower tax and refund rates such as SCT and 30-25 PT are the most beneficial in terms of resulting expected NPV. This appears to be because in economically favorable conditions, such as high metal prices, the decision to explore and extract deposits is less dependent on refunds from the state and therefore, the operator company benefits from the low taxes on the eventually mined deposits.

We now consider the how the the operator's decision making process is affected by the selected sensitivities. Therefore, in Figure 6.6 we show the percentage of potential deposits that end up with extraction for the selected sensitivities at the different tax regimes. In Figure 6.6 the percentage of potential deposits mined at each selected sensitivity is illustrated with a marker, and dotted lines are drawn between the markers. The dotted line once again does not represent a continuous development, but is included to indicate the a trend as the sensitivities are ordered by economic favorability for the operator company. As expected, a noticeable effect is that when the economic conditions are more favorable for the operator company, a larger number of potential deposits are mined. This can be observed from Figure 6.6. Additionally, another relationship is also interesting: regardless of the sensitivity level, the tax regimes of 30-25 PT and 45-40 PT yield the highest percentage of potential deposits mined, while the NPT consistently yields a significantly lower percentage of deposits mined than the other selected tax regimes. This might suggest that the NPT tax rate is too high, whereas the 30-25 PT and 45-40 PT tax regimes offer the operator company a more favorable balance between tax rate and refund rate.

The results in Figure 6.6 show that a high percentage of deposits is eventually mined, i.e. surpasses the exploration stages despite the low exploration CAPEX refund rates, in case of favourable economical conditions. As can be seen in Figure 6.6, the percentage of potential deposits mined decrease as the economic conditions become less favourable for the operator company. Nevertheless, it is the same tax regimes, 30-25 PT and 45-40 PT, that results in the highest amount of potential deposits mined across all different economic conditions. This result suggests that these tax regimes offer the best balance between tax and refund rate to for the operator company to incentivize for mineral exploration and extraction across a broad range of economic conditions.

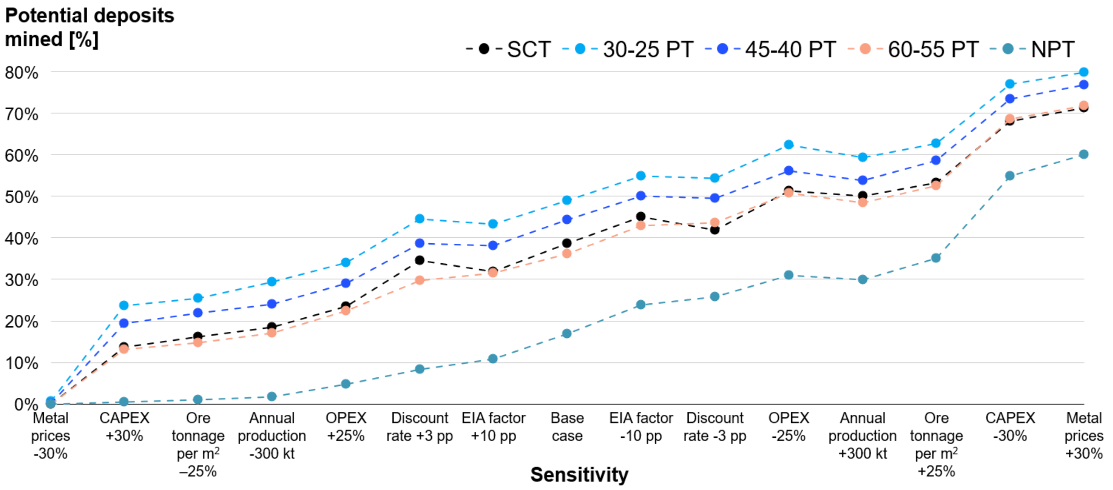


Figure 6.6: Percentage of potential deposits mined for selected sensitivities and different tax regimes, respectively

To gain insight on how the selected sensitivities affect the risk profile of the operator company we make use of box plots. Below we present the results for SCT, 45-40 PT and NPT in Figures Figure 6.7, Figure 6.8 and Figure 6.9, respectively. In order to effectively illustrate the transformation of the risk profile associated with the progression from low to high tax and refund rates, we deemed it satisfactory to only present the results for SCT, 45-40 PT, and NPT. The corresponding outcomes for 30-25 PT and 60-55 PT can be found in the appendix for the interested reader.

Figure 6.7 shows the box plots of the NPV at the different sensitivities at the SCT. As already shown above (see Figure 6.5) the metal price and CAPEX have the largest impact on the NPV of the operator company. From the box plots we see that for several of the favorable sensitivity scenarios the interquartile box spans across several 100 million USD. Specifically this holds for the +30% increase in metal prices. This shows that the range of outcomes is broad when the tax rate is relatively low, as for SCT. This is because the operator company receives a relatively large percentage of the value from deposits as tax rates are low. For the unfavourable sensitivities we observe that for the metal prices, CAPEX, Ore per m$^2$ and annual ore production, respectively, the median falls below zero. Under such conditions it is rather unlikely that an operator company would initiate exploration.

From Figure 6.7 we observe that for some sensitivity parameters, the lowest minimum outcome for the operator company occurs at a sensitivity that is, overall, positive. The lowest minimum among the metal price sensitivities occurs at metal prices +30% rather than −30%. The reason for that is because a +30% increase in metal prices encourages more exploration, leading the operator company to progress more deposits for further exploration. However, some of these deposits might turn out to be unfavorable, resulting in a significant number of cases with extensive exploration, but few deposits for extraction. In case of a reduction of metal price by 30% , conditions are so economically unfavorable for the operator that very few deposits are progressed far in the exploration process. This limits the downside at −30% metal prices.

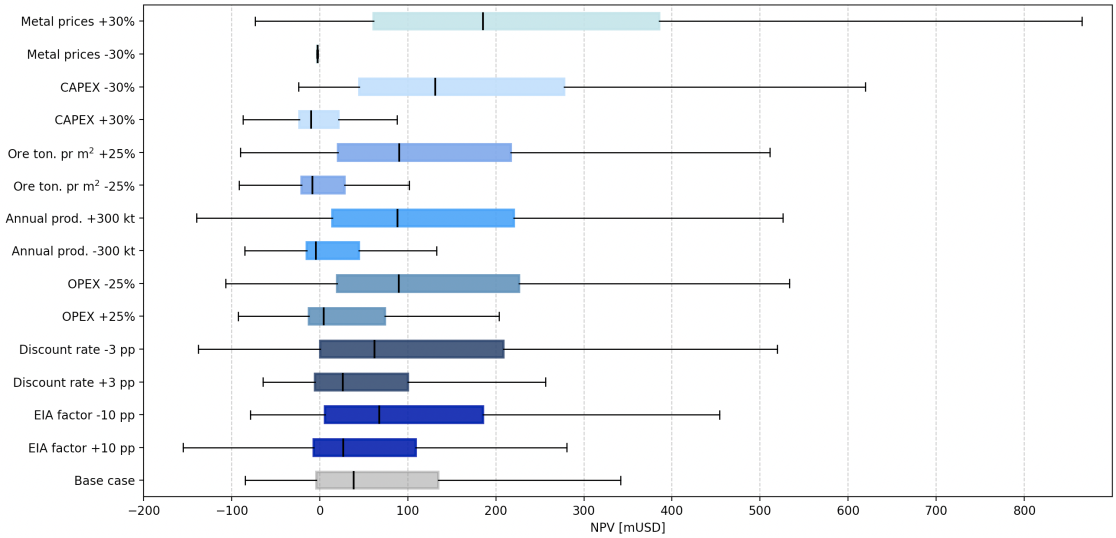


Figure 6.7: Box plot of company NPV at selected sensitivities for SCT

Figure 6.8 shows the box plots of the NPV at the different sensitivities at 45-40 PT. We can observe several of the same relationships as for the SCT. The metal prices and exploration CAPEX appears to have the largest impact among the sensitivities. We also observe that the unfavourable economic sensitivities of exploration CAPEX, ore tonnage per $m^2$ and annual ore production all results in median below zero. The most noticeable difference of Figure 6.7 and Figure 6.8 is the size of the interquartile range. The interquartile ranges span over a smaller range for the 45-40 PT. This is expected, as increasing the tax and refund rate will shift both more upside and downside risk from the operator company to the state compared to the SCT.

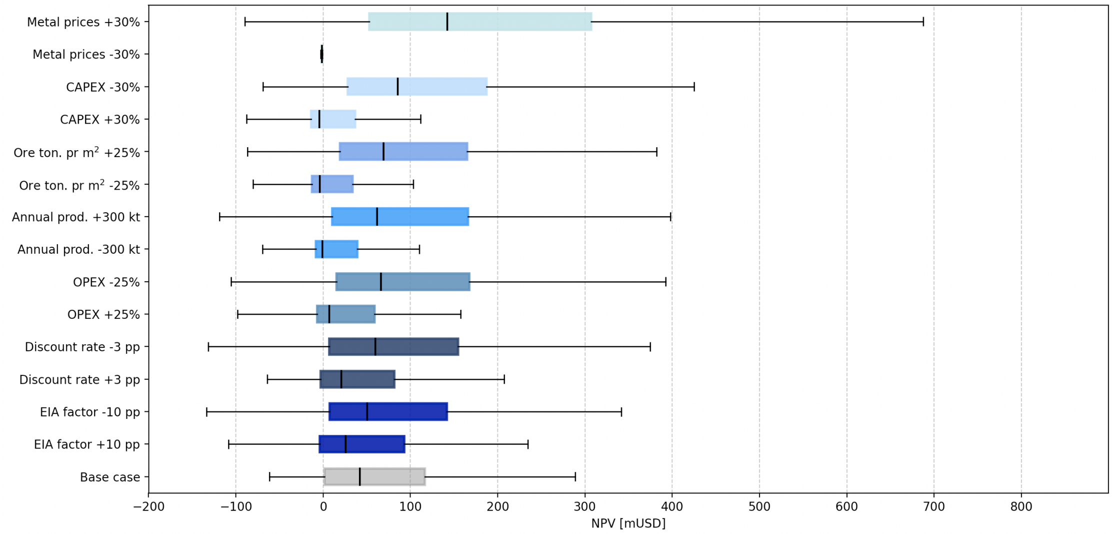


Figure 6.8: Box plot of company NPV at selected sensitivities for 45-40 PT

Figure 6.9 shows the box plots of the NPV at the different sensitivities at NPT. This box plot shows that the risk profile and potential outcomes for the the operator company is significantly different at NPT compared to the SCT and the 45-40 PT. We observe that the interquartile boxes span over a much smaller range at the favourable economic sensitivities than for SCT and 45-40 PT. The smaller range of the interquartile boxes can be explained by two things: firstly, the relatively high tax rate of the NPT leads to less value accruing to the operator company when profitable deposits are mined. Secondly, as can be seen from Figure 6.6 there is also a lower percentage of potential deposits mined for NPT. These two factors combined results in relatively small interquartile ranges at favorable sensitivities. For the unfavourable sensitivities we observe that the interquartile ranges are very limited. This is a result of the same two factors as for the favourable sensitivities.

