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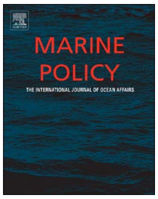

A stochastic techno-economic assessment of seabed mining of polymetallic nodules in the Clarion Clipperton Fracture Zone

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ABSTRACT

Polymetallic nodules found in the Clarion Clipperton Fracture Zone in the NE Pacific contain more nickel, manganese and cobalt than all terrestrial reserves combined. Following the 1982 Law of the Sea Convention and its 1994 Implementing Agreement, the resources of the international seabed beyond the limits of national jurisdiction will be developed for the benefit of mankind by attracting investment and technology, whilst demanding that necessary measures be taken to ensure effective protection of the marine environment. To date, no single commercial seabed mining activity has taken place in international waters, and the development of balanced and stimulating exploitation regulation is needed, based on accurate economic analysis. This paper presents the first detailed, vertically integrated, stochastic techno-economic assessment from a contractor's perspective, and contributes to the development of the world's first exploitation regulations. The economic performance measured by the internal rate of return was compared using deterministic and probabilistic commodity price forecasting models. Different levels of a financial payment regime, comprising of a royalty payment and a payment to internalize environmental costs, were considered. When real growth was included, the internal rate of return remains above the hurdle rate when a transitional, total-cost, financial payment regime is below 2 per cent during the initial period and below 4 per cent for the remaining tenure period. Following a 10-year moving average of commodity prices, including real growth, a 77.51 per cent probability was calculated of achieving a hurdle rate of 18 per cent.

1. Introduction

To serve a continuously increasing global population [1], a growing middle class that is driving urbanisation [2], and unprecedented demand for renewable, low-carbon energy infrastructure, minerals and metal supplies are essential [3,4]. Land-based deposits have been exploited for decades, sometimes centuries. Tilton explained that although humankind has consumed more resources during the past century than in all earlier centuries combined, minerals are not destroyed when consumed [5,6]. This apparently insatiable demand has led to an overall decline in the quality of terrestrial ore that remains available, thereby increasing greenhouse gas emissions when mined [5,7,8]. Norgate and MacLean et al. described that reducing our demand for primary metals by recycling and dematerialisation is essential, but despite our best efforts, there would always be a need for additional primary metals [7,9]. Furthermore, Graedel et al. explained that due to material complexity, substitution is very likely to decrease product performance, raise the price, or both [10]. In short, technological change (TC) is required across the entire mineral life cycle to address the sustainable use of resources as terrestrial economic reserves are likely to grow relatively little [5,9,11].

Although polymetallic nodules in the NE Pacific Ocean were discovered in the late 19th century, it was not until the mid-1960s that Mero documented the potential wealth in his book *The Mineral Resources of the Sea* [12]. Mero suggested that, *in the not too distant future*, seabed minerals would become one of the major sources of supply of the world's minerals. A subsequent substantial increase in maritime interests brought Ambassador Arvid Pardo to address the General Assembly of the United Nations in November 1967. Pardo quoted Mero's book and conveyed excitement about the technological progress made over the recent years, albeit warning that this may lead to conflict in the world's oceans. His speech, which recommended regulation beyond the limits of national jurisdiction, including governance of the potential wealth on the seabed, was well received. An *ad*

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hoc committee on peaceful uses of the seabed and the ocean floor beyond the limits of national jurisdiction was set up, and a process began that, after a 15-year period of negotiations, culminated in the 1982 Law of the Sea Convention (LOSC). However, the proposed LOSC Part XI on seabed mining was deemed unacceptable by many developed countries for commercial (financial payment regime) and operational (production limits and transfer of technology) objections, and an Implementing Agreement, to deal with the problematic provisions of the LOSC Part XI was adopted in 1994 [13]. The International Seabed Authority (ISA), which was an outcome of the LOSC, was to organise, regulate and supervise all mineral-related activities in the international seabed beyond the limits of national jurisdiction, known legally as “the Area”. Furthermore, both the Area and its resources were designated as the *common heritage of mankind*.

The different policy objectives and the principles underlying implementation of the overarching goal of developing the resources of the Area for the benefit of mankind have proven challenging to implement. Whilst the LOSC has called for the development of these resources by attracting investment and technology, it also requires that necessary measures be taken to ensure effective protection of the marine environment, including the protection and conservation of natural resources and the prevention of damage to the flora and fauna of the marine environment. Furthermore, the Authority shall provide for equitable sharing of financial and other economic benefits derived from activities in the Area through any appropriate mechanism, on a non-discriminatory basis.

Commercially viable subsea mining equipment has so far never been tested; hence, before any exploitation may take place, significant TC is required. According to Schumpeter, TC is driven by profitability [14]. Therefore, commercially acceptable regulations under international and national law are paramount to create an investment climate that fosters TC in today's volatile global environment. The objective of this paper is to provide decision makers with the appropriate tools to analyse the impact of different regulations on the economic performance of a seabed mining project. More specifically, the following research questions were addressed: (i) What is the probability of achieving an investor's minimum return considering the risks of seabed mining under different commodity forecast scenarios? (ii) What are the most important private cost drivers associated with a seabed mining project? (iii) Can the competitiveness of polymetallic nodule deposits be compared with terrestrial nickel deposits? (iv) How do different levels of a financial payment regime (FPR) affect the internal rate of return (IRR)? The result of this analysis provides decision makers with evidence as to the degree to which uncertainty affects the economic performance of seabed mining, thereby fostering TC and realizing significant welfare.

