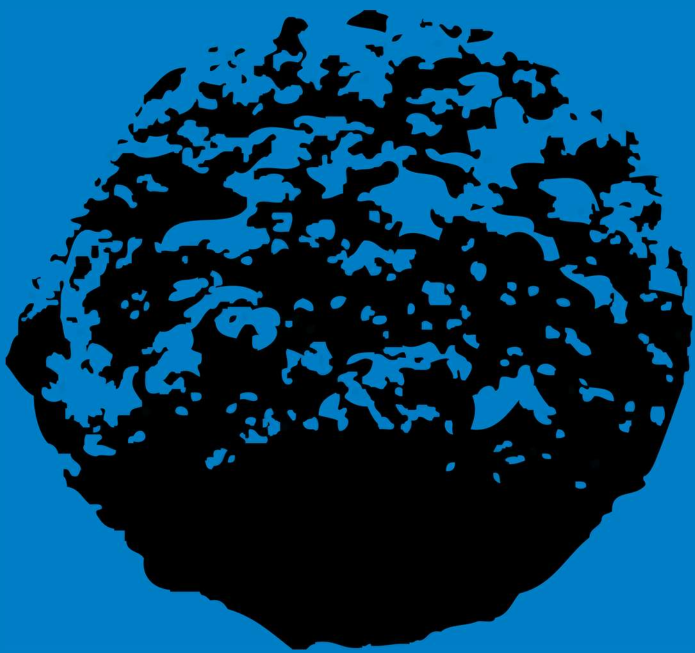
S.E. Volkmann

BLUE MINING

PLANNING THE MINING OF SEAFLOOR MANGANESE NODULES



A THESIS SUBMITTED FOR THE DEGREE DOCTOR OF ENGINEERING

Faculty of Georesources and Materials Engineering,
RWTH Aachen University

Blue Mining—Planning the Mining of Seafloor Manganese Nodules

Von der Fakultät für Georessourcen und Materialtechnik

der Rheinisch-Westfälischen Technischen Hochschule Aachen

zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften

genehmigte Dissertation

vorgelegt von **M.Sc.**

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Tag der mündlichen Prüfung: 29. Oktober 2018

Diese Dissertation ist auf den Internetseiten der Universitätsbibliothek online verfügbar.

Abstract (German)

Manganknollen sind kartoffelförmige Mineralkonkretionen, die weite Teile des Tiefseebodens bedecken. Sie enthalten verschiedene Elemente, darunter Metalle, die in High- und Green-Tech-Anwendungen verarbeitet werden und von strategischer Bedeutung für die europäische Wirtschaft sind. Der Tiefseebergbau bietet Chancen und Herausforderungen. Dennoch fehlt es an Wissen, ihn nachhaltig zu planen und umzusetzen.

Kapitel 1—Die Forschungsfrage ist, wie der Abbau der Manganknollen geplant werden kann. Die Hypothese ist, dass die Prinzipien der Abbauplanung denen des konventionellen, landgestützten Bergbaus und der Landwirtschaft ähneln. Das Ziel der Arbeit besteht darin, Bergbauingenieuren das für die Abbauplanung nötige Grundwissen bereitzustellen. Die Forschung umfasst die Entwicklung geeigneter bergbautechnischer und wissensbasierter Lösungen zur technischen und wirtschaftlichen Bewertung von Bergbauprojekten und Lagerstätten, die Definition von Anforderungen und die Validierung von Annahmen für die Planung. Dies schließt die Entwicklung einer Fachsprache mit ein.

Drei technisch-ökonomische Studien sind im Rahmen der vorliegenden Doktorarbeit zu einem neuen Forschungsgebiet, der ‚räumlichen Abbauplanung', durchgeführt worden. Die Studien basieren auf einer Fallstudie des europäischen Forschungsprojektes ‚Blue Mining', mit Fokus auf das deutsche Lizenzgebiet E1 in der Clarion-Clipperton Fracture Zone, Pazifischer Ozean.

Kapitel 2—Den Studien vorangegangen ist die Recherche von Informationen zum aktuellen Stand von Forschung und Technik sowie zu bereits erhobenen Daten zur Forschungsfrage. Es zeigt sich, dass es für eine zielführende Planung noch eklatante Wissenslücken gibt. So ist die Tiefsee noch weitestgehend unerforscht und Technologien für den Abbau befinden sich noch in einem frühen Entwicklungsstadium. Darüber hinaus gibt es noch kein gültiges Bergbaurecht als Grundlage für die Gewinnung von Manganknollen in internationalen Gewässern. Ebenso sind die Umweltauswirkungen, etwaige Risiken und die Anforderungen an eine nachhaltige Abbauplanung noch unklar.

Kapitel 3—Studie 1 untersucht die technischen Anforderungen eines Abbaus unter Berücksichtigung der Geologie des Tiefseebodens. Eine Technik zur räumlichen Analyse und Formeln zur Berechnung von Produktionskennzahlen werden vorgestellt. Angewandt auf ein von der Landwirtschaft inspiriertes Abbaukonzept, werden Bergbaugebiete identifiziert und charakterisiert. Neben Produktionsraten, Abbau- und Produktionskapazitäten werden andere Kennzahlen wie die Größe der Abbaustandorte und deren Nutzungsdauer geschätzt. Die Analyse zeigt, dass die Geologie des Untersuchungsgebietes ein streifenförmiges Abbaumuster in ausgewiesenen Abbaufeldern begünstigt.

Kapitel 4—Studie 2 befasst sich mit der Untersuchung der wirtschaftlichen Anforderungen für einen kommerziellen Abbau. Neben der Anwendung bekannter Methoden aus dem Landbergbau wird ein Ansatz zur ökonomischen Bewertung von Meeresbodenflächen erforscht. Die durchgeführte ökonomische Analyse zeigt das wirtschaftliche Potenzial einer Gewinnung von Nickel, Kobalt, Kupfer und Ferromangan. Die Preise von Nickel und Ferromangan, die Aufbereitung und Verhüttung des Erzes und die jährliche Produktionsrate sind treibende Faktoren für die Rentabilität, sodass ein Projekt nur unter guten und moderaten Bedingungen profitabel wäre (Tabelle 4.2).

Kapitel 5—Studie 3 untersucht die technisch-ökonomischen Anforderungen und die möglichen Auswirkungen eines Abbaus auf die Ressourcen- und Meeresbodennutzung. Erreicht wird dies durch die Entwicklung und Erprobung eines Abbauplanungstools und einer Bewertungstechnik für Manganknollenlagerstätten. Forschungsschwerpunkt ist die Identifizierung von Meeresbodenflächen von wirtschaftlichem Interesse. Wie die Studie zeigt, sind dies derzeit jene Gebiete mit den höchsten Knollenbelegungsdichten und den höchsten potenziell abbaubaren Anteilen. Aufbauend auf den Ergebnissen dieser Studie können Abbaustandorte ausgewiesen und Umweltauswirkungen ermittelt werden.

Kapitel 6—Die Diskussion zeigt, dass es noch nicht möglich ist, die Forschungsergebnisse im Kontext der Nachhaltigkeit zu interpretieren. Trotz dieser Einschränkung ist es gelungen, geologische, technische, betriebliche, wirtschaftliche und finanzielle Aspekte in einen räumlichen Zusammenhang zu bringen. Dies trägt dazu bei, Abbausysteme und Abbaupläne zu entwickeln oder technisch und wirtschaftlich bewerten zu können. Darüber hinaus werden Parallelen zur konventionellen, landgestützten Bergbau- und Landtechnik im Hinblick auf Maschinen-, Meeresboden- und Ressourcenmanagement deutlich und unterstützen die hier dargelegte Forschungshypothese.

Neben der Beschreibung, wie die aktuelle Arbeit von Industrie, Behörden und Wissenschaftlern genutzt werden kann, werden Empfehlungen zur Auslegung einer Raumordnungspolitik dargelegt. Es wird vorgeschlagen, ein adaptives Management anzuwenden, das versucht, Unsicherheiten im Laufe der Zeit in einem strukturierten und geregelten Prozess des Lernens durch Handeln (engl. *learning by doing*) zu reduzieren.

Abstract (English)

Seafloor manganese nodules are potatolike mineral concretions that cover large parts of the deep-sea floor. They contain various elements, among them metals, that are used in today's high- and green-tech applications, which are considered critical for the European economy. Deep-sea mining offers opportunities and challenges. Still, there is a lack of knowledge in how to plan and execute such projects in a sustainable manner.

Chapter 1—The main research question is how the mining of seafloor manganese nodules can be planned. It is hypothesized that mine planning is similar to the principles of conventional, land-based mining and farming. The main objective of this PhD thesis is to provide mining engineers with the knowledge required for "planning the mining of seafloor manganese nodules." This includes the development of appropriate mining-engineering and knowledge-based solutions to technically and economically assess such projects and deposits, the definition of requirements, and the validation of assumptions for mine planning. This also includes the development of a common technical language.