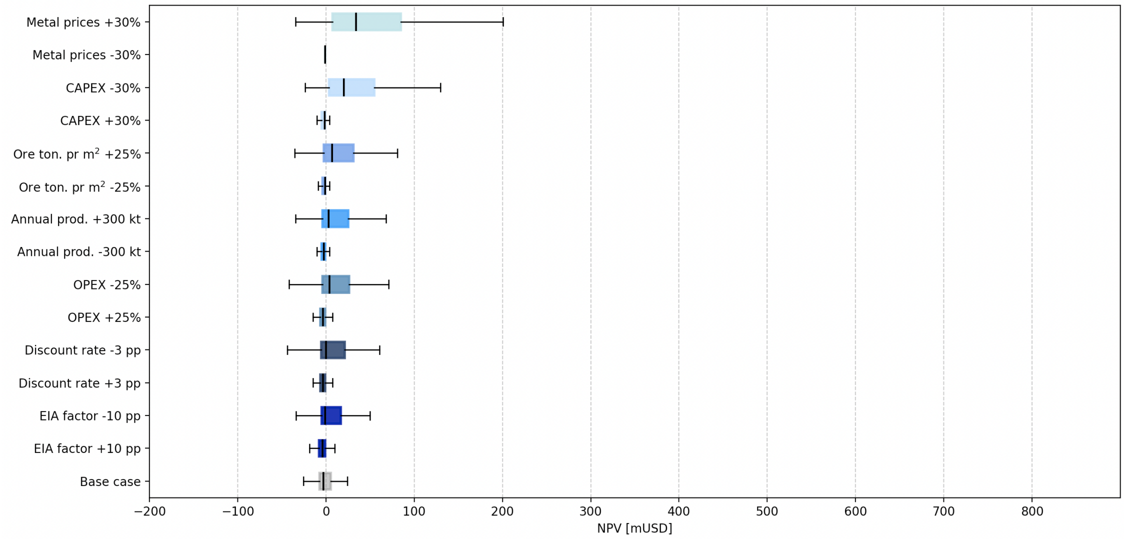


Figure 6.9: Box plot of company NPV at selected sensitivities for NPT

### 6.2.2 State

In the following section we examine how the sensitivities affect the results and decision making of the state.

Table 6.6 lists the expected net tax balance for the state at the selected tax regimes for the selected sensitivities. In Figure 6.10, the results from Table 6.6 are shown graphically. Each tax regime is represented by a distinct color, and the sensitivities are arranged based on their impact. Each sensitivity is represented by a marker. Dotted lines are drawn between the markers, but it is important to highlight that these lines do not depict continuous development. Rather, they are included to provide readers with a clearer understanding of the trends in the performance of different tax regimes as the impact of selected sensitivities change.

Table 6.6: Expected net tax balance for the state at different sensitivities [million USD]

| Parameter | Change | STC | 30-25 PT | 45-40 PT | 60-55 PT | NPT |
|---|---|---|---|---|---|---|
| Base case | - | 27.2 | 45.3 | 63.2 | 68.4 | 37.5 |
| Metal prices | +30% | 68.6 | 105.0 | 151.9 | 192.6 | 214.8 |
| | −30% | −2.6 | −3.9 | −2.5 | −1.4 | −0.9 |
| CAPEX | +30% | 10.8 | 20.4 | 26.1 | 20.8 | −3.5 |
| | −30% | 48.1 | 66.5 | 94.4 | 125.6 | 136.7 |
| OPEX | +25% | 17.1 | 27.0 | 34.9 | 38.5 | 6.4 |
| | −25% | 40.5 | 61.6 | 85.7 | 108.4 | 86.0 |
| Ore tonnage per $m^2$ | +25% | 38.8 | 57.0 | 82.6 | 102.6 | 91.6 |
| | −25% | 12.2 | 21.7 | 26.3 | 18.6 | −2.3 |
| Annual production | +300 kt | 43.2 | 68.3 | 89.7 | 114.0 | 90.7 |
| | −300 kt | 11.7 | 20.5 | 23.4 | 23.0 | −0.2 |
| Discount rate | +3 pp | 21.2 | 34.8 | 46.1 | 48.4 | 13.7 |
| | −3 pp | 37.1 | 57.8 | 80.4 | 100.9 | 70.4 |
| EIA factor | +10 pp | 23.8 | 37.9 | 51.9 | 60.3 | 21.6 |
| | −10 pp | 33.9 | 49.9 | 71.2 | 81.5 | 60.0 |

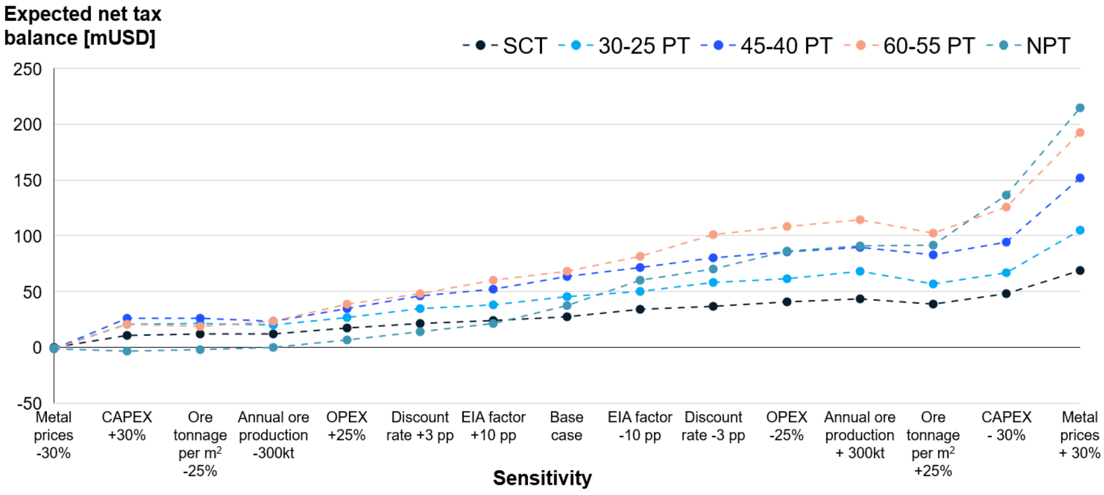


Figure 6.10: Expected net tax balance for the state at selected sensitivities

Figure 6.10 gives insights into how the state is affected by the selected sensitivities. The state is mainly affected in the same way as the operator company, as the net tax balance of the state depends on the actions of the operator company. Metal prices have the greatest impact on the state net tax balance. Net tax balance increases the most with a +30% increase in metal prices, and with a −30% metal price decrease the state receives almost no tax revenue as the decrease in metal price entails that very few deposits ends up with extraction. The exploration phase's capital expenditure sensitivities are the second most influential parameter for the state across all tax regimes. Changes in capital expenditure lead to the highest and lowest median values among all the adjusted parameters, after metal price alterations. The significant impact of capital expenditure on the state is unsurprising, given that the state indirectly funds parts of the exploration phase through refunds.

As illustrated in Figure 6.10, in cases of high metal prices and low exploration costs, the NPT yields the highest expected net tax balance for the state. However, as the economic conditions gradually becomes less favorable, the NPT's performance compared to other tax regimes deteriorates, going from the highest to the lowest expected net tax balance of all selected tax regimes. This suggests that the NPT is less robust when there are changes in economic conditions compared to the other selected tax regimes. In contrast, the 45-40 PT and 60-55 PT perform more stable for the state over a wide range of sensitivities. For favourable economic sensitivities, the high tax rate appears to translate into relatively high tax revenue, while in neutral and unfavourable economic conditions, the balance between refund and tax rates appears to still provide incentives for the operator company to undertake exploration and extraction, resulting in tax revenue for the state. The 45-40 PT and 60-55 PT appears more robust across the range of different economic conditions an operator company may encounter, whilst ensuring relatively high net tax balance for the state.

To gain insight on how the selected sensitivities affect the risk profile of the state we will make use of box plots. We will examine the box plots SCT, 45-40 PT and NPT shown in Figure 6.11, Figure 6.12 and Figure 6.13, respectively. In order to effectively illustrate the transformation of the risk profile associated with the progression from low to high tax and refund rates, we deemed it satisfactory to only present the results for SCT, 45-40 PT, and NPT. The corresponding outcomes for 30-25 PT and 60-55 PT can be found in the appendix for the interested reader.