2. Methods

2.1. Stochastic techno-economic assessment

A stochastic techno-economic assessment (TEA) is a straightforward and reliable decision-making tool that allows costs and benefits to vary following a given probability distribution, modelled using Monte Carlo Risk Analysis (MCRA) [15,16]. A deterministic model will fail to capture the complexity (as it does not account for the variability in the data, and provides only a point value), and most likely will not be representative of a venture engaged in polymetallic nodule exploitation. Following the weighted average cost of capital of equity and debt financing, reflecting provisions for technical, institutional and market risk, a minimum return (hurdle rate) an investor would want to realise, is established [17]. These provisions are unfavourable for a project with a long development phase (due to the exponential effect of discounting) and will be different between first movers and fast followers, as perceived risk will decrease over the lifetime of a project. For this article, a hurdle rate of 18 per cent was assumed, corresponding to industry expectations for this type of project. Similar to standard private and economic investment analysis, the IRR as indicator for economic performance was chosen. Only projects with an IRR above the hurdle rate (HR) will attract funding.

An investment model based on a case study to identify the impact of the different variables in explaining the variation in economic performance was developed. Similar as to Johnson and Otto, it was assumed that this simplified model will provide estimates within 1 per cent of the IRR of more complex models considering similar cost and revenue assumptions [18]. The following step-by-step approach, adapted from Tan *et al.* and Campbell and Brown, was identified as useful towards building a comprehensive and effective TEA [19,20]:

1. Decide on system boundaries and develop a realistic programme from pre-feasibility stage (PFS), through feasibility stage (FS), up to the construction and operation of a seabed mining project;
2. List all capital expenditures during the mine life of the project for the offshore and onshore mining infrastructure;
3. List all operational expenditures during the mine life of the project for the offshore and onshore mining infrastructure from a total-cost perspective, including the environmental monitoring and estimated regulatory costs (Appendix B);
4. Forecast commodity prices using deterministic and probabilistic methods (Appendix C);
5. Identify uncertain model inputs and assign probability distributions, including correlations between variables;
6. Apply MCRA software (Oracle Crystal Ball®) and model 10,000 simulations. For each simulation, the software fills in a random value by means of the probability distributions assigned to each variable, recalculates the spreadsheet and saves the forecast value in its memory for later analysis. The results are displayed in interactive histograms, or frequency charts, showing the probability of a certain outcome. MCRA allows us to calculate the probability of the IRR achieving the HR, and the sensitivity of each assumption.

Following Mero's book in 1965, the first economic assessment for seabed mining was published by Sorensen and Mead [21]. In total, 12 publications on four-metal scenarios were analysed for capital and operational expenditure estimates. The results of this analysis, including a list of these articles, can be found in Appendix A. Many scholars concluded at the time that seabed mining could be competitive with land-based mining. However, there was no such thing as an everlasting advantage of seabed mining over land-based mining, and the result was heavily dependent on factor and commodity prices [22].

2.2. Forecasting commodity prices

2.2.1. Correcting prices for inflation effects to determine real growth

Given a total development period of 15 years and an operational mine life of 25 years, different forecasting methods are used to generate future commodity prices. According to Wood et al., the choice of time series for which a trend is defined may have a serious effect on the result [23]. Therefore, a historical time series of the past 32 years (1985–2016) was analysed, representing two commodity cycles. The nominal values were adjusted for inflation into real values using historical US inflation rates calculated from the consumer price index. The real growth of the value of polymetallic nodules was calculated using deflated yearly averages of the respective commodity prices.

2.2.2. Deterministic and probabilistic model

The deterministic models are based on spot prices and deflated, historical moving averages. To reduce the erratic fluctuations in commodity prices over time, a moving average calculates the mean over x years. For this article, one-year averages, five- and ten-year moving averages were calculated. The probabilistic models used the minimum and maximum values of the respective time series as minimum and maximum values of a uniform probability distribution.

Table 1
Manganese substitution.

Type of manganese	Total annual market (10^6 t)	Assumed market share (%)	Manganese production (10^3 t)
HC FeMn (High-carbon ferromanganese)	4.2	7.7 (delta)[a]	324.0
MC/LC FeMn (Medium-carbon/low-carbon ferromanganese)	1.6	15.0	217.0
EMM (Electrolytic manganese metal)	1.4	15.0	210.0
Total Mn Market[b]	7.2		769.5

[a] EMM & MC/LC FeMn market share penetration is considered maximum. Should production increase over time, the additional EMM will be distributed in the HC FeMn market.
[b] AlloyConsult, 2015.

2.3. Market impact of one mining operation

One mining operation as described in this paper would produce 37.050 × 10^3 t of nickel, 32.400 × 10^3 t of copper and 6.375 × 10^3 t of cobalt annually, representing approximately 2.32 per cent, 0.20 per cent and 7.50 per cent of their respective markets. Because manganese is the most abundant constituent metal in the polymetallic nodules, it is important to understand the market dynamics to avoid significant price changes. Given that all manganese was assumed to be processed into electrolytic manganese metal (EMM), the total EMM market would be too small to absorb these quantities. Therefore, following Cornel's substitution theory to increase the market for EMM, a premium manganese metal was assumed to be sold in lower-quality ferromanganese markets, as shown in Table 1 [24]. Following this approach, which may only be valid for *first-movers*, it was assumed that all metals could be sold and these volumes would not have an impact on commodity prices.