Three techno-economic studies were carried out on a new research area called spatial mine planning. The studies were based on a specific case study of the European research project Blue Mining, with focus on the German license area E1, located in the Clarion-Clipperton Fracture Zone, Pacific Ocean.

Chapter 2—Preceding the studies was research of information on the current state of the art of research and technology and on data already collected regarding the research question. It turns out that there are still gaps in knowledge for proper planning. Different research areas raise different uncertainties that must be considered in the studies. While the deep sea is largely unexplored, mining technologies and methods are not yet fully developed, and there is yet no mining code for the exploitation of manganese nodules in international waters. Moreover, the environmental impacts, risks, and requirements for sustainable mine planning and mining are uncertain.

Chapter 3—Study 1 investigates the technical requirements of nodule mining considering seafloor geology. A technique for spatial analysis and formulas for calculating production key figures are developed. Applied to an agricultural-inspired mining concept of the Blue Mining case study, it is demonstrated that mining areas can be identified and characterized. In addition to production rates, mining and production capacities and

other figures such as the size of mine sites and their useful lives are estimated. The spatial analysis shows that the geology of the study area favors a striplike mining pattern in the designated mining fields of a mine site.

Chapter 4—Study 2 investigates the economic requirements for commercial mining. Besides the adoption of known methods from land-based mining, an approach for the evaluation of the costs and revenues (i.e., the profits) of seafloor areas is researched. The economic analysis demonstrates the economic potential of nodule mining for the Blue Mining case study in selling the nickel, cobalt, copper and ferromanganese. The prices of nickel and ferromanganese, the processing and refining of ore, and the annual production rate are driving factors for profitability, potentially making the project profitable under good and moderate conditions (Table 4.2).

Chapter 5—Study 3 investigates the techno-economic requirements and the impacts of nodule mining in terms of resource and seafloor utilization. This is achieved by the development of a spatial mine planning tool and deposit valuation technique exemplified for the Blue Mining case study. A research highlight is the identification of areas of potential commercial interest. These are the largest contiguous areas with the highest nodule abundances and potentially mineable proportions. This achievement may allow one to define mine sites and mining fields and may also be a further step forward in identifying environmental impacts in the deep sea.

Chapter 6—In this chapter the main findings and contributions of the thesis are discussed and summarized. The discussion shows that it is not yet possible to interpret the research findings in the context of sustainability. Despite this restriction, geological, technical, operational, economic, and financial aspects have been successfully brought into a spatial context. This achievement may allow one to develop or to technically and economically assess mining systems and mine plans. Moreover, parallels to conventional, land-based mining and agricultural engineering in terms of machine, seafloor (land), and resource management become evident and support the research hypothesis.

In addition to a description of how the current work can be used by industry, authorities, and scientists, recommendations for the development of a spatial planning policy are presented. It is proposed to apply adaptive management that attempts to reduce uncertainties over time in a structured and regulated process of learning by doing.

Acknowledgments

Although this PhD thesis was accomplished under the framework of the Blue Mining project (GA-no. 604500), its contents in every way reflect the opinion of the author and do not necessarily coincide with the opinion of the consortium, the European Commission (EC), or any other person mentioned in the following.

The author would like to thank his doctoral supervisors, Univ.-Prof. Dr. B. Lottermoser (MRE Institute) and Univ.-Prof. Dr. P. Kukla (EMR Group, RWTH Aachen University, Germany), as well as the European Commission (EC) and the Blue Mining consortia, who made this thesis possible. The author would additionally like to thank Univ.-Prof. em. Dr.-Ing. Dipl.-Wirt.Ing. P. N. Martens, Prof. Dr.-Ing. L. Rattmann and Dr.-Ing. R. Randaxhe (former BBK I Institute, RWTH) for initial project support. The author would particularly like to thank Dr.-Ing. Dipl.-Wirt.-Ing. F. Lehnen (MRE Institute, RWTH) who, as his project supervisor and coauthor of the journal articles comprising Chapters 3, 4, and 5, critically examined the author's research work. The author would also like to thank his colleague M. Rahn (EMR Group, RWTH) for her expert discussions on marine geology.

Furthermore, the author would like to thank the Federal Institute for Geosciences and Natural Resources (BGR, Hanover, Germany) and particularly Dr. T. Kuhn for valuable feedback, for coauthoring (Chapter 5), and for providing and processing exploration data. The author would like to thank Dr. S. Petersen (GEOMAR | Helmholtz Centre for Ocean Research, Kiel, Germany) for a critical review of the introduction Chapter 1, Prof. Dr. A. Vanreusel (research group Marine Biology, Ghent University, Belgium) for valuable feedback on the environmental aspects considered in Chapters 2 and 6, and S. Boel (DEME Group, Belgium) and Dr. S. Knodt (MH Wirth, Germany) for a critical review of the technical and technological parts of Chapter 2. Big thanks go to Dr. Annemiek Vink (BGR) for linguistic support. The author also would like to thank the editors and the anonymous reviewers of the journal articles.

Thanks to my beloved wife, family and friends.

Table of Contents

Nomenclature

List of Abbreviations

Abbreviation	Name
2-D	two-dimensional space
3-D	three-dimensional space
3M	three-metal recovery (Ni, Co, Cu)
4M	four-metal recovery (Ni, Co, Cu, Mn)
5-YR MA	5-year moving average(s)
AUV	autonomous underwater vehicle
BGR	Federal Institute for Geosciences and Natural Resources, Hanover, Germany
CAPEX	capital expenditure(s)
CBM	continuous-line bucket mining system
CCZ	Clarion-Clipperton (Fracture) Zone
Co	cobalt
CoV	coefficient of variance
Cu	copper
DCF	discounted cash flow (analysis)
DSM	deep-sea mining
DPS	dynamic positioning system
DR	discount rate
E1	Eastern German License Area E1, CCZ
EC	European Commission
EIA	Environmental Impact Assessment
EU	European Union
FeMn	ferromanganese
GAP	good, average, poor analysis
GIS	geographic information system
GPS	Global Positioning System
IRR	internal rate of return
IRZ	impact reference zone
ISA	International Seabed Authority, Kingston, Jamaica
JORC	Joint Ore Reserves Committee
LARS	Launch and Recovery System
Li	lithium
LOM	Life of Mine
Mn	manganese
MSP	marine spatial planning
MSV	mining support vessel
MUV	manufactured exports unit value (MUV) index
Ni	nickel
NiEq	nickel-equivalent
NP	net profit
NPV	net present value
NSR	net smelter (processor) return
OPEX	operative expenditure(s) (per annum; p.a.)
PKF	production key figure

PMT	pilot mining test
PRZ	preservation reference zone
PPI	Producer Price Index
PVAF	present value annuity factor
REE	rare earth elements
ROM	run of mine
ROV	remotely operated vehicle
SDG	Sustainable Development Goal
SMnC	seafloor manganese crusts
SMnN	seafloor manganese nodules
SMS	seafloor massive sulfides
SMT	seafloor mining tool
SMP	spatial mine planning
S/SD	sustainability/sustainable development
TC/RC	treatment charge and refining charge
TRL	technological readiness level
UK	United Kingdom
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea.
UNOET	United Nations Ocean Economic and Technology Branch
US	United States (of America)
USGS	US Geological Survey
VTS	vertical transport system

List of Formula Symbols

Symbol	**Name**	**Unit**[1]
α	gross mineable proportion	%
β	net mineable proportion	%
φ	utilization of mineable area	%
ϑ	rotation angle theta	°
η_A	area coverage performance	%
η_C	collecting efficiency	%
η_M	overall mining efficiency	%
η_{MF}	in-field mining efficiency	%
η_T	time efficiency	%
$\eta_{R\,m}$	average recovery rate for metal m	%
$A_M{}^*$	annual consumption of seafloor	km²/a
$A_{TOT}{}^*$	total seafloor requirement	km²
$A_{Crit\,i}$	area excluded from mining by criterion i	km²
A_F	area of mining fields	km²
A_M	mineable area	km²
A_{TOT}	total area	km²
C'_f	specific operating costs to mine field f	$/t
D	duration of mining operation	a
DP_f	daily profit of field f	$/d
e	extraction efficiency	%
g_m	selling price of product containing metal m	$/kg
g_{NiE}	average nickel-equivalent grade	%
MR	mining rate	m²/s
MR_A	annual average mining rate	m²/s