Figure 6.11 shows the box plots of the expected net tax balance for the different sensitivities at the SCT. As can be seen from the figure the state has limited downside at the SCT. The state pays no refunds for the exploration phase to the operator company at SCT, and therefore never see negative outcomes. For the favourable economic sensitivities we observe that metal prices and exploration CAPEX has the largest affect on the net tax balance. The interquartile range of the box plots are relatively small, which appears to be a result of the relatively low tax rate compared to the other selected tax regimes. The relatively low tax rate limits the upside potential as most of the value from extraction accrues to the operator company. This gives good insight on the risk profile of SCT: there is both limited upside and downside.

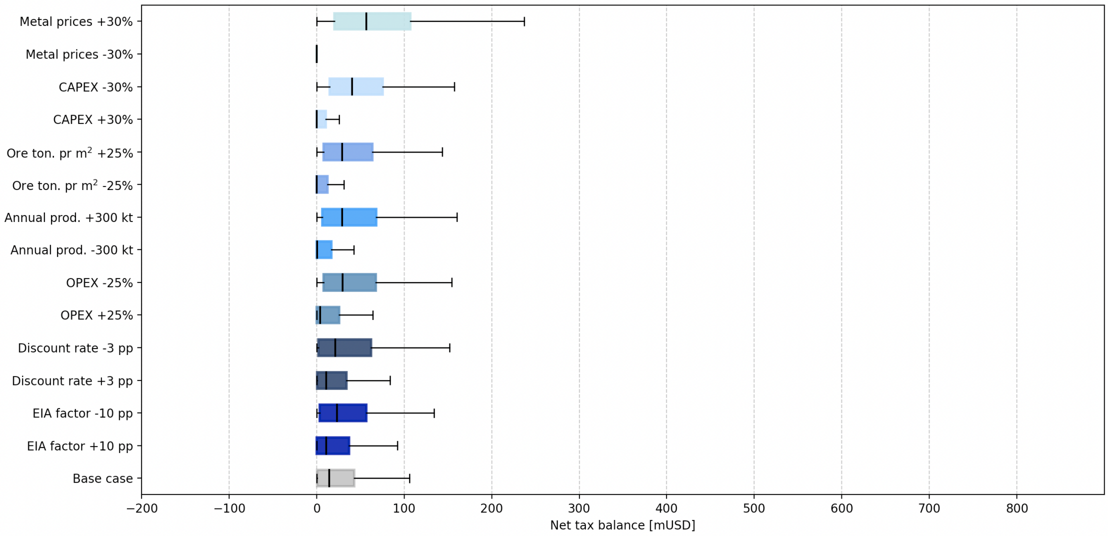


Figure 6.11: Box plot of state net tax balance at selected sensitivities for SCT

Figure 6.12 shows the box plots of the expected net tax balance for the different sensitivities at the 45-40 PT. We observe that the risk profile for the state is significantly different from the SCT. As can be seen the downside is larger, and for the unfavourable economic sensitivities for CAPEX, ore per $m^2$ and annual ore production gives a median net tax balance below zero. The most negative cases (occurs at the +30% metal price) show the risk the state sits with even in positive cases. Compared to the SCT we observe that the interquartile ranges span over a larger area for the favourable sensitivities. This suggests that the upside is larger when the state through higher taxes gets a larger share of the value created from mineral extraction.

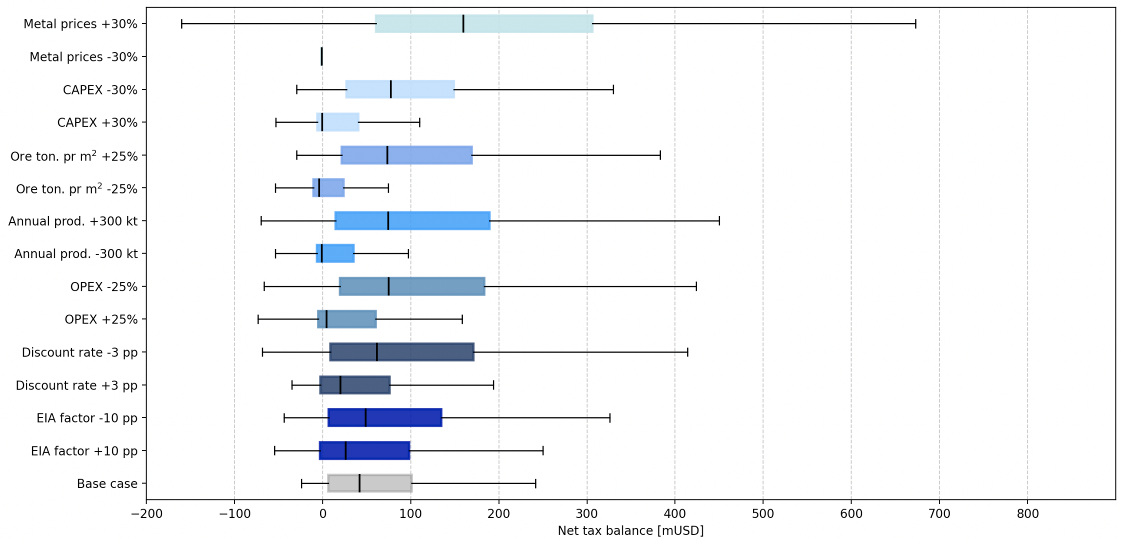


Figure 6.12: Box plot of state net tax balance at selected sensitivities for 45-40 PT

Figure 6.13 shows the box plots of the expected net tax balance for the different sensitivities at the NPT. We notice that the downside risk for the unfavourable economic sensitivities appear limited. The interquartile range and minimum value outcomes are lower than for 45-40 PT. As the refund rate is higher for NPT than 45-40 PT one could believe that the downside risk should be larger for NPT. The reason for the limited downside risk can be explained by looking at Figure 6.6. As can be seen there is a low number of potential deposits that gets mined with the NPT for the unfavourable economic sensitivities. This results in that the amount of refund paid for exploration is on average smaller for the NPT than for example the 45-40 PT, even though the refund rate is higher. For the favourable sensitivities we observe that the NPT results in relatively large net tax balance. As seen in Figure 6.6, even with the relatively high tax rate of NPT a large share of deposits still gets mined at +30% metal prices, −30% CAPEX etc. When the tax rate is relatively high, a large part of the value created from mineral extraction accrues to the state.

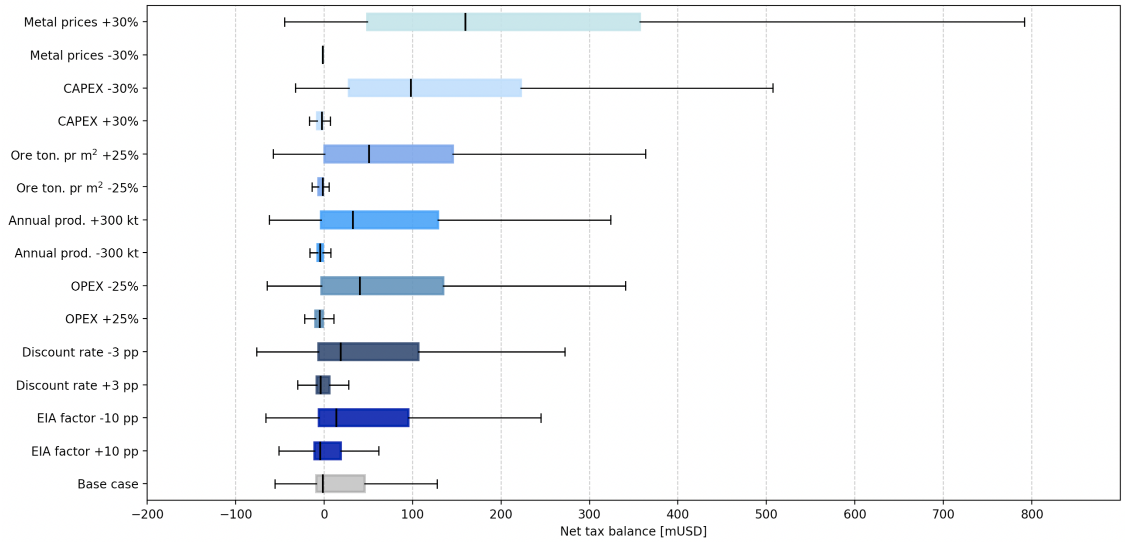


Figure 6.13: Box plot of state net tax balance at selected sensitivities for NPT

## 6.3 Metal sensitivity analysis

Motivated by the results of the sensitivity analysis above, we now look into the effect of metal prices in more detail. Since the sensitivity analysis showed that metal prices were the most impactful factor, we conducted a more granular sensitivity analysis for metal prices to better understand the performance of different tax regimes in various economic conditions. We derive the results for metal prices ranging between −30% to +50% compared to the base case for a 10% granularity for each of the selected tax regimes.

Table 6.7 shows the expected net tax balance for the state resulting from different metal sensitivities tested for at each of the selected tax regimes. The net expected tax balance listed in Table 6.7 is illustrated in Figure 6.14.