2.4. Financial payment regime

The FPR is defined as a payment to share the economic benefit of the resource with the resource owner in the form of a royalty and a payment to internalize the cost to society of the environmental impact.

2.4.1. Royalty payment

Profit- and economic-rent-based royalties may initially be difficult to implement, especially in a multilateral, international context [25]. Therefore, for the purpose of this article, an *ad valorem* royalty considered by the Deep Seabed Mining Payment Regime Workshop held in 2016, was calculated [26]. Similar to Nyhart and Triantafillou, it was proposed to determine the "fair market value" of the commercially recoverable volumes that have a readily ascertainable market price [27]. An *ad valorem* royalty would be levied on the gross turnover (mouth of mine) calculated using the basket value of the constituent metals' (six-monthly) average price derived from the London Metal Exchange (LME), multiplied by the production of polymetallic nodules of the contractor measured on board the mining vessel within the jurisdiction of the ISA. Although polymetallic nodules contain a significant amount of metals, not all metals can be extracted economically. Three- to four-metal scenarios are commonly discussed (Appendix A). Rarely, more than four metals are extracted, leading to a marginal increase of turnover. When calculating the gross turnover, a 100 per cent yield was inherently assumed, as no reduction was made for inefficient mining and processing technologies. It was suggested that nickel, copper, cobalt and manganese represent a respectable approximation of the gross turnover, leading to the following formula:

$$TO_{(MoM)} = Q_{PN}*((Ni\%_{PN}*NiP_{LME}) + (Cu\%_{PN}*CuP_{LME}) + (Co\%_{PN}*CoP_{LME}) + (Mn\%_{PN}*MnP_{CRU})) \quad (1)$$

In which
$TO_{(MoM)}$ = Turnover at the mouth of the mine (*in situ*)
Q = Quantity mined (tonnes)
PN = Polymetallic nodules
P_{LMEi} = Average price of Ni, Cu and Co on LME (USD $tonne^{-1}$)
P_{CRU} = Average price of Mn through Metal Bulletin or CRU (USD $tonne^{-1}$)
Ni = Nickel
Cu = Copper
Co = Cobalt
Mn = Manganese

According to Jaffe et al., appropriability of technology spillovers is considered a negative externality, which leads to under-provision of new technology that can be overcome with the right policy [28]. Uncertainty on the costs and returns of developing new technology compounds the issue. The cost of capital of a successful *first mover* would be significantly different compared with the *fast follower,* who can free ride and learn from the risk-taking first mover. This may result in a *wait-and-see* position between the contractors. However, since the payment mechanism should attract investment in the Area, two consecutive *ad valorem* royalties representing different phases in the project were suggested during the Deep Seabed Mining Payment Regime Workshop.

Given that a royalty payment would be a recurring income for the ISA in the following decades, an average long-term real social discount rate of 2.27 per cent was assumed, as determined by Drupp et al. [29].

2.4.2. Environmental payment

Environmental degradation (even to the smallest degree), which is a common example of a negative externality, will be unavoidable. Given the environmental consequences of seabed mining being largely unknown, they remain unquantifiable at this stage. As a result, the cost to society of the environmental impact is a major unknown variable in the construct presented here. Different policy instruments such as an environmental liability trust fund, a seabed sustainability fund or an environmental bond have been proposed under a FPR. However, as no details are available on these policies, this article looks into the sensitivities of different levels of a FPR on the economic performance of seabed mining, levied by means of an all-inclusive total-cost *ad-valorem* rate.

2.5. Nickel grade equivalent and C1 cash cost

When comparing nickel mines with different (economically recoverable) by-products, the nickel grade equivalent (NiG_{Eq}) expressing the different by-products in nickel quantities following long-term price relationships, can be calculated. Dick developed the below formula for polymetallic nodules, which was adapted following the different end products considered for this case study (assuming fixed and uniform distribution of different ore deposits or space and time) [30]. Furthermore, the values were updated according to our long-term metal forecasting scenario for this case study (10-year moving average over 32 years).

$$NiG_{Eq} = \frac{Q_{Ni} + \frac{1}{3.5}Q_{Cu} + 3.0Q_{Co} + \frac{1}{10.3}Q_{Mn\ Mix}}{Q_{PN}} \quad (2)$$

In which
NiG_{Eq} = Nickel grade equivalent
Q = Quantity in (dry) tonnages per annum
PN = Polymetallic nodules