MR_{Max}	mining capacity	m²/s
M''	average nickel-equivalent content	kg/m²
NA	nodule abundance	kg/m², dry
NA_F	average nodule abundance in mining fields	kg/m², dry
NA_M	average nodule abundance in the mineable area	kg/m², dry
NA_{TOT}	average nodule abundance in the total area	kg/m², dry
NP'	net profit per unit of output	$/kg
p_m	selling price of product containing metal m	$/kg
$\hat{p}_{Ni}$	break-even nickel equivalent price	$/kg
P	production rate	kg/s, dry
P_A	annual production rate	t/a, dry
P_{Max}	production capacity	kg/s, dry
$\hat{R}_A$	annual break-even revenue	$/a
R'	revenue per dmt SMnN (sales value)	$/kg, dry
$\hat{R}'$	break-even revenue per dmt SMnN (sales value)	$/kg, dry
R'_{NSR}	net smelter return (NSR) per dmt SMnN	$/kg, dry
$\hat{R}'_{NSR}$	break-even NSR per dmt SMnN	$/kg, dry
$\hat{R}'_{TC/RC}$	break-even TC/RC per dmt SMnN	$/kg, dry
R''	the seafloor's average cash value	$/m²
$\hat{R}_A''$	the seafloor's break-even cash value	$/m²
RSC	resource quantity	t, dry
RSV	reserve quantity	t, dry
RSV_F	in-field reserve quantity	t, dry
RU	resource utilization	%
RU_{Max}	theoretical resource utilization	%
SMT_{Max}	collecting capacity	kg/s
T_A	annual operating time (scheduled)	h/a
$T_{A\,MC}$	annual operating time at mining capacity (measured)	h/a
VTS_{Max}	lifting capacity	kg/s
v	collecting speed	m/s
w	collecting width	m
Y	yield of SMnN	kg/m²

[1] Note that the units listed here are not always used in the formulas; the unit depends on the intended use. The corresponding units are listed in the respective chapters and assigned to the formulas.

List of Unit Symbols

Unit Symbol[2]	Name	Explanation
°	degree	
%	percent	
$, US$	United States dollar	Unless otherwise stated, it refers to US dollars.
$BN	billion dollars	
$M	million dollars	
a	annum/year	Unless otherwise stated, it refers to a calendar year of 365 days.[3]
d	day	Unless otherwise stated, it refers to a

		calendar day of 24 hours.[3]
dmt	dry metric ton	Although equal to "t, dry," this unit is explicitly used for the traded bulk material (SMnN).
dwt	deadweight tonnage	Commonly used to indicate a ship's carrying capacity.
h	hour	Unless otherwise stated, it refers to a calendar hour of 60 minutes.[3]
kg	kilogram	For bulk solids, the information "dry" or "wet" is provided. For metal-containing materials, the metal content is provided.
km	kilometer	
kW	kilowatt	
MW	megawatt	
m	meter	
Mt	million metric ton	For bulk solids, the information "dry" or "wet" is provided.
s	second	See footnote 3.
t	metric ton	For bulk solids, the information "dry" or "wet" is provided.
wt%	weight percent	

[2] SI units are not necessarily used; see footnote 1. Derived units such as m/s (meter per second) or m² (square meter) are not listed.

[3] Note that in the formulas, the operating time is used as specified in the text. The operating time indicates how long a technical device or system is in operation. Derived figures (e.g., the average production rate in "t/h") refer to the operating time (5,000 hours per calendar year; Table 2.2).

List of Tables

List of Figures

List of Formulas

1 General Introduction

This chapter introduces the topic of the PhD thesis, presenting the central research question and objective as well as the opportunities and challenges inherent in deep-sea mining. The structure and research topics of the individual chapters as well as the background and scope of the thesis are outlined.

1.1 Seafloor Manganese Nodules

1.1.1 Opportunities and Challenges

Around 70% of the Earth's surface is covered by the oceans, but their depths are still largely unexplored today. The deep sea is potentially rich in mineral resources such as "seafloor manganese nodules," denoted as SMnN (Hein 2016; SPC 2016; Sharma 2017). "Deep-sea mining" (DSM), which relates to the exploration for and mining of marine minerals (other than petroleum) on the seabed and ocean floor and the subsoil thereof, presents mankind with both opportunities and challenges.

The Opportunities of Deep-Sea Mining

Our planet provides natural resources, among them fuel, metallic, and nonmetallic minerals, that are important for economies and societal progress. However, the mineral deposits eligible for mining are limited and non-renewable (Meinert et al. 2016). Since the beginning of the Industrial Revolution (around 1750), our world has changed rapidly through groundbreaking discoveries and achievements in science, technology and medicine (Folta 2007). Within just one century, the world's population has increased fivefold, from around 1.6 billion in 1900 to 7.5 billion in 2017, and it is expected to reach the 10 billion mark by 2050 (UN 2017b). Many formerly developing countries, such as China and India, are growing rapidly today and aspire to become developed and highly industrialized countries in the vein of Germany, Japan, the US, and the UK—if they are not already (O'Neill 2001; Liu 2015).

The risk of an increasing scarcity of critical mineral resources deemed important for economies and societal progress (Lusty and Gunn 2015; EC 2017), declining ore grades, and increasing costs for exploration, mining, and processing (West 2011; Prior et al. 2012; Calvo et al. 2016) have recently brought the marine mineral resources of the deep sea into strategic focus. Beside seafloor manganese nodules (SMnN) and crusts (SMnC), massive sulfides (SMS) have the highest economic potential (Hein 2016; SPC 2016; Sharma 2017). SMnN are solid concretions of manganese oxide minerals that form on sediment-covered deep-sea plains in all oceans at a water depth between 4,000 and 6,500 m (Hein and Koschinsky 2014; Petersen et al. 2016). Discovered during the HMS Challenger expedition of 1872–1876, they were advocated for as a potential commercial source of metals in the early 1950s by John Mero (Mero 1962).

Generally, SMnN lie loosely on the pelagic sediment (Figure 1.1), usually half buried, but can be completely covered with sediment and are therefore not visible in photos. Size, shape, and texture are highly variable and depend on many factors such as the dominant mechanism of formation and their natural environment. Their surface texture varies from smooth to rough, sometimes with a botryoidal texture on the upper surface. SMnN appear in different sizes—from tiny particles that are only visible under the microscope to large lumps with a diameter of more than 20 cm. Dark brown, almost black in color, they typically vary between 1 and 10 cm and from being almost spherical in shape to ovoid. SMnN grow extremely slowly, at rates of about 1 to 10 mm per million to up to several hundred mm per million years (SPC 2013; Hein and Koschinsky 2014).

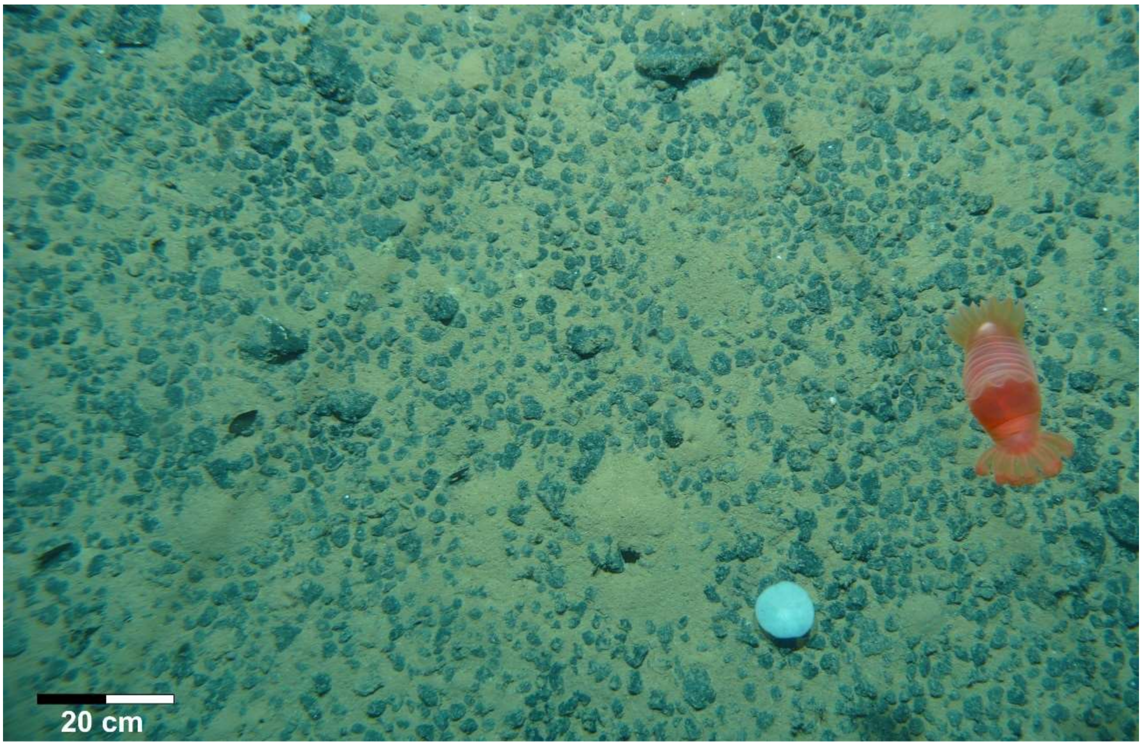


Figure 1.1. Near-distance photo taken from the seafloor located within the German exploration area E1, Clarion-Clipperton Fracture Zone (CCZ), Pacific Ocean (courtesy of BGR).