Table 6.7: Expected net tax balance for state at metal sensitivities [mUSD]

| Parameter | Change | STC | 30-25 PT | 45-40 PT | 60-55 PT | NPT |
|---|---|---|---|---|---|---|
| Metal prices | −30% | 0.0 | −0.9 | −1.3 | −1.2 | −1.5 |
| | −20% | 3.2 | 7.2 | 5.0 | 1.4 | −1.7 |
| | −10% | 13.8 | 23.6 | 31.2 | 30.9 | 2.6 |
| | 0% | 27.2 | 45.3 | 63.2 | 68.4 | 37.5 |
| | 10% | 44.4 | 64.1 | 93.6 | 113.0 | 95.1 |
| | 20% | 60.0 | 83.2 | 128.6 | 155.9 | 162.5 |
| | 30% | 68.6 | 105.0 | 151.9 | 192.6 | 214.8 |
| | 40% | 84.3 | 116.5 | 170.3 | 227.9 | 271.6 |
| | 50% | 100.4 | 135.7 | 195.6 | 265.6 | 325.9 |

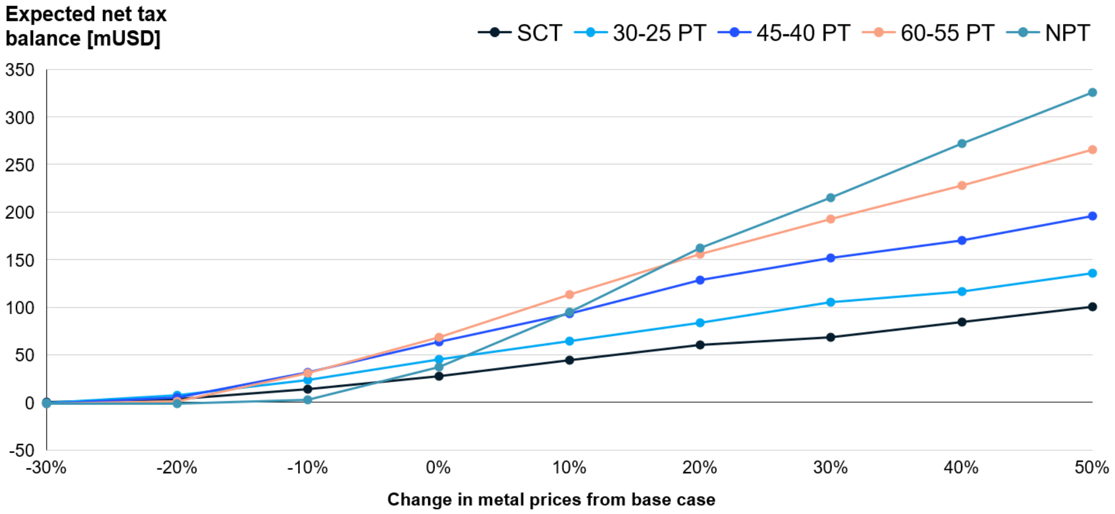


Figure 6.14: Expected net tax balance for state for selected metal sensitivities at different tax regimes [mUSD]

What can be observed in Figure 6.14 is similar to what was seen in Figure 6.10. The NPT results in the highest net tax balance for the state when metal prices are high (in this case above +20%). However, as the metal prices gradually decrease the NPT goes from delivering the highest expected net tax balance to the lowest expected net tax balance. This once again highlight that the NPT does not appear to perform well in terms of expected net tax balance across a broad range of economic scenarios. From Figure 6.10 we see that the 60-55 PT and 45-40 PT results in relatively high net tax balance across all ranges of metal prices (and therefore appear more robust for changes in metal prices).

From the state's perspective it is not only net tax balance that is taken into consideration when deciding on a tax regime for mineral exploration and extraction on the NCS. Other considerations that could potentially be included in the decision making is the combined NPV for operator company and net tax balance for the state, and the percentage of potential deposits that are mined.

Figure 6.15 shows the combined expected NPV for the operator company and the expected net tax balance for the state at different metal price sensitivities for the selected tax regimes. Figure 6.16 illustrates the percentage of potential deposits that are mined at the different metal sensitivities for the selected tax regimes.

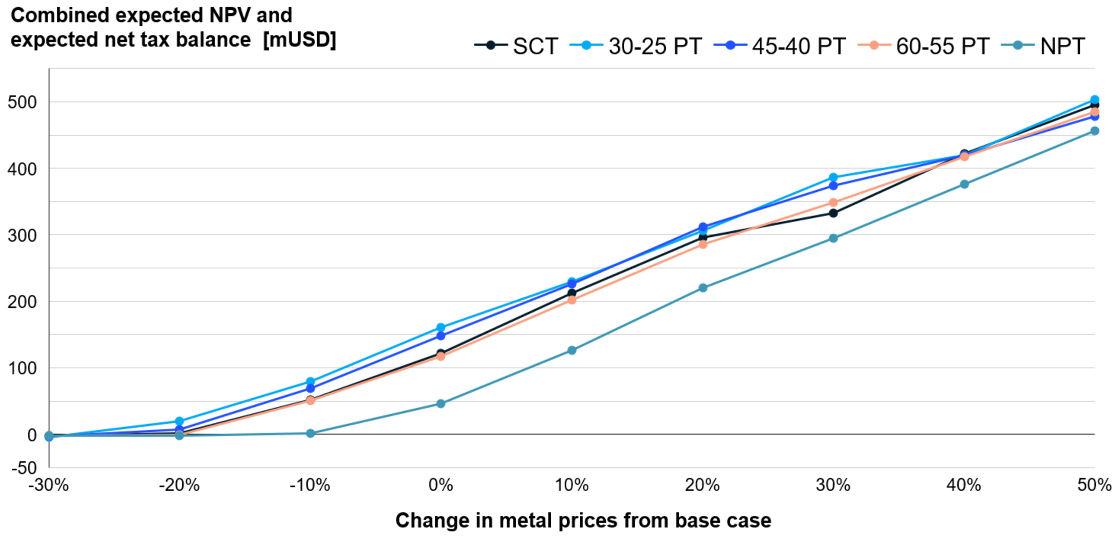


Figure 6.15: Combined expected NPV for operator company and expected net tax balance for state for selected metal sensitivities at different tax regimes

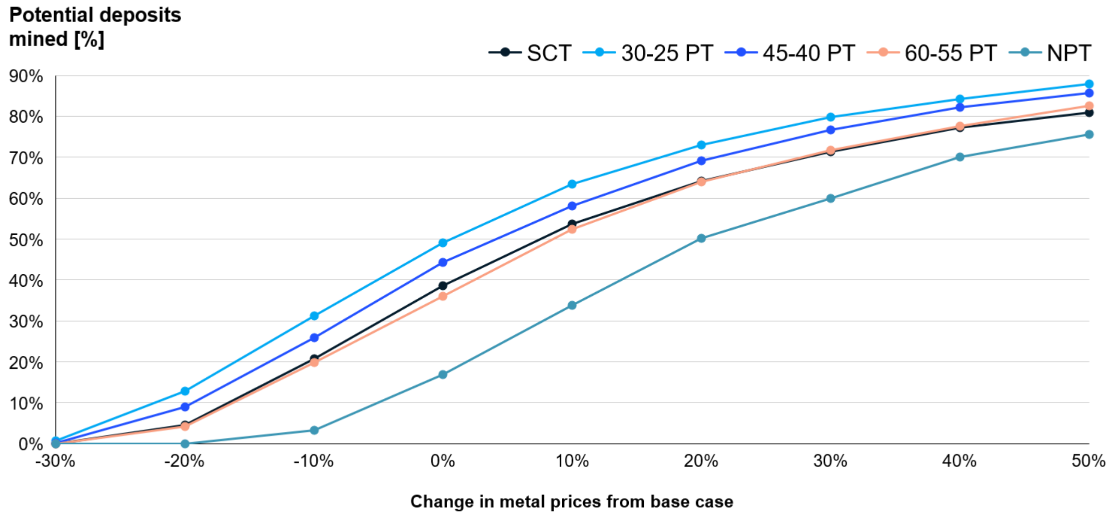


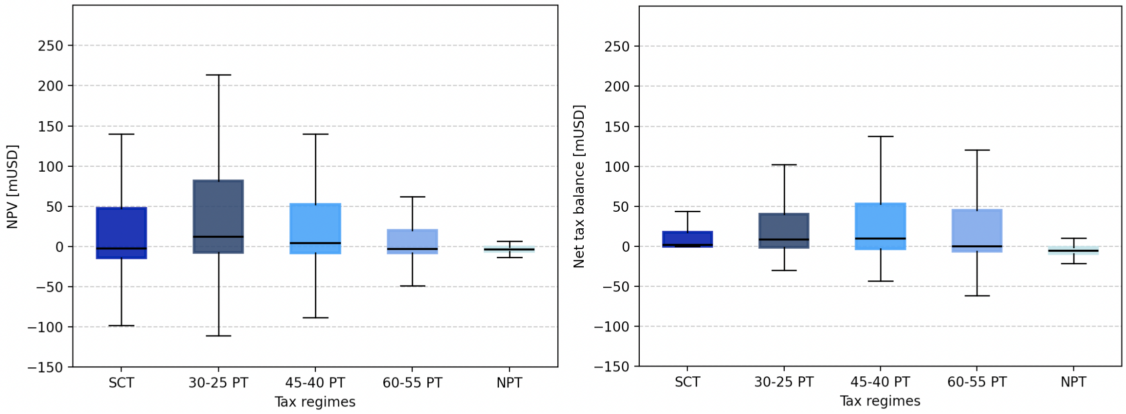
Figure 6.16: Percentage of deposits mined at different sensitivities

As can be observed in the Figure 6.15 and Figure 6.16, the NPT results in the lowest combined NPV and net tax balance and percentage of potential deposits mined off all the selected tax regimes across all metal prices. This demonstrates that although the state receives the highest net tax balance with NPT when metal prices are high, it may not be the optimal tax regime if a wider range of criteria beyond net tax balance is considered. Figure 6.15 and Figure 6.16 demonstrate that the 30-25 PT and 45-40 PT tax regimes result in the highest combined NPV and net tax balance and potential deposits mined across all metal price sensitivities. This highlights that these tax regimes appear to strike a good balance between tax and refund rates, as these regimes result in higher combined NPV and net tax balance than the alternative tax regimes. In scenarios with high metal prices, one might assume that exploration and extraction would not depend that on state refunds. In the scenarios with high metal prices the risk of a potential deposit being unprofitable is lower. Since the risk of economic loss is lower, one could believe that an operator company is less dependent on a high refund rate to de-risk the exploration phase. However as can be seen in Figure 6.15, tax regimes that includes a refund rate at the expense of higher tax rates, such as 45-40 PT and 30-25 PT, result in higher percentage of potential deposits mined and higher combined NPV and net tax balance than the SCT over all economic conditions tested for. This suggests that incorporating a refund rate into the tax regime is crucial in all economic environments to incentivize operator companies to engage in exploration and extraction activities.