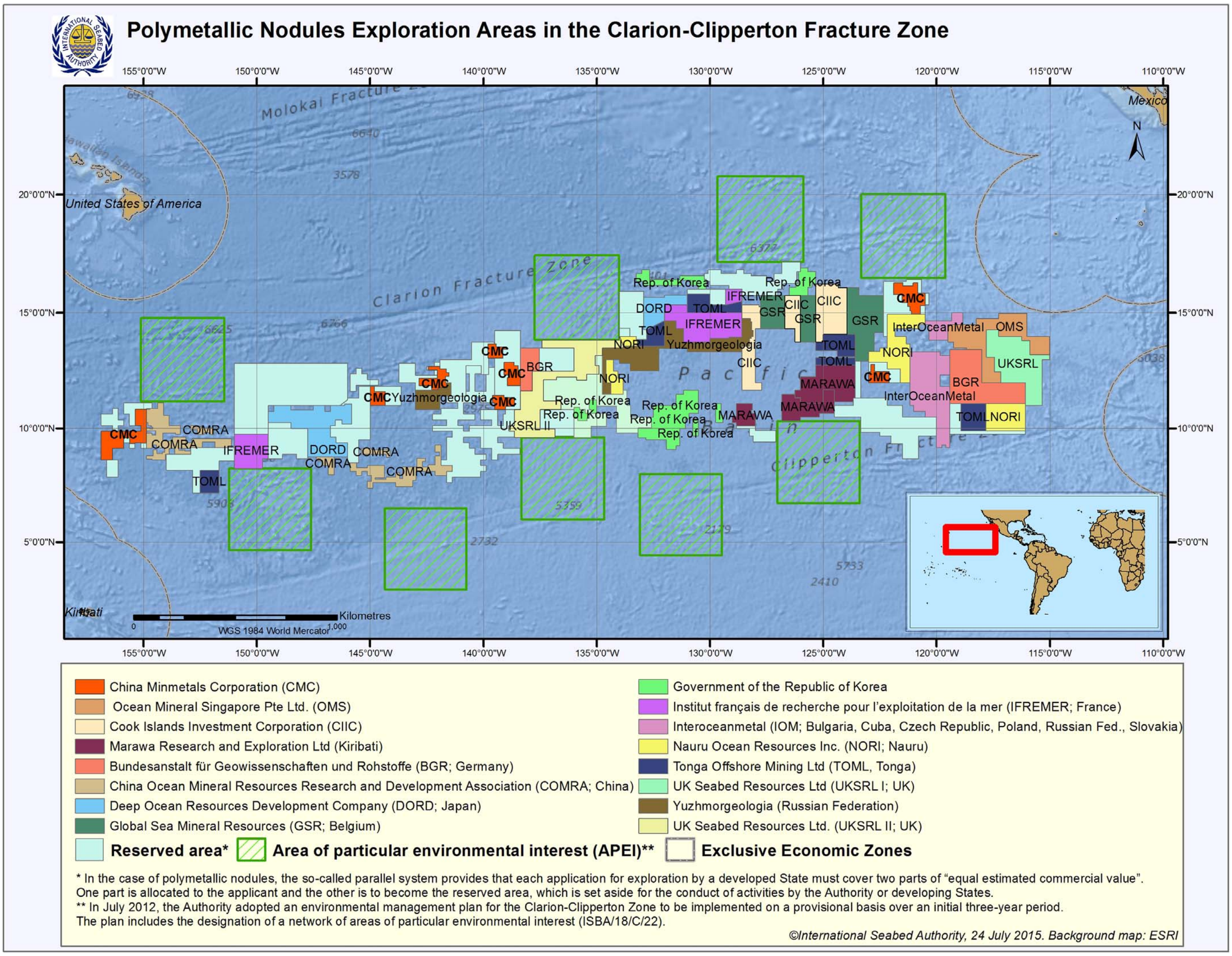

Fig. 1. Polymetallic nodule exploration areas in the Clarion Clipperton Fracture Zone (Reproduced with permission from ISA, 2015).

Ni = Nickel
Cu = Copper
Co = Cobalt
Mn Mix = Manganese mix following substitution of EMM into MC/LC FeMn and HC Mn

To analyse the economic performance (expressed in operational expenditure) a cost curve is often used. Cost curves show the relationship between (cumulative) mine production and operational expenditure. Each bar represents a mine, showing the total annual production of that mine and the cost of production (USD x lb^{-1}) of one pound of nickel. Cost curves can change over time due to variations in factor costs, and are considered the main differentiator when prices are low.

The C1 cash cost represents the total costs minus the revenues obtained from by-products, allowing comparison between the economic performance of different nickel ore deposits with different by-products. Given the number and value of by-products, a C1 cash cost can be negative. To compare the C1 cash cost on the Ni cost curve of 2016, we used the average commodity prices (arithmetic mean) for 2016.

3. Case study: seabed mining in the Clarion Clipperton Fracture Zone

3.1. Project boundaries

To date, the most economically interesting nodules have been found in the Clarion Clipperton Fracture Zone (CCFZ), an area in the North Pacific Ocean (Fig. 1). Historically, most literature on seabed mining projects has compared 1.5 and 3×10^6 tonne of (dry) polymetallic nodules per year of operations. For this article, a 3×10^6 (dry) tonne operation was assumed from the contract area of the Belgian contractor, Global Sea Mineral Resources (GSR) and a net exploitation period of 25 years (excluding PFS, FS and construction period) for the TEA. A tenure of sufficiently long duration can increase economic efficiency and economic benefits to society by incentivising contractors to make the requisite investments and to lower risk.

An overview of the case-study input is provided in Appendix B.

3.2. Exploration and feasibility stage

Similar to land-based mining projects, in order to attract financing for the project's development, it will be necessary to report the stage of the mine development by means of standard reporting templates. As recommended by the ISA, the different development stages follow the International Reporting Template for the public reporting of Exploration Results, Mineral Resources and Mineral Reserves [31]. Understanding these interdependencies is critical when quantifying risk during a new mine development. Following this step-by-step approach, the overall schedule from pre-feasibility to commercial production is expected to be 15 years, as shown in Fig. 2.