The Clarion-Clipperton Zone (CCZ), Pacific Ocean, is the occurrence with the highest economic potential (Volkmann et al. 2018b). Their geochemistry is characterized by high contents of iron and manganese (Figure 1.2) and "is associated directly with the geochemistry of underlying and parent sediments, pore water, oceanic water, i.e. with the geochemistry of the ocean as a whole" (Baturin 1988). SMnN contain interesting contents of the metals nickel (Ni), copper (Cu), and manganese (Mn) and critical metals such as cobalt (Co), rare earth elements (REE), tellurium (Te), lithium (Li), and gallium (Ga; Hein et al. 2013). Their use in high- and green energy technologies could make SMnN a promising metal source for expanding economies (Hein et al. 2013; Marscheider-Weidemann et al. 2016). However, their commercial value is speculative as methods to extract SMnN and their metals need further testing (Volkmann et al. 2018b).

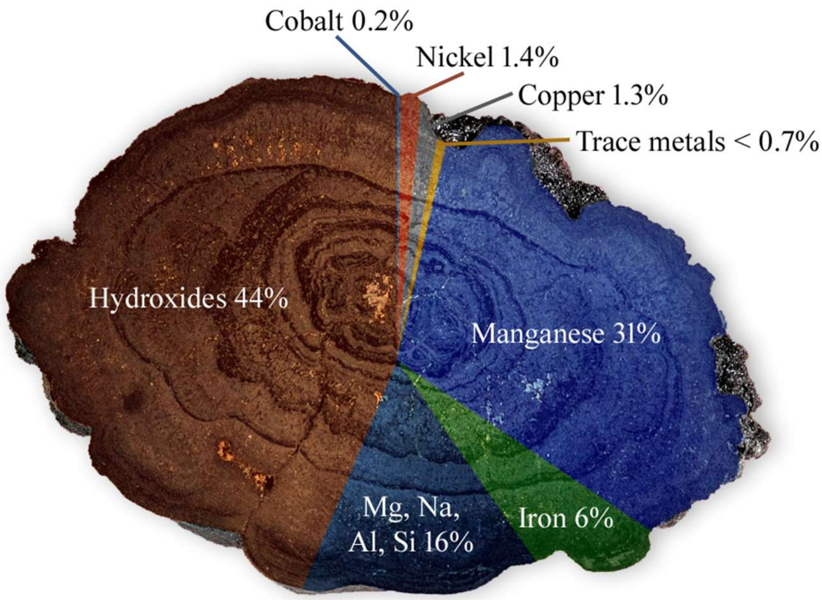


Figure 1.2. Image of a sliced nodule showing the concentric layers. The chemical composition (in wt%) is characteristic of the German exploration area E1, Clarion-Clipperton Fracture Zone, Pacific Ocean (courtesy of BGR). Note that percentages slightly differ from those assumed for the calculations (Table 4.2).

The Challenges of Deep-Sea Mining

The feasibility of SMnN mining was intensively studied in the 1970s and 1980s and led to the first pilot mining tests carried out in the CCZ, Pacific Ocean (Figure 2.1). Falling metal prices, technological advances in land-based exploration and mining, and the onerous provisions imposed by the *U.N. Convention on the Law of the Sea* (UNCLOS) are seen as reasons for the decline in activity (Yates and Gupta 1990; Glasby 2002; Yamazaki and Brockett 2017). Peaking metal prices, advances in technology development, and the adoption of the legal and regulatory framework for the exploitation of SMnN in international waters by the year 2020 could be the reasons companies, governments, and their agencies have entered into exploration contracts and intensified their exploration, research, and development activities in the recent past (Chapter 2).

Although the technologies have not yet attained sufficient technical readiness for DSM, there is still a lack of knowledge of how to plan and execute such projects. SMnN mining poses specific challenges in view of the extreme working conditions in the deep sea compared to land-based mining "such as high operating depth (3–6 km), distance from shore (> 1,000 km), high pressure (300–500 bars), low temperatures (0–10 °C), as well as physical forces like currents, winds and others" (Sharma 2015). Moreover, the techno-economic feasibility still needs to be demonstrated on a commercial scale and in a real environment, while further progress must be made toward sustainable development. On the one hand, effective regulations, monitoring and control systems are required, and on the other, best mining practices have yet to be investigated (Volkmann et al. 2018a).

1.1.2 Research Topics and Questions

Ultimately, engineering and knowledge-based solutions must be researched, developed, and tested. The aim of these activities must be to contribute to a "sustainable utilization" of SMnN. This is the challenge of Blue Mining (Section 1.2).

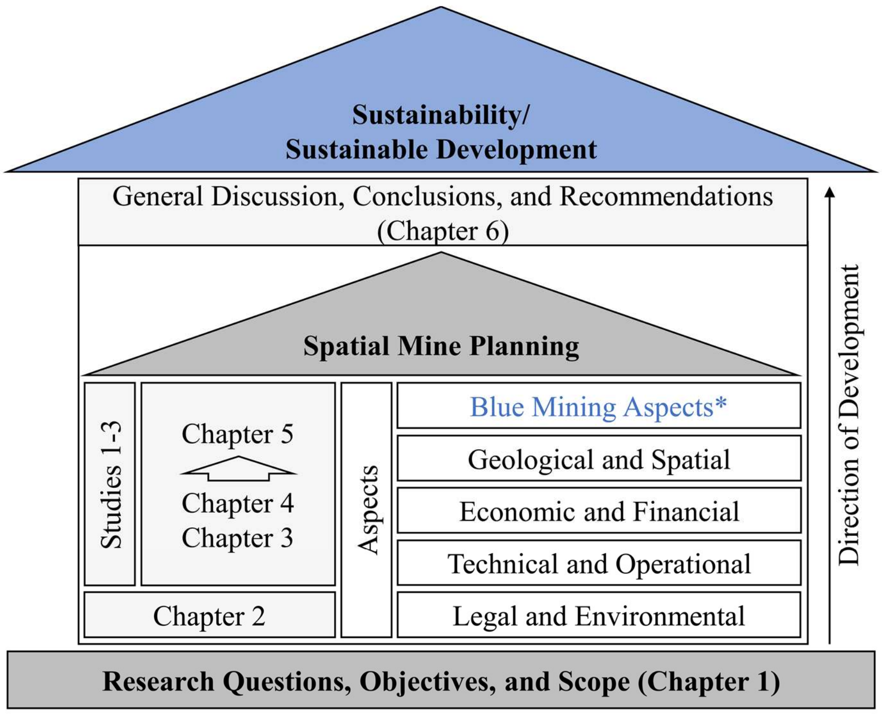
Main Research Question and Objective

The main research question of this thesis is: How can deep-sea mining be planned for SMnN? Due to their spatial distribution, geochemical and physical characteristics, and the technical possibility of harvesting them (Chapter 2), it is hypothesized that mine planning for SMnN is similar to the principles of conventional land-based mining and farming. The main objective of the PhD thesis is to provide mining engineers with the knowledge required for "planning the mining of seafloor manganese nodules"; this includes research into appropriate mining engineering and knowledge-based solutions for the assessment of the techno-economic feasibility of SMnN projects and deposits as well as the definition of requirements and the validation of assumptions for mine planning. Furthermore, this involves the development of a common technical language.

Research Topics and Questions

The PhD thesis consists of six chapters; Chapters 1, 2, and 6 form the framework of the research work (Figure 1.3). Three studies were carried out and are dedicated to a new field of research, referred to as "spatial mine planning" (SMP; Section 1.2.2). The studies are based on a specific case study of the European research project Blue Mining (Section 1.2.1), with focus on the German license area E1 in the Clarion-Clipperton Fracture Zone, Pacific Ocean. The research work presented in these studies is mainly technical and economic in nature and covers a wide range of topics, including geological, technical, economic and financial aspects.

"Study 1" examines the technical, "Study 2" the economic, and "Study 3" the techno-economic feasibility of SMnN mining. The research work is divided into three chapters (Chapters 3, 4, and 5), each dedicated to one of the three studies. Each chapter consists of an introduction, background, methodology, result, discussion, and a conclusion section. The respective background sections contain information related to the Blue Mining project. The discussions of the individual studies focus on the applicability of the methodologies and tools developed and on the validity of the results. The contents, objectives, and research questions of Chapters 2 to 6 are described below.