Based on the results and insights obtained from simulations we believe that a tax regime along the lines of the 45-40 PT seems to be a reasonable tax and refund rate level. This tax regime consistently results in relatively high combined NPV and net tax balance and percentage of potential deposits mined across all sensitivity ranges. Furthermore, the 45% tax rate of the 45-40 PT seems to ensure that the state receives a relatively large amount of the value that is created from mineral extraction, especially under conditions with high metal prices or other favorable conditions.

It may appear from Figure 6.14 and Figure 6.15 that the state faces little or no downside risk and will never experience losses. However, this is not entirely accurate as these figures display the expected net tax balance and not the distribution of potential outcomes.

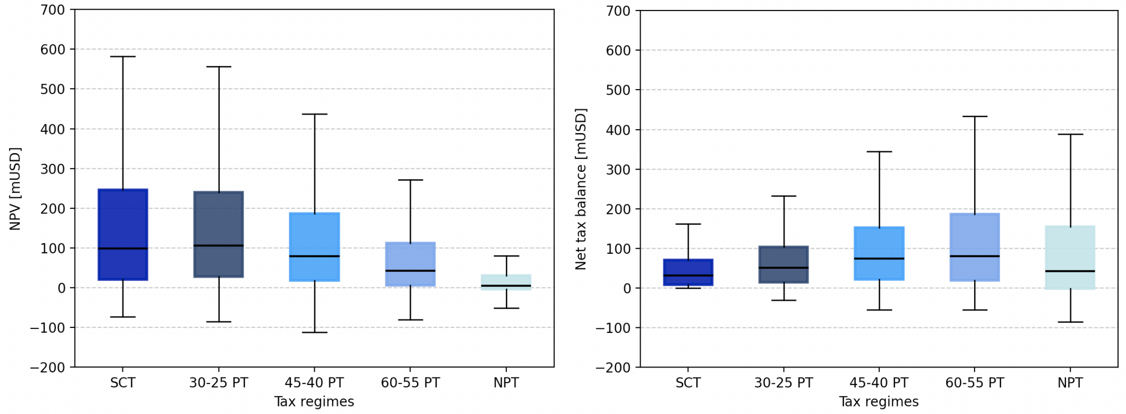
The distribution for both operator company and state at −10%, +10% and +30% is shown in Figure 6.17, Figure 6.18 and Figure 6.19. As can be seen the range of possible outcomes generally becomes wider (and thus more uncertain) for the state as the tax rate and refund rate is increased, and vice versa for the operator company. The 45-40 PT also therefore represents a middle ground for the operator company and state to share risk associated with deep sea mining.



(a) Company

(b) State

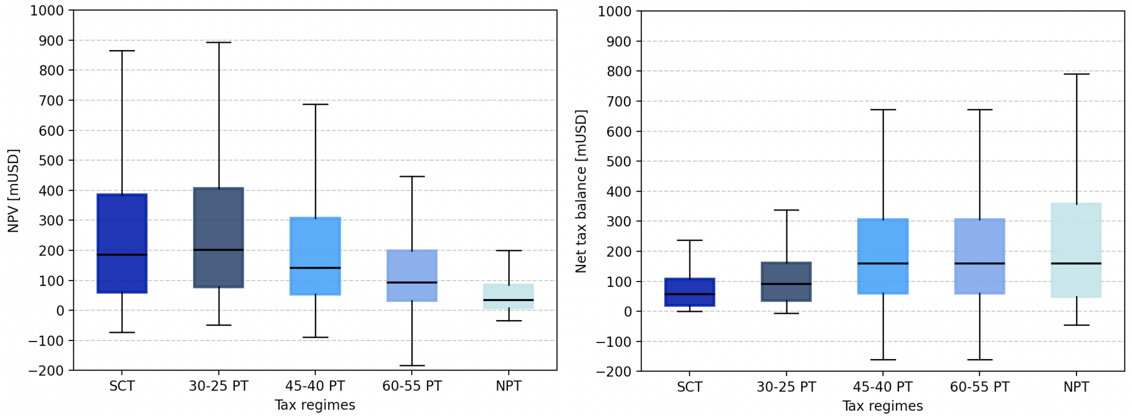
Figure 6.17: Box plots for −10% metal prices



(a) Company

(b) State

Figure 6.18: Box plots for +10% metal prices



(a) Company

(b) State

Figure 6.19: Box plots for +30% metal prices

## 6.4 Discussion

In this section we discuss the effect on the results of our most important modeling assumptions.

### 6.4.1 Political risk

As described in Section 3.2.1, a company that intends to start mineral extraction on the NCS must submit an extraction plan with an impact assessment of commercial and environmental factors (NPD 2021a). In this thesis, we have made two significant assumptions about the extraction plan: first, that the extraction plan is always approved and secondly, that there is minimal lead time between the submission and approval of the plan. The minimal lead time results from that the modeled stage 5) *pilot mining*, between stage 4) *extensive test drilling* and 6) *full-scale mineral extraction*, only last one year, as seen in Table 5.3. However, there exists a degree of political risk that can impact the assumptions regarding the extraction plan that has not been accounted for in the proposed model in this thesis. Deep-sea mining is a contentious issue due to potential impact on marine life and environment. Environmental organizations such as World Wildlife Fund are actively lobbying to prevent mineral mining of the NCS (WWF 2022).

Political risk is a concern for companies engaged in deep-sea mining. If the political pressure from environmental organizations and other opponents is strong enough, it could potentially lead to extraction plans being rejected. In addition, increased political pressure could lengthen the approval process for extraction plans. Industry experts have varying opinions on how long the approval process could take, with the most optimistic estimates being a few months and the most conservative estimates being up to five years. The most conservative estimates from industry experts are based on the fact that approval of similar plans for terrestrial mining in Norway has taken more than five years in cases of political controversy (Ellefmo, personal communication).

The political risk would have different degree of impact for the operator company depending on the applicable tax regime. The NPT regime would be the most protective against political risk from the perspective of an operator company. If a company's extraction plan for a deposit is rejected, the company will not be able to mine it and thus generates no revenue. However, the refund scheme in the NPT regime would significantly reduce the loss related to CAPEX in the exploration phase. With the SCT regime, the CAPEX loss would not be refunded, and thus the negative impact on the operator company becomes larger compared to the NPT.

The NPT regime is also the most beneficial for an operator company when the approval process is prolonged. Regardless of applicable tax regime, it is beneficial for an operator company to begin extraction as early as possible. The reason for this is that when production begins earlier, the discounting effect of cash flows will be lower, thereby increasing the likelihood of the project being profitable. However, how quick an extraction plan is approved has less impact for project profitability under the NPT than the SCT. With the NPT, a significant share of the CAPEX loss gets refunded. Consequently, the loss that must be recovered through mineral extraction in order to achieve profitability is relatively small. In contrast, with the SCT the operator company faces a considerable CAPEX loss. As a result, there is a increased reliance on initiating mineral extraction promptly to offset these losses. Delaying the start of extraction could lead to a significant increase in the discounting effect, making it increasingly challenging for the generated cash flows to compensate for the CAPEX loss.

### 6.4.2 Choice of discount rate

We conclude from our sensitivity analysis in Section 6.2 that the discount rate is not the most sensitive parameter among the selected parameters within the selected boundaries. However, the choice of discount rate is still significant for the profitability of a marine minerals project. Since there will be a time gap between exploration start and generation of positive cash flows for mineral extraction, the discounting effect on cash flows is significant. In this thesis, we use a base case discount rate of 15% as described in Section 5.1.8.

Considering the significant political and technological risks associated with deep-sea mining, certain industry experts have suggested the possibility of discount rates reaching as high as 30%. Discount rates of such magnitude could significantly influence the decision making processes of operator companies. Primarily, a higher discount rate would result in fewer deposits deemed financially viable, leading to a reduction in the number of deposits selected for extraction. This can be seen in Figure 6.6, where it can be observed that number of potential deposits that are mined decreases significantly when the discount rate is increased from 12% to 18%. An increase of the discount rate towards 30% also has the potential to alter the dynamics of which potential tax regimes that are most economically beneficial to the operator company. At a discount rate of 15%, tax regimes with rates of 30-25 PT and 45-40 PT seem to be the most beneficial for the operator company , as can be seen in Figure 6.1. However, when applying a discount rate of 30% instead of 15%, the relative value of refunds from exploration increases compared to revenue from mineral extraction. Due to discounting, the refunds have a larger weight in terms of the expected NPV than the cash flows stemming from mineral extraction when the discount rate is increased. Consequently, a significant increase in the discount rate could potentially make tax regimes with higher refund rates comparatively more beneficial for operator companies, even though they also have higher tax rates.

### 6.4.3 Modeling of metal prices

As explained in Section 4.3.3, we assume the prices of metals as constant. This is because only resource related uncertainty is modeled in this thesis, rather than market risk. The uncertainty related to metal prices is accounted for as a premium in the discount rate in our model.

Explicitly accounting for uncertainty in metal prices could have impacted the company's decision making process in various ways. Firstly, modeling metal prices would have increased the upside potential of the operator company and state. With dynamic metal prices the metal prices could reach higher values that the constant metal prices. As seen in 6.3, higher metal prices results in both an significant increase in percentage of potential deposits mined and the expected net present value for the operator company and expected net tax balance for the state. However, the increase in downside risk can however be expected to become larger than the increase in upside potential for the operator company if applying metal price uncertainty in the form of stochastic prices, for example, to our framework. From Figure 6.16 we see that a 30% increase in metal price from our base case correspond to 60-80% of the potential deposits on the licence block being mined, depending on the tax regime. A 30% decrease in metal prices, however, corresponds to zero potential deposits being mined regardless of tax regime. At the 30% decrease in metal price, most deposits are abandoned very early in the exploration phase and thus limit the losses for the operator company. The early abandonment of deposits is a consequence of known unfavorable metal prices, which render the eventual potential revenues of mining deposits too low to justify the CAPEX that must be spent on further exploration. However, with dynamic metal prices, a situation could occur where for example the 60-80% of the potential deposits from the 30% metal price increase scenario are ready to be mined after going through all exploration stages. Then, a plummet in metal prices could deem most or even all of these deposits unprofitable to mine, leaving the operator company with large CAPEX losses from the exploration phase. This would also yield large losses for the state in cases where varieties of the NPT regime is applied. This is because the absence of revenues for the operator company translates into a lack of tax income for the state, rendering the refunds provided by the state during the exploration phase ultimately futile.