During pre-feasibility, a contractor may apply for an exploration

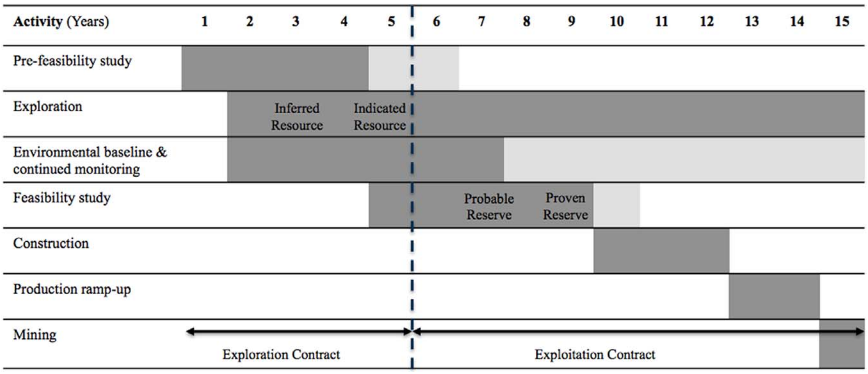

Fig. 2. Project development schedule.

contract for polymetallic nodules in the CCFZ. By organizing survey expeditions, the contractor is able to chart the deposit at 4500 m water-depth using multi-beam survey equipment, autonomous underwater vehicle technology and boxcore sampling. Furthermore, the contractor will be able to take samples *via* Niskin bottles; conductivity, temperature and depth measurements; multi-corer; remotely operated vehicle; epibenthic sled; sediment trap and/or baited camera (traps) to study the biodiversity of the abyssal plain and develop and environmental baseline. The duration of mapping a polymetallic nodule deposit up to a "measured resource" to allow further expenditure, is expected to require three to five expeditions. Once sufficient confidence has been obtained in the presence of a substantial polymetallic nodule field, the contractor may develop and test the technology required to mine and process the nodules, demonstrating not only feasibility but also competitiveness.

Component testing of a collector, a vertical transport system and, finally, system integration tests, will take four to six years. Parallel laboratory tests ranging from 1 to 100 kg day^{-1} during PFS and 1–100 t day^{-1} during FS may be performed to validate the extraction process. Given the high expenditure of the FS, it is expected that an exploitation contract is to be obtained before the feasibility phase can start.

A successful FS would include information on environmental, legal, economic, technological and social modifying factors, allowing the contractor to source funding for the construction of the infrastructure.

3.3. Exploitation stage

3.3.1. Capital expenditure

Various mining techniques have been evaluated over time [32]. For this article, the technical (end-to-end) solution to calculate the capital expenditure, is similar to Nyhart and Triantafillou, and Ingham, which consists of a hydraulic nodule collector, mounted on a tracked undercarriage [27,33]. This mining vehicle will collect the nodules on the seabed, from which they will be transported to the surface using a flexible and rigid steel riser fitted with a series of single-stage centrifugal pumps. The total production will be achieved by a minimum of two independent vessels, each fitted with a complete and independent mining system, allowing for improved operational continuity. The mining vessels stay on site permanently, while the crew vessels and three to four (depending on offloading port) bulk carriers sail back and forth to the offloading port.

Polymetallic nodules are very similar to land-based nickel laterite; consequently, most of the metallurgical processes that have been tried are similar to the techniques used on lateritic ores [34]. The Cuprion process, initially developed by the Kennecott Corporation and demonstrated on a pilot scale in the 1970s, was never commercialised due to a declining interest in deep sea mining, primarily triggered due to a regulatory vacuum and the availability of sufficient terrestrial reserves [35]. However, in comparison to the other methods, it holds promising advantages. With a working temperature of 45 °C, at atmospheric pressure, it is significantly more energy efficient than, for example, the pyro-metallurgical or the high-pressure acid leaching method. Furthermore, it allows for selective refining. No energy is wasted on economically non-viable elements; moreover, no toxic refining products are used during the cycle, and therefore has the potential to be the cheapest and most environmentally friendly refining option [36].

Once nodules have been brought to land, we assume that the Cuprion process is used to retrieve the nickel, copper and cobalt, leaving the manganese in residue ($MnCO_3$). Depending on market conditions, an EMM installation can convert the $MnCO_3$ tailings into manganese metal, with purity levels reaching $>$ 99 per cent.

The total capital expenditure for a vertically integrated consortium is shown in Table 2.

3.3.2. Operational expenditure

Nodule mining is a continuous process and the mining vessels never leave the mining site, unless they are required for a classification survey docking every 7.5 years. However, it will not be possible to mine or transship uninterruptedly. First, the mining and transshipment operation will be limited to a predefined environmental condition. Second, the mining vehicle, riser and pumps are susceptible to both failure and wear and tear. A significant amount of time will be spent on weather delay and planned or unplanned maintenance and repair while the vessel stays on site. The availability of the system has been adjusted based on impacts such as weather (12.1 per cent); maintenance (5.5 per cent); failure of components and systems (10.3 per cent); transshipment delays (5.9 per cent); docking delays (3.6 per cent) and delays due to

Table 2
Total capital expenditure for mining and processing.

Description	Cost (10^6 USD)	(%)
Pre-feasibility phase (Desktop study, exploration, environmental baseline, resource definition)	35.0	0.9
Feasibility phase (System integration tests, environmental impact assessment)	325.0	8.0
Construction of collection system(s) (Collector(s), vertical transport system)	584.0	14.4
Construction of surface vessels(s) (Mining vessel, crew change vessels)	692.0	17.1
Construction of onshore processing plant (Cuprion and EMM plant)	2415.0	59.6
Total cost	4051.0	100.0

Table 3
Operational expenditure offshore mining.