* Economic-environmental aspects such as seafloor utilization (consumption), and socio-economic aspects, e.g., tax revenues, resource utilization and metal supply, are considered in the studies on the techno-economic feasibility of SMnN mining.

Figure 1.3. Scope and structure of the PhD thesis.

Chapter 2—The studies are preceded by a presentation of research on the current state of the art in research and technology and on data already collected on the research question. This chapter provides a general overview of topics that are not in the focus of research but are considered important for SMP. These are topics such as the legal and regulatory situation and environmental impacts of SMnN mining. Also presented are the state of the art and the mining concept developed within the framework of the Blue Mining project on which this research work is based. This chapter aims to answer the following research questions:

- Which information/data are relevant for mine planning?
- How do the information/data contribute to the research?

Chapter 3—Study 1 examines the technical requirements of commercial nodule mining considering seafloor geology (Volkmann and Lehnen 2017). The research contributes to a mining concept inspired by the high-tech farming industry. Although concepts have been proposed, the adaption of definitions, methods, and practices from agriculture represents the innovation of this work. Potential mining fields are identified and characterized through the use of developed image filters that are applied to exploration maps provided by the Federal Institute for Geosciences and Natural Resources (BGR), Hanover, Germany. Both the mapping technique and the mining concept can be used in techno-economic feasibility studies to calculate production key figures. The most important research questions of this study are:

- Is SMnN mining technically feasible?
- Under which conditions would SMnN be technically feasible?

Chapter 4—Study 2 contributes to the investigation of the economic conditions required to realize commercial SMnN mining under consideration of cost and price trends (Volkmann et al. 2018b). Although the economic viability of SMnN mining was first investigated in the first rush into the deep sea in the 1970s and 1980s, the transfer of knowledge from land-based mining is not yet complete and is a focus of this work. This contribution offers knowledge-based solutions to evaluate the economic viability of SMnN-mining projects. A new approach based on a discounted cash flow model is presented in addition to the determination of economic key figures such as the present value (NPV) or the internal return (IRR). The approach may be used in spatial planning tools for SMnN to investigate the areas of commercial interest. The most important research questions of this study are:

- Is SMnN mining economically feasible?
- Under which conditions would SMnN be economically feasible?

Chapter 5—Study 3 investigates the techno-economic requirements and the impacts of nodule mining in terms of resource and seafloor utilization (Volkmann et al. 2018a). The research covers a whole range of disciplines, from exploration to the financing of a project to the study of its economics. The deep sea is far from explored, and comprehensive planning approaches are lacking. The main innovation of this work is a spatial planning tool to assess the techno-economic requirements and the implications of SMnN mining in terms of resource and seafloor utilization. The spatial mine planning tool may also apply for an assessment of other spatially distributed mineral resources (e.g., marine phosphate nodules) and may contribute to the investigation of the environmental impacts on the seafloor. The main research questions of this study are:

- Is SMnN mining technically and economically feasible?
- Under which conditions would SMnN be technically and economically feasible?

Chapter 6—In contrast to the discussion of the previous chapters, the key findings of the thesis are here discussed in a broader context of sustainability/sustainable development according to Blue Mining's objective (S/SD; Section 1.2). Following the discussion, the most important results and contributions of the thesis, the limitations of current work, and directions for future research are summarized to answer the research question. As the legal and regulatory framework is currently being developed, the thesis concludes with recommendations for the development of a spatial management policy.

1.2 Background and Scope of Research

The thesis deals with a new field of research related to SMnN mining. The new field of research that has emerged within the framework of the Blue Mining project is referred to as "spatial mine planning" (SMP). Eventually part of a feasibility study, "SMP is a process of analyzing and allocating the spatial and temporal distribution of human activities on the seafloor, which are related to a mining project" (Volkmann et al. 2018a). The focus and scope of research in the context of SMP are described below.

1.2.1 The Blue Mining Project

The PhD thesis was accomplished under the framework of the Blue Mining research project (2014–2018), which received funding from the European Commission (GA-no. 604500). The project was carried out by a group of 19 European industry and research organizations with various maritime fields of expertise. The main objective was to provide solutions for a "sustainable" DSM value chain up to a technical readiness level (TRL) of 6 (i.e., system/subsystem model or prototype demonstration in a relevant environment). Research covered different aspects related to DSM, from resource discovery to assessment and from exploitation technologies to the legal and regulatory framework. This included the development of the technical capabilities to adequately and cost-effectively discover, assess, and exploit deep-sea mineral deposits (Blue Mining 2014).

The basis for this thesis was the investigation of the techno-economic feasibility of DSM projects for SMnN and SMS[1] deposits. Techno-economic feasibility implies that a deposit has proven to be economically and technically mineable and that a project has proven economically viable under reasonable assumptions and estimates (JORC 2012). For most land-based mining projects, techno-economic feasibility is a basic requirement to obtain mining permits and financial support. Usually, a feasibility study covers a wide range of thematic areas, from exploration to the financing of such projects and to the study of economics (Mackenzie and Cusworth 2007; AusIMM 2012). In addition to common approaches, sustainability aspects such as resource utilization were considered by Blue Mining research (Volkmann 2014; Volkmann and Osterholt 2017).

1.2.2 Scope of Mine Planning

Similar to mine planning for land-based mining projects (Mahdi and Morteza 2014), SMP covers a wide range of topics, including geological, technical, economic, financial, environmental, and legal aspects. Unlike conventional mine planning, mine planning for SMnN projects requires that these aspects be ultimately placed in a spatial context to create mine plans (Volkmann et al. 2018a). The focus is on strategic planning. In conventional land-based mining, strategic planning is the first stage that defines the overall objectives and framework of a mining project (Hall and Hall 2006; Godoy and Dimi-

[1] Seafloor Massive Sulfides (SMS) are magmatic-hydrothermal systems that formed around submarine volcanic arcs in the deep sea. Other than active systems, which exhale high-temperature, sulfide-rich mineralizing fluids, extinct SMS deposits are inactive systems and are therefore difficult to detect; see, for example, Herzig and Hannington (1995); Hannington et al. (2011).

trakopoulos 2011). Long-, medium-, and short-term production planning is not possible with the available information. In the current work, the investigation of the so-called mineable area is at the forefront of research (Chapter 2).

In line with Blue Mining's objective, this thesis addresses sustainability/sustainable development (S/SD). The so-called Agenda 2030 adopted by the United Nations (UN) commits the world community "to achieve sustainable development in its three dimensions—economic, social and environmental—in a balanced and integrated manner" (UN 2015). However, there is currently no definition of S/SD for SMnN mining. It is uncertain what S/SD implies and how it can be achieved (Chapter 2). The current work focuses on certain key figures suggested by Blue Mining (Volkmann 2014) that are expected to be relevant for future DSM projects (Figure 1.4). In addition to economic aspects (profitability and economic viability), economic-environmental aspects, such as seafloor utilization, and socio-economic aspects, including resource utilization, tax revenues, and metal supply (or mine production), are considered in this thesis.

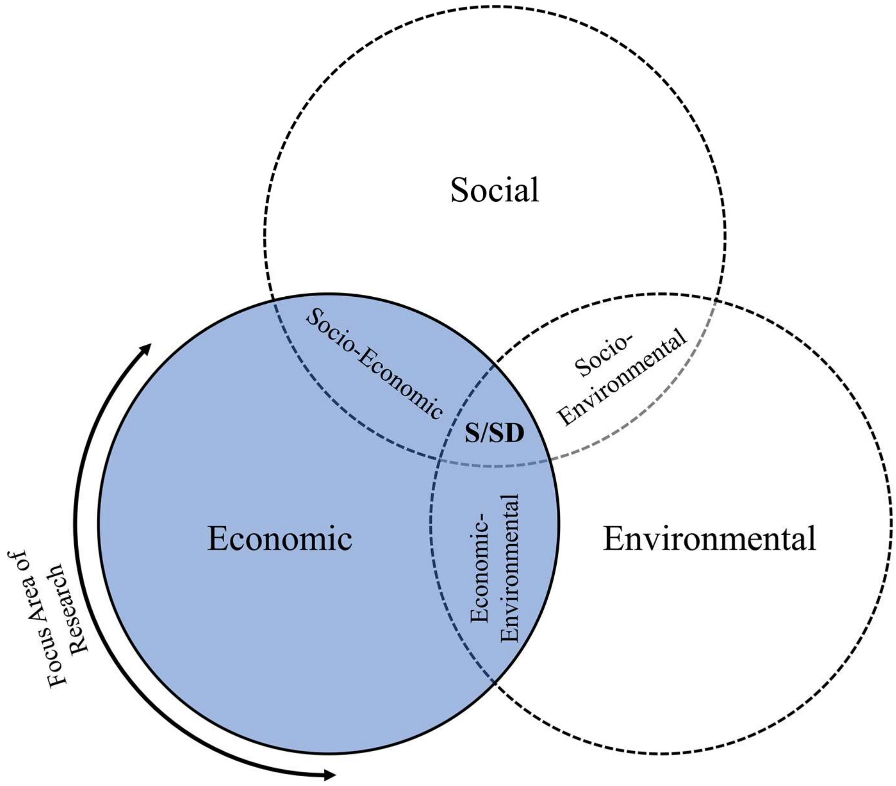


Figure 1.4. Focus area of research in the context of sustainability/sustainable development (S/SD). Economic aspects such as profitability and economic viability, economic-environmental aspects such as seafloor utilization (consumption), and socio-economic aspects, e.g. tax revenues, resource utilization and metal supply, are considered in this thesis.