As described in Section 4.1, we model the operator company's decision to progress or abandon deposits as strictly binary. This means that the company does not have the option to wait at the decision gates and cannot make the decision of progression or abandonment later on. Furthermore, once the company has abandoned a deposit it cannot bring it back into its portfolio at a later time. If the operator company had the option to wait in a situation with dynamic metal prices, it would be possible for to wait out periods with low metal prices in hope of future price increase. Then, the effects of dynamic metal prices on risk for the operator company and the state described above would likely be reduced.

### 6.4.4 Modeling grades of different metals within the same deposit as independent

In this thesis, we have made the assumption that the grades of different metals within a deposit are independent. This means that the presence or grade of for instance copper in a deposit does not correlate with the grades of zinc, gold, or silver within the same deposit. To the best of our knowledge, there have not been collected enough physical samples of potential deposits on the NCS to draw conclusions regarding any correlation between metal grades, let alone to determine the appropriate correlation coefficients between different metal grades.

To expand our understanding of the interdependency of metal grades within a deposit, we examine the results of physical sampling from various sulphide prospects aside from the NCS and analyse the correlations between copper, zinc, gold and silver. We examine the metal grades of three separate groups of sulphide deposits where physical samples have been collected, described in SRK Consulting (2010), Hannington et al. (2010) and NPD (2023). The resulting correlation coefficients between metals from the three separate analyses are presented in Appendix A. These results imply that certain correlations between metal grades within deposits exist. However, the only correlation that seems consistent in all three groups of sulphide deposits is a slight negative correlation between copper and silver. The inconsistency in correlations makes it difficult to define these parameters, which is why we have left the metal grades independent from each other in our model. However, if data from physical samples collected from SMS deposits on the NCS becomes available in the future it may be possible to update our framework and incorporate potential correlations between metal grades.

The presence of correlation between metal grades could have implications for the decision making process of operator companies, both reducing downside risk and increasing upside potential. A positive correlation of metal grades could reduce downside risk, as it might lead to increased rate of early abandonment of unfavorable deposits. When the metal grades are not positively correlated, the operator company may encounter situations where the grades of multiple metals in a deposit are low, but the grade of one particular metal appears high based on preliminary exploration. What appears as a high metal grade for one metal could be enough to justify further exploration. However, further exploration could reveal the grade of this metal to be insufficient to justify continued exploration or extraction of the deposit. However, if there had been significant positive correlations among the metal grades, the operator company would more likely experience deposits were all metal grades appear low, and therefore abandon early. Early abandonment of unprofitable deposits reduces the CAPEX loss for both the operator company and the state. Positive correlations could also increase the upside potential, as the operator company would encounter more deposits were the metal grade of all relevant metals are high. Deposits were there is a high grade of all metals are very profitable. The probability of discovering such super profitable deposits increases when the correlations are positive, thus increasing upside potential.

### 6.4.5 Effects of choice of metal grades on corporate decision making

As explained in Section 5.2.3, the metal grades of SMS deposits on the NCS are subject to substantial uncertainty. To generate our results, we use scaled-down metal grade distributions based on the distributions presented by Ellefmo and Søreide (2019). The scaling allows us to use more conservative metal grade estimates than presented by Ellefmo and Søreide (2019) in our base case, while sustaining the properties of their distributions. The choice of metal grade distributions applied to our framework impacts the decision making process of the operator company.

The probability density of the metal grade distributions used in this thesis exhibit a relatively high "lowest case" scenario (as can be seen in Figure 5.2 in Section 5.2.3). This is a result of that the standard deviation of the distribution is relatively low. For copper and zinc, it is apparent that the grades rarely fall below 2%, and never fall below 1.5%. However, this may not be reflective of real-life sulphide occurrences (Hannington et al. 2010; NPD 2023; SRK Consulting 2010). In reality, deposits do exhibit grades close to zero for certain metals at specific prospects. We acknowledge the disparity between the chosen metal grade distributions and the observations from physical test samples. The level of geological risk might therefore be higher in reality for a operator company conducting exploration.

Employing metal grade distributions with a different standard deviation than what is currently used in the model would alter the degree of geological risk that the operator company faces. As the geological risk of the operator company is altered, it is of interest to understand how increasing the geological risk impacts the decision making of the operator company. To examine this, we apply metal grade distributions with both higher and lower standard deviations compared to the distributions used in our base case, while keeping the expected grade value at the same levels as the metal grades used in our base case. This corresponds to adjusting both $\mu_{\text{grade,original},m}$ and $\sigma_{\text{grade,original},m}$ parameters for $m \in \{\text{copper}, \text{zinc}, \text{gold}, \text{silver}\}$, in Equation (4.19) and Equation (4.24). The result is shown in Figure 6.20, which shows the percentage of potential deposits that are mined at different tax regimes at different standard deviations for the metal grade distributions.

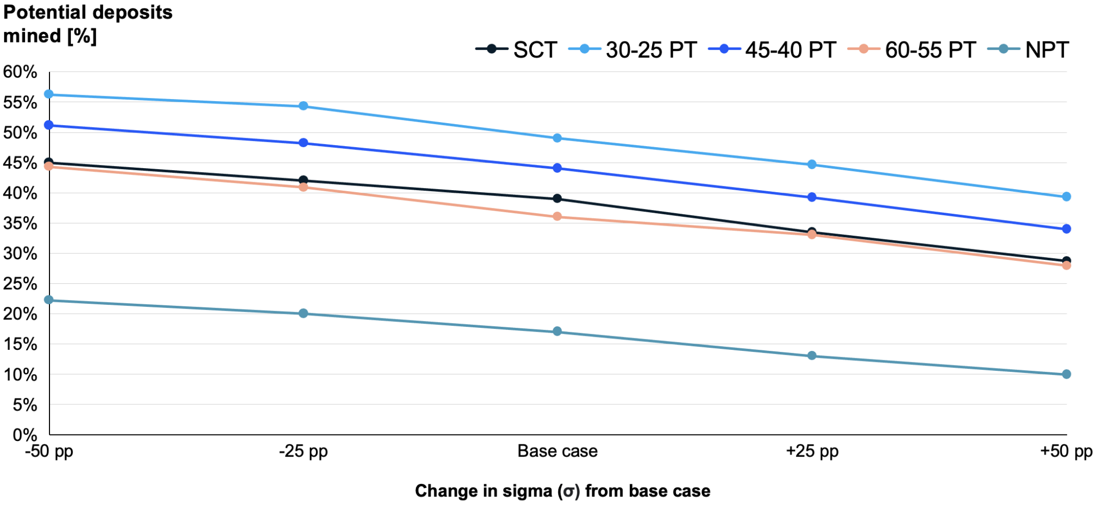


Figure 6.20: Percentage of deposits mined at different sigma sensitivities

First, we observe that introducing larger standard deviation to the metal grade distributions overall results in fewer deposits meeting the criteria for progression and eventually being mined. This is evident from Figure 6.20. It can be observed that across all tax regimes, increasing the standard deviation of the metal grades results in fewer deposits being mined while decreasing the standard deviation results in more deposits being mined, compared to the base case. This is because higher variance lead to increased geological risk. As we assume that the operator company is relatively risk averse, the increase in risk leads to more deposits being abandoned during the exploration phase.

Second, the outcomes emphasise the fact that our model primarily provides managerial insights and trend analysis rather than precise numerical values. From Figure 6.20 we see that the specific numerical percentage of potential deposits mined are dependent on which numerical values that are used for describing the metal grade distributions. However, when considering various standard deviations for the metal grade distributions, it is evident that the ranking of tax regimes yielding the highest percentage of potential deposits mined remains consistent. This highlights that the insights the model provides and the trends observed is relevant across a wide range of parameter values.

### 6.4.6 Decision making and risk management from the company's perspective

The solution approach of the model proposed is based on a spanning tree to account for managerial flexibility, as presented in Section 4.6. We assume that the investor deciding whether to progress or abandon deposits at the different decision gates is risk-averse and base its decision on the P75 value obtained through the spanning tree, as described in Section 4.6.1. The choice to apply P75 as the decision metric is based on conversations with industry experts who expect investors in marine minerals projects to be risk averse.

Given the assumption of a risk-averse investor in this thesis, it would be of interest explore how the investor's risk appetite influences the decision making and the resulting expected NPV for the operator company and expected net tax balance for the state. Deep-sea mining is an industry characterised by significant technological and political risk. Furthermore, there are geological risks associated with the number of deposits on the NCS, and the ore tonnages and metal grades of these. In a high-risk industry, if an investor holds a highly conservative stance, it is likely that the investor could abandon a project with a positive expected NPV, if the probability of the project resulting in a negative NPV is above the investor's liking.

Conducting a sensitivity analysis to explore alternative decision metrics with lower risk aversion, such as P60, P50, P40, etc., would be interesting. If the P75 metric turns out to be overly conservative, leading to the abandonment of multiple projects with positive expected NPV, adopting a less risk-averse approach could potentially yield higher expected NPV for the operator company and expected net tax balance for the state. However, it is important to note that being less risk-averse entails higher potential downsides. Therefore, it is valuable to compare the changes in risk profiles for both the operating company and the state by examining box plots associated with various decision metrics representing different risk appetites. This should be a subject of future research of our framework.