Description	Annual cost (10^6 USD)	(%)
Energy (Fuel & lubricants for mining, crew change & offshore supply vessel and bulk carriers)	43.6	10.7
Labour (Crew, staff)	64.0	21.4
Materials (Consumables, wear & tear)	19.4	6.5
Capital-dependent (Insurance, maintenance & repair)	102.2	33.6
Environment, regulatory and others (Environmental monitoring, charter bulk carrier, charter offshore supply vessel, selling general & administrative expenses, utilities)	95.7	28.0
Total cost	325.0	100.0

Table 4
Operational expenditure onshore processing.

Description	Annual cost (10^6 USD)	(%)
Energy (Electricity cost electrowinning)	424.7	61.7
Labour (Labour, staff)	33.1	4.8
Materials (CO source methane, ammonia, hydrogen, sulphide, sulphuric acid, other reagents)	174.0	25.3
Capital-dependent (Insurance, maintenance & repair)	25.4	3.7
Environment and others (Environmental, tailings disposal)	31.5	4.6
Total cost	688.7	100

logistics (3.5 per cent). The annual availability based on full production capacity is complemented with specific events when production is possible, but at a reduced rate. For instance, this is the case during ramp up and ramp down, or when production is continued with reduced capacity due to a single failed pump in the riser system. The total effective mining availability (capacity utilisation) is therefore 59.1 per cent. Due to the dynamic forces of the steel riser and mining vessel, the average speed of the mining collector is expected to be $0.55\,\mathrm{m\,s^{-1}}$. Based on an initial average nodule abundance of $15\,\mathrm{kg\,m^{-2}}$ (saturated) and a pick-up efficiency of 90 per cent, the approximate collector width will be 15 m.

When the mining vessels' buffer holds are filled, the ore needs to be offloaded onto a bulk carrier. The offloading operation shows a number of similarities with existing operations in the offshore oil and gas industry. The current practice of tandem offloading in the oil and gas industries was found to be the most suitable choice. The mining vessels are fitted with a self-unloading system. This system will transport the nodules from the holds into a fluidizing hopper on-board the mining vessel, from which the water and nodule mixture is pumped into floating pipelines. For this article, it was assumed that bulk-carriers will be sourced from the market and refitted to allow for a dewatering system.

Mining operations will take place at a location nearly 1250 nautical miles offshore. The mining vessels therefore need to be fully self-supporting. A complement of 70 people will remain on board each mining vessel. This includes not only vessel crew, mining operators and maintenance and repair teams, but also personnel responsible for project management, work preparation, survey, quality, health and safety, environment, medical and support.

In the TEA, environmental monitoring is part of the offshore operational expenditures. Given its financial, legal, logistical and operational impact on the operations, it is described here separately. As the environmental regulations remain to be drafted, a description of a detailed monitoring plan seems premature. Nevertheless, one can assume that continuous monitoring and management of the marine environment during deep-sea mining operations to assess potential environmental impacts will be required. This will be in addition to the baseline monitoring needed to establish the initial ecosystem status prior to anthropogenic activities, and post-monitoring activities after the mining activities during the closure phase to determine ecosystem recovery status.

Environmental monitoring during the operation phase will focus mainly on the potential direct and indirect impact of mining operations. The direct impact is considered as the mineable area granted under the environmental permit. The monitoring of the direct impact should confirm the assumption provided in the environmental impact assessment (EIA). The monitoring frequency of the direct impact within the mineable area was expected to be low and spread out over a longer time, mostly after mining operations, to assess recovery status. The monitoring of the indirect impact mostly caused by sediment plumes from the mining operations would ideally be performed in near-real time to inform the environmental management of the mining operations and assess compliance. The assessment of water quality in near real-time will allow adaptive management through monitoring and modelling. The hydrodynamic model setup during the EIA can play an important role in the environmental management of the operation, and as a compliance tool.

The total annual operational expenditure for offshore mining is listed in Table 3.

During the Cuprion process, the nodules enter a solution of "cuprous" ions (Cu^{+}). These ions penetrate the porous nodule structure, reducing the manganese oxide from Mn^{4+} to Mn^{2+}. The reduction of the MnO_2 also disintegrates the nodule, which liberates the other metal oxides locked in the nodule structure [37]. As a second step, the "cupric" ions (Cu^{2+}) are recycled to cuprous ions by adding CO gas.

The $MnCO_3$ can either be sold directly on the market, or be converted further to pure manganese metal through an EMM plant. Today, the EMM process is predominantly carried out in China (98 per cent), with South Africa delivering the remaining percentages. Via electrolysis, the manganese fraction from the dissolved $MnCO_3$ is deposited on a cathode. The metal is regularly removed, and sold in the form of manganese flakes. Electrolysis consumes significant amounts of electricity and therefore represents a major component of the operational expenditure (Table 4) [38]. As a consequence, the location of the processing plant should be capable of providing affordable, renewables-based electricity. The recovery efficiencies of the different metals contained in the nodules are listed in Appendix B.

The total annual operational expenditure for onshore processing is listed in Table 4.

4. Results

The economic performance and its probability in the function of the different commodity forecasts is summarised in Table 5. A 32-year time

Table 5
Economic performance and commodity forecasts.