2 General Overview of the Current Status of Manganese Nodule Mining on the Seafloor

This chapter gives an overview of various topics that are important for mining planning. These are issues such as the legal and regulatory situation and environmental issues that are not the focus of research. Also presented are the state of the art and the mining concept developed within the framework of the EU-funded Blue Mining project on which the follow-up studies are based.

2.1 Legislation and Environment

2.1.1 Mining Legislation

SMnN mining will mostly take place in international waters, on the seabed and ocean floor and the subsoil thereof beyond the limits of national jurisdiction, termed "the Area" (Jenisch 2013). Entered into force in 1994, the *United Nations Convention on the Law of the Sea* (UNCLOS, or "the Convention") defines the rights and responsibilities of currently 167 countries and the European Union with respect to their use of the world's seas and oceans (UNCLOS 1994, 2017). According to the Convention, article 136, "the Area and its resources are the common heritage of mankind," on whose behalf the *International Seabed Authority* (ISA, or "the Authority") shall act (UNCLOS 1994). The ISA, or "the Authority," is an intergovernmental body based in Kingston, Jamaica, which is obliged to organize, regulate, and control all activities in the Area, particularly with a view to administering its resources (Jaeckel et al. 2017).

Implications for Spatial Mine Planning

At present, spatial management is considered on a rather regional scale—that is, for the entire CZZ (Volkmann et al. 2018a). A strategy for a sustainable utilization of SMnN on a project scale that takes into account environmental, economic, and social aspects such as marine spatial planning (MSP) has to be developed and adopted into "the Mining Code" (SPC 2013; Mengerink et al. 2014; Volkmann et al. 2018a). The Mining Code sets the legal and regulatory framework for the prospecting, exploration, and exploitation of marine minerals in the Area. Furthermore, the Mining Code will define the framework for SMP. So far, only prospection and exploration are regulated (ISA 2000);

the exploitation part is at a draft stage (ISA 2017b). The ISA has itself set a 2020 deadline to approve the exploitation part of the Mining Code (ISA 2017c).

As of 2017, sixteen 15-year contracts have been awarded to private or public entities that allow them to carry out exploration work in the CCZ (Figure 2.1; ISA 2017a). The first contracts expire in 2021, including those of China, Germany, France, Japan, Russia, South Korea, and the Interoceanmetal Joint Organization (ISA 2017a).[2] "The Contractor" has the exclusive right to explore an area of up to 150,000 km² but must relinquish half of this area to the ISA over the first 8 years of the contract. An economic equivalent area is reserved to ensure that a nation does not seize the most attractive areas for itself (ISA 2000). Thereby, the ISA complies with the Convention but also supports the United Nations Sustainable Development Goals (SDGs) 9 and 10 (UN 2017a).

According to the Convention, article 140, activities in the Area shall "be carried out for the benefit of mankind as a whole […] taking into particular consideration the interests and needs of developing States and of peoples who have not attained full independence or other self-governing status […]" (UNCLOS 1994). SDG 9 calls to develop infrastructure to "support economic development and human well-being, with a focus on affordable and equitable access for all" and SDG 10 "to reduce inequality" (UN 2017a).

Apart from the contracted and the reserved areas, nine peripheral areas of particular environmental interest (APEIs) have so far been established in the CZZ (Figure 2.1) in accordance with the "Environment Management Plans" (EMP) and "EMP-Strategies" of the ISA (ISA 2016). "The EMP is a proactive spatial management strategy that anticipates mining of polymetallic nodules and that includes the designation of Areas of Particular Environmental Interest (APEIs) […]" (Lodge et al. 2014). An APEI is 400 km × 400 km in size, and its core area is surrounded by a buffer zone of 100 km "to safeguard biodiversity and ecosystem function" (ISA 2008b). With the establishment of APEIs, the ISA complies with the Convention and supports the implementation of SDG 14.

According to the Convention, article 145, the Authority "shall adopt appropriate rules, regulations and procedures" to ensure an "effective protection for the marine environment from harmful effects which may arise from such activities" (UNCLOS 1994).

[2] The Interoceanmetal Joint Organization Countries includes Bulgaria, Cuba, the Czech Republic, Poland, Russia, and the Slovak Republic. With the exception of Germany, all other countries mentioned above entered into the Treaty in 2001.

SDG 14 calls for the "Conservation and sustainable use of the oceans, seas and marine resources for sustainable development" (UN 2017a).

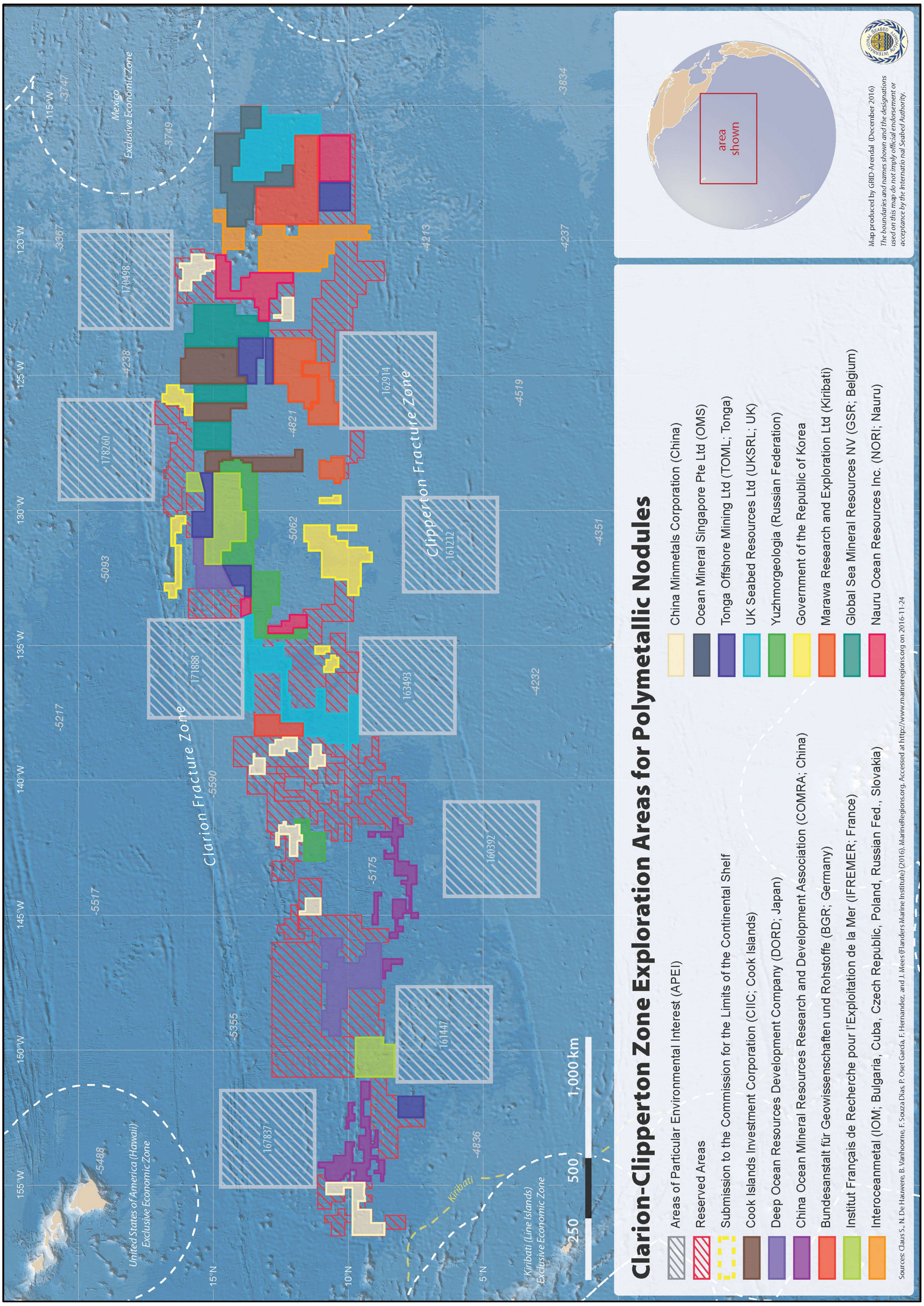


Figure 2.1. Exploration areas for SMnN located in the CCZ, Pacific Ocean, published by the ISA in 2016 (courtesy of ISA; check *www.isa.org.jm* for updates).