### 6.4.7 Effects of aggregation of deposits

In this thesis the life of a license block is calculated (see Equation (4.4)) by aggregating the total ore tonnage across all deposits remaining in an operator company's portfolio and dividing it by the annual production rate. In the aggregation process, average metal grades for the license block are calculated by using weights based on the ore tonnage of each deposit. These average metal grades are used to calculate the cash flows throughout the whole lifetime of a license block. However, this is a simplifying assumption. In reality, companies will establish a mining plan that accounts for the best time strategy to optimise the value of the portfolio. Our model does not emulate this process. Thus, the expected value of a license block might therefore be lower than if the mining process had been optimised. If a deep-sea mining company were to begin extraction of the most promising deposits first, this would increase the expected NPV of the license block. This is because higher cash flows stemming from the most favourable economic deposits are generated in the early stages of extraction. Due to the discounting, these have a larger weight in terms of the expected NPV than the cash flows stemming from the less favourable economic deposits later on.

We do not believe that the aggregation of metal grades has a major impact on our results, considering our geological assumptions. The standard deviation in the metal grade distributions that we apply to the base case are relatively small. Thus, the differences between the individual and aggregated grade rates are not significant. If metal grades with larger standard deviations were to be used, there would be significant differences between the individual and aggregated metal grades. In such cases the aggregation of metal grades would have a larger impact on the results.

### 6.4.8 Possible effects of increased flexibility in the operator company's decision making

In this thesis, we make the simplifying assumption that the decision situation is strictly sequential. Thus, we do not account for the possibility of bypassing stages in the exploration phase. This assumption is based on the relatively low granularity of our modeled stages and on the risk and novelty of the deep-sea mining industry. According to industry experts, an operator company would not skip any of the currently modeled stages because the risk reduction of these stages are essential to go through with a project. However, our framework could be extended to include more sub-stages for exploration, especially in our two test drilling stages, 3) *preliminary test drilling* and 4) *extensive test drilling*. According to industry experts, these two stages could be split into for instance 3a), b), c) and 4a), b), c). This would better reflect the reality being that smaller decisions have to be made during these stages. Such decisions could for instance be on how many core-samples that must be collected depending on the findings from previous exploration stages and the mineral contents of the core-samples collected initially. Adding these sub-stages to our framework would allow for decision making through the principles of value of information, which would reflect how managers often make decisions under uncertainty in the real world (Bratvold et al. 2009; Eidsvik et al. 2015). Value of information is mainly used to evaluate whether an exploration activity is worth undertaking with regards to the expected value add such an exploration activity corresponds to versus the cost of performing the exploration activity (Bratvold et al. 2009; Eidsvik et al. 2015). Following a value of information philosophy, an exploration stage would be bypassed if the expected cost of the stage outweighs the expected added value performing the stage would contribute to the project. We do not add a value of information methodology to our model as we assume that a marine minerals company always would complete all our modeled exploration stages before initiating extraction. Addition of sub-stages along with a value of information philosophy to our proposed framework could reduce risk for corporate decision makers in marine minerals project, as it would provide a higher degree of managerial flexibility. Thus, marine minerals projects could yield higher expected NPV for the company and net tax balance for the state, as instances with large losses could be more rare. However, addition of many sub-stages would be very computationally expensive with the solution approach used in this thesis.

Another extension to our framework that could better reflect the flexibility of decision making in real-life projects is adding a decision gate between exploration stages 1) *regional survey* and 2) *local survey*. We assume that for all the potential deposits discovered in exploration stage 1, the company will proceed with exploration stage 2 to obtain initial information about the ore tonnages. However, this may not always be the case in reality. According to industry experts, it would not be unrealistic for a company to set a threshold for the expected total amount of years of mining that is required to go through with a project. A situation that could occur is that a company in stage 1 only finds a very limited amount of potential deposits in its license area. Then, the amount of years of mining that the company could expect may be lower than the threshold. Thus, it is likely that the company would abandon the project. This scenario is not considered in our framework. As a result, the current model may slightly overestimate the percentage of potential deposits mined. This is because in reality, some deposits would be abandoned after exploration stage 1 whilst all potential deposits are progressed from stage 1 in the proposed model.

# 7 Conclusion

In this thesis, we define a framework for valuating a marine minerals project from the perspective of an operator company and from the perspective of the Norwegian state, given the tax regime applied to the Norwegian marine minerals industry. This in light of the ongoing process of opening the NCS for commercial minerals activity with a definite tax regime yet to be defined for the industry. We model the decision framework relating to mineral exploration and extraction stages that an operator company is likely to face on the NCS. The resulting multi-stage decision problem is evaluated by taking a dynamic programming approach based on simulations. Thus, the framework allows for evaluation of how different tax regimes affect decision making by an operator company through a project. By stochastic modeling of geological uncertainty, we use the framework to provide understanding of how different tax regimes affect the risk of a marine minerals project from both a corporate and a regulatory perspective.

We contribute by presenting a framework and results that may provide insight for the Norwegian government in how different tax regimes incentivize companies to invest in marine minerals projects on the NCS. To the best of our knowledge, analysis of how a regulator can incentivize commercial exploration and extraction of marine minerals through legislation is not previously covered by the literature.

The numerical implementation of the framework developed in this project has provided insights into the impact the various tax regimes could have for both an operator company and the state. First, there appears to exist a trade-off relationship between tax and refund rates for both the operator company and the state. The operator company seems to benefit from increased tax and refund rates up to a certain threshold compared to the SCT, as the increase in refund rates seem to reduce risk related to the exploration process. On the other hand, the state appears to benefit from lower taxes and refund rates than the NPT, as this incentivizes operator companies to engage in mineral exploration and extraction. Given this trade-off, it should be possible to identify tax regimes that satisfy both the operator company and the state, such as the 45-40 PT regime. Second, the model suggests that certain tax regimes exhibit greater resilience across various economic environments. Specifically, the 45-40 PT regime consistently yields one of the highest economic surpluses and percentages of potential deposits being mined regardless of the economic environment. In contrast, the NPT proves beneficial for the state only in highly favorable economic environments. However, in unfavorable economic environments, the NPT leads to a scarcity of deposits being mined. Third, the model suggests that metal prices play the most important role in determining project profitability and shaping the decision making process for operator companies. When metal prices are subject to significant decrease, the likelihood of mineral extraction is low regardless of the exploration incentives offered to the operator company through the tax regime. Conversely, when metal prices substantially increase, a high percentage of identified potential deposits are likely to be extracted, irrespective of the tax regime and exploration incentives in place.

Considering that deep-sea mining is a nascent industry, there remains considerable uncertainty surrounding the technology and the numerical values associated with relevant parameters in this thesis. While we consider the parameter values used in the base case as realistic, it is essential to acknowledge the inherent uncertainty surrounding these numbers. Therefore, we place greater emphasis on the trends and main insights derived from the model rather than focusing solely on specific numerical values obtained.

There are several possible extensions to the framework presented in this thesis that could yield additional insights. One such extension involves modeling of market risk in the form of stochastic metal prices, as opposed to applying constant metal prices as in the current model. By incorporation of dynamic metal prices, the model would more accurately capture companies' and the state's risk associated with declining metal prices, which can render projects unprofitable. This extension would better align the decision making process of the operator company in the model with what is expected in real-world scenarios. Another possible extension of the framework is the incorporation of an option to wait at the decision gates, rather than limiting decision making to be strictly binary with progression or abandonment of deposits the two sole alternatives. This extension could be particularly relevant in combination with modeling of market risk in the form of metal price uncertainty. This is due to the possibility that the effect of market risk could be mitigated by giving the operator company the option to wait, in anticipation of favorable metal price increases for instance. By adding metal price uncertainty and the option to wait to the framework, it may be able to provide additional insights into decision making strategies in the context of deep-sea mining on the NCS.

Another possible extension to the framework that could provide closer resemblance of the managerial flexibility in decision making from the perspective of an operator company could be addition of sub-stages to the exploration stages we model in this thesis. This could allow for modeling of the decision situation beyond the strictly sequential project process assumed in this thesis and implementation of decision making through the principles of value of information. The increased flexibility added to the model could allow the operator company in our framework to take decisions that closer resemble what would be optimal in projects in reality.

At last, it could prove insightful to reformulate our model as a multi-objective optimization problem. Currently, the framework has been implemented with a limited number of tax regimes, revealing some regimes more beneficial than others for both companies and the regulator. However, we do not claim to identify the optimal tax regime for the Norwegian marine minerals industry in this thesis. Defining what is truly optimal is challenging since the state and operator companies may have conflicting interests. Nevertheless, it would be intriguing to explore the possibility of defining an objective function that represents the optimal balance between the two parties' interests and attempt to find the optimal tax regime based on the given criteria. This approach might provide a more comprehensive understanding of the trade-offs and considerations involved in determining the most favorable tax regime.

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# Appendix

## A Correlation between metal grades within an SMS deposit

To examine whether metal grades within SMS deposits should be modeled as correlated we examine three separate groups of sulphide deposits where physical samples have been collected. This analysis results in the three different correlation matrices presented in Table A.1, Table A.2 and Table A.3 respectively.

Examining 18 deposits of Nautilus Minerals' Solwara project, from Table 9-1 of SRK Consulting (2010), gives us the correlation matrix presented in Table A.1.

Table A.1: Correlation coefficients for metal grades at Solwara prospects

| | Cu [%] | Zn [%] | Au [ppm] | Ag [ppm] |
|---|---|---|---|---|
| Cu [%] | 1 | | | |
| Zn [%] | 0.268 | 1 | | |
| Au [ppm] | 0.374 | 0.043 | 1 | |
| Ag [ppm] | −0.178 | −0.039 | 0.653 | 1 |

Examining deposits from the mid-ocean ridges considered in Table 7.3 in NPD (2023), originally gathered from Hannington et al. (2010), gives us the correlation matrix presented in Table A.2.