Nr.	Scenarios	CAGR[a](%)	IRR (%)	Probability A[b](%)	Probability B[c] (%)
1a	**10-year moving average, incl. real growth**	**0.74**	**18.08**	**75.30**	**77.50**
1b	10-year moving average, excl. real growth	0	15.87	69.44	20.23
2a	5-year moving average, incl. real growth	0.74	18.58	82.14	89.58
2b	5-year moving average, excl. real growth	0	16.40	79.28	49.16
3a	1-year average, incl. real growth	0.74	18.16	100.00	100.00
3b	1-year average, excl. real growth	0	15.95	100.00	98.32
4a	Spot prices, incl. real growth	0.74	18.30	65.57	73.43
4b	Spot prices, excl. real growth	0	16.10	57.49	10.55

[a] Compounded annual growth is calculated using deflated one-year averages over 32-year time series.
[b] Probability of achieving IRR.
[c] Probability of IRR > HR (18%).

Table 6
Factor input electricity.

Location	Energy Mix (Nuclear/Renewables/Fossil, %)	Bulk carriers	Cost (USD Kwh^{-1})	IRR[b] (%)
British Columbia[a]	NA / 98.00 / 2.00	4	0.05	18.08
Mexico[c]	3.20 / 18.40 / 78.39	3	0.08	14.50

[a] British Columbia Hydro and Power Authority.
[b] Ten-year moving average, including real growth, Table 5 (1a).
[c] http://www.eia.gov/beta/.

series (1985–2016) was analysed and the yearly averages, the five- and ten-year moving averages were determined. A fourth scenario looked at the economic performance of the project using spot prices on 1 March 2017. All scenarios have been modelled with and without real growth, expressed as the compounded annual growth (CAGR). For the purpose of the MCRA, probability distributions were allocated to different variables, as indicated in Appendix B. Furthermore, commodity forecasts varied each year, using a uniform distribution between the minimum and maximum historical values of each time series, including calculated correlations between commodity prices.

Similar to Johnson and Otto, the impact of the cost of electricity on the IRR was calculated for a processing plant in British Columbia (BC) and Mexico [18]. The electricity in BC is mostly sourced from inexpensive hydro-power; however, due to the longer sailing distance, four (as opposed to three for delivery in Mexico) bulk carriers are required. The results are shown in Table 6, which indicates that the cost of electricity outweighs sailing distance in our IRR analysis.

Assuming pricing scenario 1a (Table 5) and a processing plant in BC, the impact of the variability and uncertainty of a particular input cell (Appendix B) on the economic performance of the base-case scenario was measured. The input values for the base-case scenario are mentioned in the first column. The second and third columns indicate the range of the variable being modelled. The five most important variables determine 85.70 per cent of the variability of the IRR. (Table 7) A 10 per cent change in the annual production may influence the IRR within a range of 4.33 per cent. Given the early stage of the economic model (pre-feasibility), the accuracy of both the capital and operational expenditure of the processing plant (+ / − 25 per cent) have the second- and third-highest impact on the economic performance expressed by the IRR. Being able to ramp up production within the expected two years, and the assumption on the CAGR of the metal prices, would also significantly improve the economic performance. Table 7 outlines the impact of those changes on the IRR. Although the model assumes commodity price variations between deflated historical minimum and maximum values, a sensitivity analysis on its impact was not considered, as commodity prices are considered mean reverting and the probability of the extremes being maintained throughout the project lifetime is low.

Next, different levels of a FPR were considered. Following (Eq. (1)) and assuming pricing scenario 1 (Table 5), the turnover (mouth of mine) was calculated and multiplied by different FPR rates (Fig. 3). In case real growth was not extrapolated, the IRR remains below the HR in

Table 7
Sensitivity analysis of the base-case scenario.

	Input			IRR			
Input Variable	Base Case	Downside	Upside	Explained Variation[a] (%)	Downside	Upside (%)	Range
Production (10^6 tpa)[b]	3.00	2.70	3.30	33.32	16.01	20.34	4.33
Capex processing plant (10^9 USD)	2.42	3.02	1.81	51.89	16.83	20.07	3.23
Opex processing plant (10^9 USD)[c]	0.69	0.84	0.50	66.95	16.98	19.89	2.91
Production ramp Up (Y)	2.00	3.00	1.00	77.01	17.24	19.62	2.38
CAGR (%)	0.74	0.00	0.74	85.70	15.87	18.08	2.21
Corporate income tax rate (%)	25.00	30.00	15.00	92.08	17.41	19.31	1.90
FPR (Light) (%)	2.00	6.00	0.00	94.66	17.27	18.48	1.20
Opex surface vessels (10^9 USD)	0.33	0.41	0.24	97.12	17.71	18.89	1.18
FPR (Full) (%)	4.00	8.00	2.00	98.05	17.59	18.31	0.72
Capex surface vessels (10^9 USD)	0.69	0.74	0.52	98.89	17.93	18.62	0.69

[a] Explained variation is cumulative.
[b] Tpa or tonnes per annum.
[c] Processing plant in BC.