While APEIs are located around the contracted areas, the ISA has instigated the contractors' obligation to erect preservation reference zones (PRZ) and impact reference zones (IRZs) in their license area (Wedding et al. 2013; Vanreusel et al. 2016). Protected areas shall be defined "in which no mining will occur to ensure representative and stable biota of the seabed in order to assess any changes in the flora and fauna of the marine environment caused by mining activities" (ISA 2000). PRZs shall be located outside of "areas influenced by the plume," whereas IRZs shall "be used for assessing the effect of activities […] on the marine environment" (ISA 2000).

In land-based mining, most regulatory agencies require land reclamation and closure plans, which are important parts of feasibility studies (McHaina 2001; Otto 2010). Such plans contain information on how environmental protection will be achieved and how the mine site will be returned to an acceptable state for a prearranged "land use"[3] (Warhurst and Noronha 2000; Garcia 2010). For SMnN mining, there is currently a lack of knowledge to protect, restore, and foster the recovery of the epibenthic fauna. The conservation of seafloor areas is a precautionary approach since "the presence of nodules may still enable the recovery of the local fauna in the long term" (Vanreusel et al. 2016). However, it is not clear at what scale seafloor areas should be protected. Furthermore, criteria have yet to be defined for PRZs (Vanreusel et al. 2016).

2.1.2 Environmental Impacts

While the deep sea is a hostile place for the human species, this extreme environment represents a habitat for a large number of species (Grassle 1989; Duarte 2006; Jobstvogt et al. 2014; Drazen and Sutton 2017). Today, there is still little known about the deep sea, its life forms and their interaction with the environment, and the impacts of DSM (Ozturgut et al. 1981; Thiel 2001; Turner et al. 2017). In the last centuries, numerous experimental tests and studies were carried out on the environmental impact of SMnN mining (Thiel et al. 2001). Most of these studies implied a small-scale disturbance of the seabed to simulate the mining process—for example, by using a plough or rake, followed by continuous observation and investigation on the effects on the pelagic and benthic biota (Ozturgut et al. 1981; Foell et al. 1990; Fukushima 1995; Schriever et al. 1997; Trueblood et al. 1997; Shirayama 1999; MIDAS 2016a).

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[3] As in land-based mining, this may include the reclamation, remediation, rehabilitation, and restoration; see Vymazal and Sklenicka (2012). The term *land use* is used here to illustrate the similarity with mining and agriculture on land, although in this context, the use of the seafloor is meant.

Implications for Spatial Mine Planning

The estimation of the affected seafloor area will be a key part of SMP. At the time being, the effects of these impacts on the benthic ecosystem and the "impacts and effects of mining surrounding the directly mined area are poorly understood" (MIDAS 2016a). Relating thereto, it is not possible to define absolute threshold values or to predict the severity of impact (MIDAS 2016a). According to MIDAS (2016a),[4] it can be distinguished between direct and indirect mining impacts.

Direct impacts would be caused by operating on the seafloor and include the mortality of fauna living on mined substrates, the removal of substrate and thus habitat loss, and habitat fragmentation and modification beside other smaller-scale impacts (MIDAS 2016a). SMnN mining is predicted to directly impact an area about the size of Luxembourg (~2,600 km²) over a period of 20 years (Volkmann and Lehnen 2017). It is assumed that mining leads to significant biodiversity loss, which can be considered permanent due to the low growth rate of SMnN (Vanreusel et al. 2016). Based on observations of former (up to 37 years ago) test sites, it is assumed that it would require decades or more for the soft-sediment fauna and thousands to millions of years for the biota reliant on hard substrates to recover (Glover and Smith 2003; Hannides and Smith 2003; Greinert 2015; Vanreusel et al. 2016).

Indirect impacts would be caused by the resedimentation of particle-laden plumes, generated by operating on the seafloor or by discharging seawater and fines of the dewatering process at sea into the ocean (Oebius et al. 2001). The redeposition of particles impacts the smothering and clogging of structures and tissues, which interferes with the feeding mechanisms of pelagic and benthic biota (MIDAS 2016a). These particles can settle over distances of several to hundreds of kilometers, forming a thin sediment layer that may overlap and suppress the benthic ecosystem (Sharma 2013; MIDAS 2016b). Furthermore, areas might be indirectly affected "as a result of loss or degradation of seabed habitat or effects on populations of deep-sea fauna within the directly affected areas […]" (MIDAS 2016a). It is expected that these effects are "likely to be particularly relevant where large areas of habitat are affected by a mining operation […] or where incremental loss of habitat occurs […]" (MIDAS 2016a).

[4] The MIDAS project (Managing Impacts of Deep-seA reSource exploitation) was a multidisciplinary research program (2013–2016) funded by the European Commission to investigate the environmental impacts of extracting mineral and energy resources from the deep-sea environment.

2.2 Mining Technology and Method

2.2.1 State of the Art

Technologies from the offshore oil and gas sector and marine mining are the nucleus of DSM (Knodt et al. 2016). The first pilot mining tests (PMTs) were carried out by multinational consortia in the CCZ in the 1970s and 1980s and provided a proof of technical feasibility (ISA 2008a; Chung 2009; Knodt et al. 2016).[5] At that time, three mining concepts were considered: a towed or self-propelled collector in combination with either an airlift or hydraulic pumping system, a continuous-line bucket mining system (CBM) dragging up buckets with a rope or cable, and a modular or shuttle mining system utilizing a dredge-type collector and having the collector ascend by the force of its own buoyancy (ISA 2008a). Contemporary concepts basically built on OMCO's mining concept and include a mining support vessel (MSV) using either an air-lift or hydraulic pumping system (VTS), which is flexibly connected to a self-propelled seafloor mining tool termed SMT (ISA 2008a; Chung 2009; Ecorys 2014; Knodt et al. 2016).

Mining Support Vessel

The mining support vessel (MSV) is the main infrastructure; its main purpose is to support the mining operation taking place on the seafloor of the deep sea. The floating infrastructure must provide space for power supply, accommodation, ore and spares storage, workshops, and other purposes. Thus, the MSV must fulfil various functions not directly related to the mining operation itself. Operating in the midst of the Pacific Ocean requires additional equipment and services for, for example, the shipping of ore, supply, and personnel. At that time, the MSV was at a conceptual stage and not all of the value chain-suited ship components were developed (ISA 2008a; Chung 2009; Ecorys 2014; Knodt et al. 2016). The Hughes Glomar Explorer (Figure 2.2) employed by OMCO in 1976 and 1979 would have met most of today's basic requirements to undertake SMnN mining (Knodt et al. 2016).

[5] The PMTs were carried out by Kennecott Consortium (KCON), Ocean Mining Associates (OMA), Ocean Management Incorporated (OMI), and Ocean Minerals Company (OMCO). Furthermore, two groups of private companies and public agencies, the Association Française pour L'Etude et La Recherche des Nodules (AFERNOD), France, and the Deep Ocean Resources Development Company Ltd (DORD), Japan conducted tests. See ISA (2008a).

Figure 2.2. Photo taken from the Hughes Glomar Explorer employed by OMCO in 1976 and 1979 in the North Pacific. Although the vessel was scraped, it would have met today's basic requirements for DSM (U.S. Government photo; published in Aid et al. 2010).

According to Blue Mining's specifications (Table 2.1), the MSV is about 240 m long and 40 m wide. It consists of a moonpool through which the up-to-5,000-m riser pipe, umbilicals, pumps, and other parts of the vertical transport system (VTS) would be deployed. The derrick and platform holding the VTS must withstand high loads of about 1,200 metric tons and strong sea motion to avoid destructive forces on the mining equipment (Figure 4.2). Larger tools employed in the deep sea would be launched and recovered from deck of the vessel using a heavy lift system (LARS). A dynamic and a global positioning system (denoted as DPS and GPS) are envisaged, which would make it possible to follow the mining at speeds of less than 1 m/s. The MSV is designed to provide accommodation for 89 persons and about 30 MW of electrical power.