Table A.2: Correlation coefficients for metal grades in various deposits at mid-ocean ridges

| | Cu [%] | Zn [%] | Au [ppm] | Ag [ppm] |
|---|---|---|---|---|
| Cu [%] | 1 | | | |
| Zn [%] | −0.002 | 1 | | |
| Au [ppm] | 0.712 | 0.228 | 1 | |
| Ag [ppm] | −0.201 | 0.458 | 0.035 | 1 |

Examining terrestrial sulphide deposits along the Scandinavian Caledonides that may be analogies to SMS deposits, from Table 7.1 in NPD (2023), gives us the correlation matrix presented in Table A.3.

Table A.3: Correlation coefficients for metal grades in terrestrial deposits along the Scandinavian Caledonides

| | Cu [%] | Zn [%] | Au [ppm] | Ag [ppm] |
|---|---|---|---|---|
| Cu [%] | 1 | | | |
| Zn [%] | −0.078 | 1 | | |
| Au [ppm] | 0.433 | −0.043 | 1 | |
| Ag [ppm] | −0.164 | 0.672 | 0.152 | 1 |

# B Additional box plots from sensitivity analysis

In the following section we present the box plots for the tax regimes 30-25 PT and 60-55 PT for the sensitivities described in Section 6.2. These were not included in Section 6.2, but are included here for completeness.

## B.1 Operator company

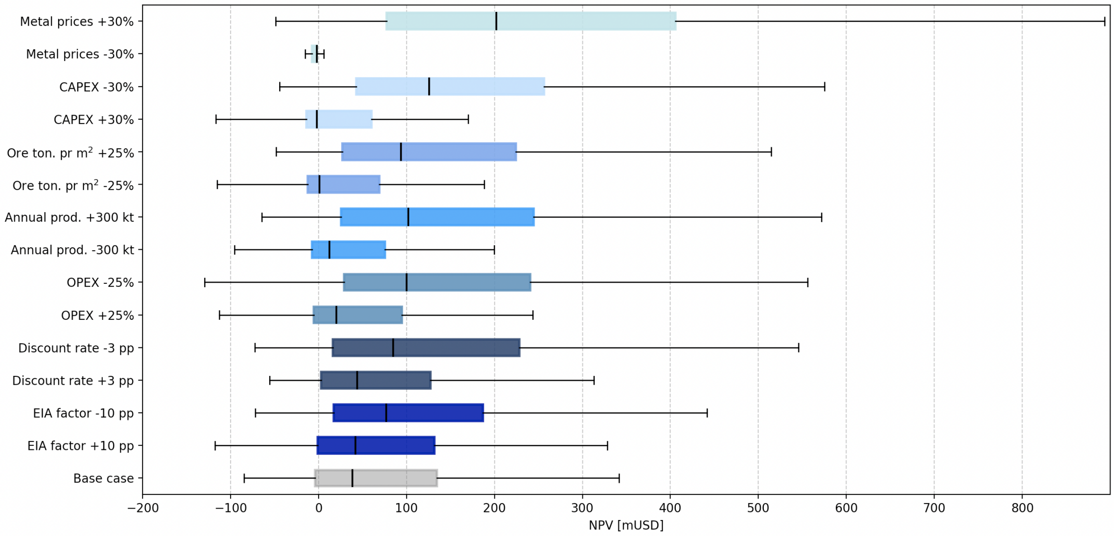

Figure B.1: Box plot of company NPV at selected sensitivities for 30-25 PT

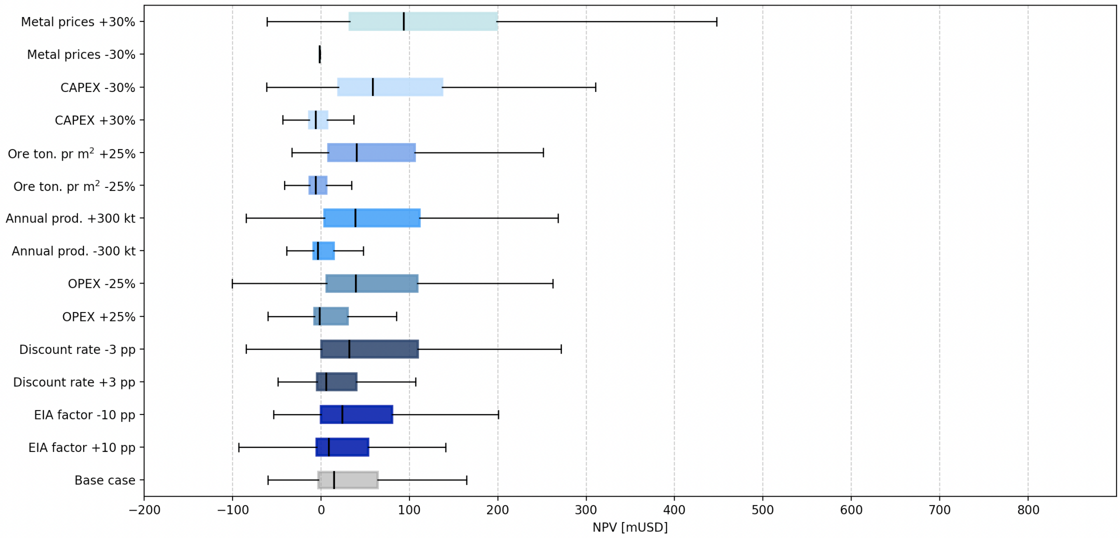

Figure B.2: Box plot of company NPV at selected sensitivities for 60-55 PT

## B.2 State

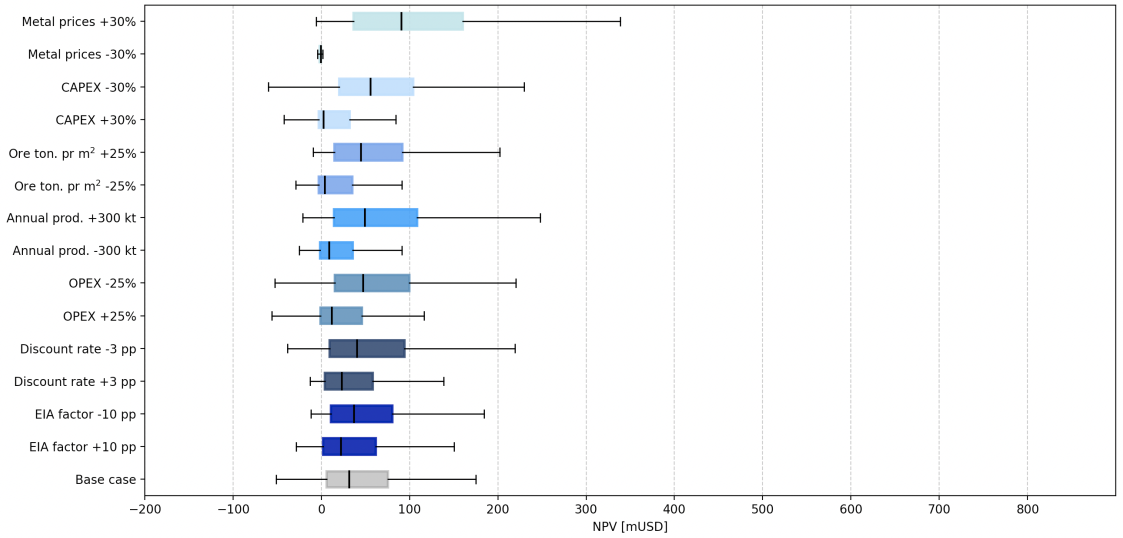

Figure B.3: Box plot of state net tax balance at selected sensitivities for 30-25 PT

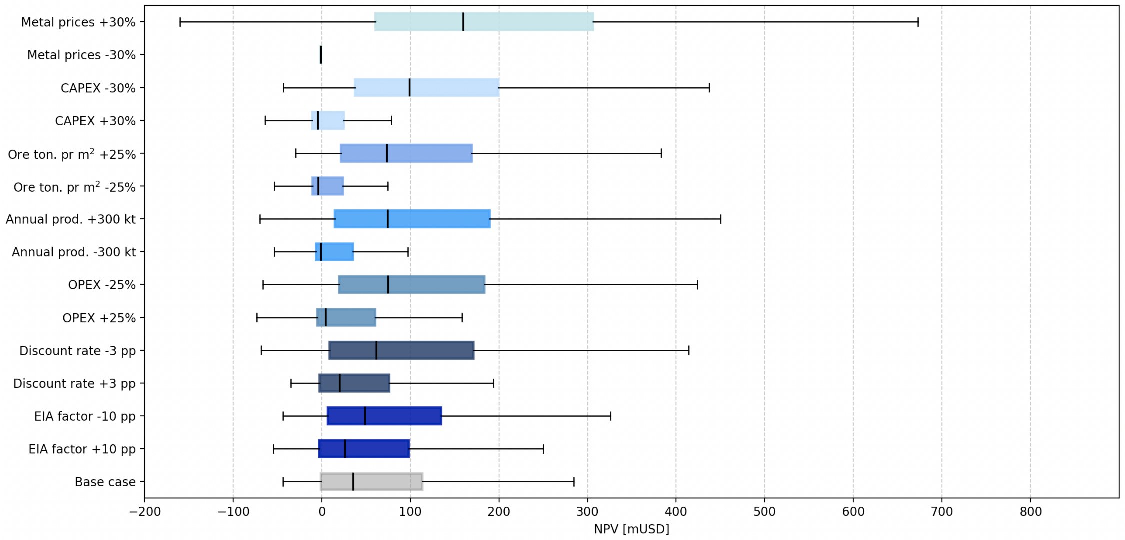

Figure B.4: Box plot of state net tax balance at selected sensitivities for 60-55 PT

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