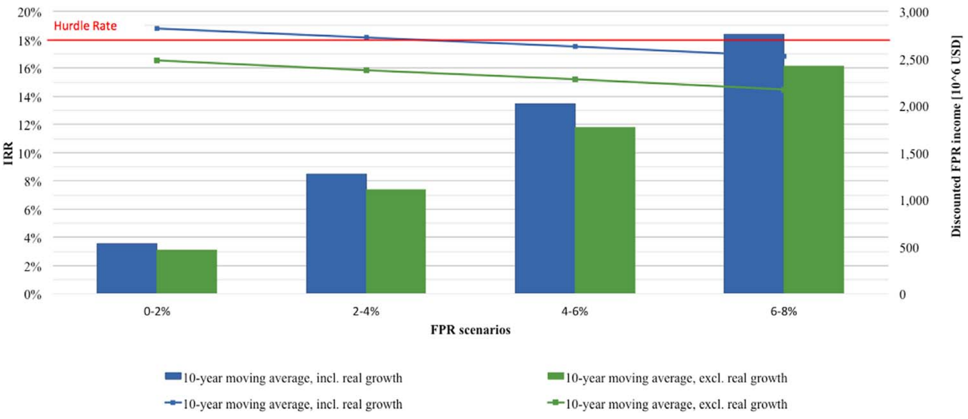

Fig. 3. Impact of different levels of a financial payment regime on the internal rate of return.

all scenarios. However, when real growth was included, the IRR is higher than the HR in the initial two FPR scenarios (0–2 per cent; 2–4 per cent). Given the fact that no information is available on the requirements of an environmental liability trust fund, a seabed sustainability fund or an environmental bond, the FPR is assumed from a total-cost perspective, thereby including a royalty payment, a payment to internalize environmental costs and all other payments that may be due to additional international or national regulation.

Finally, a NiG_{Eq} of 4.67 per cent was calculated using a ten-year moving average. A comparison with the NiG_{Eq} and the C1 cash cost (using 2016 average commodity prices) of terrestrial nickel mines can be found in Appendix E. Both metrics reveal an important economic advantage due to the "polymetallic" nature of the nodule deposit.

5. Discussion

Significant risk remains before a seabed mining venture may take off. However, when the right conditions emerge, seabed mining of polymetallic nodules has the potential to displace some of the high-cost land-based mines. The most important assumptions are production estimates and the capital and operational expenditure of the processing plant. Regulatory costs, including different levels of a FPR comprising of a royalty payment and a payment to internalize environmental costs, have been studied. As royalty mechanisms are designed to reflect different policy objectives, this article provides more insight into the calculation of a transitional *ad valorem* royalty mechanism, balancing progressivity, simplicity and transparency, proposed by the Deep Seabed Mining Payment Regime Workshop held in 2016. A "light" FPR would be applied during a well-defined initial period to implicitly provide the welfare-increasing ("Pigouvian") subsidy that covers the benefits from developing a new technology that are otherwise not enjoyed by the new technology developer (that is, the external benefit). A "full" FPR would be applied in the remaining tenure period when the new technology has been developed, diffused, and adopted, and the risk and uncertainty diminished. Environmental monitoring costs have also been included following marine dredging operations best practices. The results provided in this TEA contribute to the understanding of decision makers and stakeholders involved with the development of the world's first seabed mining exploitation code for the Area.

As an emerging activity, deep-sea mining enjoys the advantage of learning from and applying the experience of established marine industries. Mero [12] called this one of the most important advantages, claiming that a seabed mining venture could be designed from the bottom-up, employing best available technology with the highest standards. Nevertheless, environmental degradation (even to the smallest degree), which is a common example of a negative externality, will be unavoidable. Externalities exist when costs (negative) or benefits (positive) of an activity are not borne by the actor, but by society. The cost to society of the environmental impact is a major unknown variable in the construct presented here. This is due in large part to the environmental consequences of nodule mining in the CCFZ being largely unknown, and hence unquantifiable at this stage. Therefore, the associated environmental costs cannot as yet be presented to society for it to decide on how to allocate the costs and benefits of the activity between it and the actor, and thus the extent to which the environmental costs are to be internalised (that is, borne) by the actor and society in exchange for the benefits of the activity. Bearing in mind that the LOSC as currently drafted envisages that nodule mining will take place under appropriate environmental safeguards, the development of sophisticated regulations that achieve the delicate balance between environmental protection and commercial practicality is essential.

Other externalities, both positive and negative – such as possible strategic access to critical metals (EU policies), capacity building, no social displacement of indigenous people, contribution to marine scientific research, technology spillovers (although the latter is a negative externality for first-movers), and others – remain valid today and will need to be evaluated in an overall cost–benefit analysis.

6. Conclusion

To calculate the probability of achieving a minimum return for an investor in a seabed mining project, eight different commodity forecasting scenarios are modelled based on the base metals nickel, copper, cobalt and manganese and using manganese substitution to increase market potential. The most important variables for a TEA were addressed both qualitatively and quantitatively. Following a ten-year moving average, including real growth of the commodity prices, a 77.51 per cent probability of achieving an IRR higher than the HR of 18 per cent was calculated. For each commodity forecasting scenario, the impact of different levels of a FPR on the economic performance of the project were analysed, and it was concluded that the $IRR > HR$ only in cases where the real growth of commodity prices is included, and up to an FPR rate of 2–4 per cent (from a total-cost perspective, thereby including any additional costs due to international and national regulation). Both the NiG_{Eq} and the C1 cash cost were calculated, both of which exhibited competitiveness compared to conventional terrestrial nickel mines.

Topics for further research may include an assessment of the market impact of the manganese production and distribution following more than one operation as described in this article. Furthermore an overall cost–benefit analysis, including a life-cycle assessment of a seabed mining venture and CO_2 emission per kilogram nickel produced may also be calculated, which would enable comparison with land-based alternatives.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2018.02.027.

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