The MSV, whether newly built or converted, would need to be equipped with several extras according to the requirements of the process chain (Figure 4.2). The system considered by Blue Mining is designed for an average production of 400 dmt per operating hour and 2 Mt per calendar year. SMnN shall be dewatered and stored in the MSV's hull providing storage for about 40,000 dmt. The double-deck screening process is intended for the dewatering of SMnN, which is widely used in land-based mining. Undersized particles are to be filtered out and pumped back as close to the seafloor as environmentally reasonable. Regulations have yet to be specified. SMnN shall be pumped as slurry to bulk carriers, which arrive at the mine site in a 5-day-cycle. For a one-way distance[6] of 1,800 km, at least two bulk carriers of class Supramax[7] would be required.

Table 2.1. Key specifications of the MSV defined by Blue Mining.

Item	**Value**	**Unit**
Length	240	m
Width	40	m
Power supply (capacity)	30	MW
Ore storage	40,000	dmt
Manning (max)	89	persons
Operating speed (max; mining)	1	m/s
Operating depth (max)	5,000	m
SMTs operated	1 to 2	units
Remoteness (E1 to the western coast of Mexico)	1,800	km

Vertical Transport System

The vertical transport system (VTS) is primarily used for lifting the ore onboard the MSV. It would also provide the mining equipment with energy and enable the transmission of signals. According to the state of the art (ISA 2008a; Chung 2009; Ecorys 2014; Knodt et al. 2016), the VTS basically consists of a rigid riser section the length of several kilometers and a flexible riser section of only a few hundred meters. Further parts are umbilicals, and depending on the technology, pumps and a clump or a material buffer are installed at the riser end. The PMTs carried out in the 1970s and 1980s showed potential for airlift and hydraulic technology, which are yet to attain a TRL for commercial production. Although similar technologies are applied in today's oil and gas drilling and dredging operations, ore properties and the conditions the VTS would be exposed to are different for SMnN (Knodt et al. 2016).

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[6] According to the Blue Mining case study, this is the distance between the western coast of Mexico and the German license area E1.

[7] The maximum load of this class ranges between 50,000 to 60,000 dwt (deadweight tonnage).

The Blue Mining project focused on the study of the lifting behavior and system integration for airlift and pumping technology, including computer simulations and laboratory tests (van Wijk et al. 2016). According to Blue Mining's specifications (Table 2.2), the VTS is designed to lift 400 t of solids on average per operating hour over a vertical distance of up to 5,000 m. Using airlift technology, compressed air is injected at one or even more points of the riser and leads to a reduction of the slurry's density and to a hydrostatic pressure displacement. Using centrifugal pumps, overpressure is generated at several points of the rigid riser by means of an impeller. Six booster stations, each with two centrifugal pumps, are considered at different riser stages (Figure 3.1). However, further testing is required to determine which technology is best suited with respect to costs, reliability, and ease of repair, among other criteria.

Table 2.2. Key specifications of the VTS (pumping system) defined by Blue Mining.

Item	Value	Unit
Max operating depth	5,000	m
Envisaged annual operating time	5,000	h/a
Envisaged annual production	2	Mt/a, dry
Average production (at 5,000 h/a)	400	kg/h, dry
Lifting capacity	150	kg/s, dry
Number of booster stations	6	units
Number of centrifugal pumps per booster station	2	units
Nominal pump power	500	kW
Total mass	1,200	t

Seafloor Mining Tool

The seafloor mining tool (SMT) is a special type of autonomous or remote-controlled underwater vehicle similar to those used in marine diamond mining, trenching, or cable laying. Similar to an agricultural harvester, its main function is to collect SMnN. SMnN are freed from sediment for economic and environmental reasons. Depending on the concept, the ore is crushed to obtain a reasonable particle size distribution for transportation. The basis of today's most recognized concepts is basically the prototype tested by OMCO at 5,000 m depth on the seafloor of the North Pacific. The remotely controlled, self-propelled SMT used Archimedes screws to travel on the soft bottom sediment and was equipped with a collector device to collect SMnN (Chung 2009).

Since the 1990s, China, India, and Korea in particular have increased their research efforts building upon the findings of the first PMTs carried out in the CCZ. State of the art concepts are self-propelled, crawler-type SMTs with hydraulic, mechanic, or hybrid collectors (ISA 2008a; Chung 2009; Ecorys 2014; Knodt et al. 2016). Of particular note is the SMT termed "MinRo" (mining robot), which was tested in shallow water by the Korean Institute of Ocean Science and Technology (Kim et al. 2013; Yeu et al. 2013; MOF and KIOST 2014). The SMT can be navigated on the seafloor while SMnN are collected hydraulically; it represents one of the most advanced prototypes having been tested. Adopted in this thesis are concepts developed by MH Wirth in cooperation with the BGR (Kuhn et al. 2011) and the partner project Blue Nodules[8] (Figure 2.3).

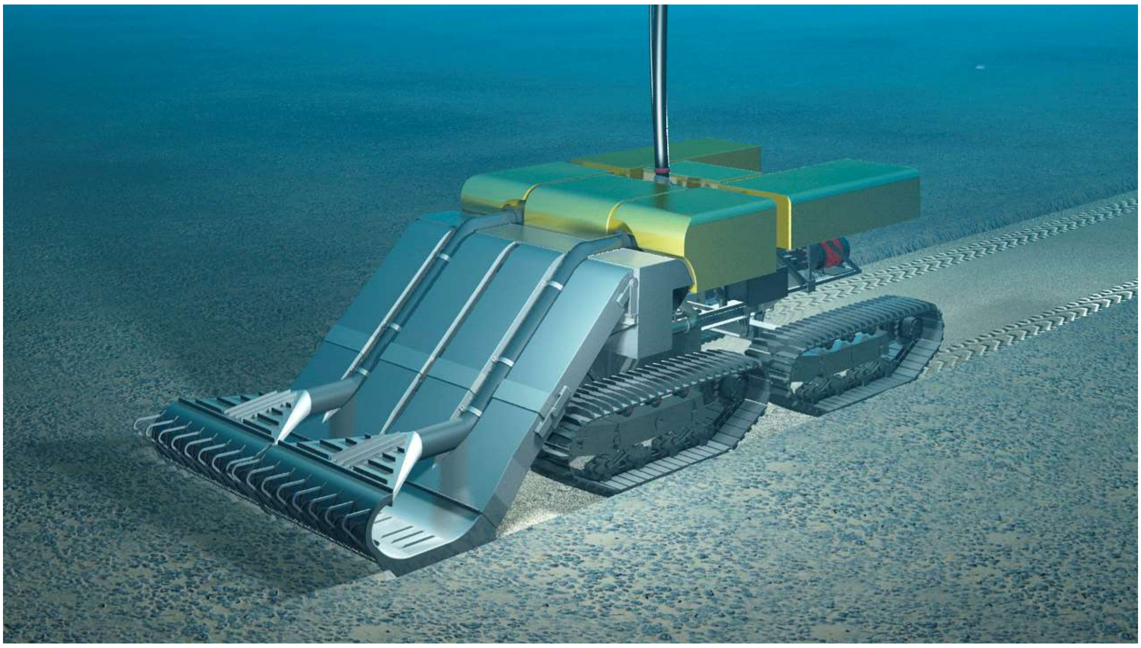


Figure 2.3. An artist's rendering of a seafloor mining tool (SMT) designed by Dutch company Royal IHC to harvest SMnN from the seabed (courtesy of Royal IHC).

For spatial planning and operation, design parameters such as climbing ability, collecting efficiency, and mining and production capacity are important (Volkmann and Lehnen 2017; Volkmann et al. 2018a). Maximum slope angles between 3 and 7°, nomi-

[8] Blue Nodules is an EC-funded research project (2016–2020). The objective of Blue Nodules is the development of a new highly automated and technologically sustainable DSM system for the harvesting of SMnN. For further information, see www.bluenodules.eu.

nal mining speeds in the range of 0.2 and 0.5 m/s, and collecting efficiencies of 80% or even higher have been reported as state of the art (Atmanand 2011; Kuhn et al. 2011; MOF and KIOST 2014; BMWi 2016). Under current economic conditions, an SMT would be at least 15 m wide (Volkmann and Lehnen 2017). Critical design parameters for environmental protection are mainly related to the turbidity generated by operation on the seafloor and the disposal of sediments from the MSV (Amann et al. 1991; Amann and Beiersdorf 1993; Oebius et al. 2001; Knodt et al. 2016).

Table 2.3. Key specifications of the SMT defined by Blue Mining.

Item	**Value**	**Unit**
Number of SMTs	1 to 2	units
Mining capacity	9	m^2/s
Envisaged annual production	2	Mt/a, dry
Envisaged operating time	5,000	h/a
Time/field efficiency	unknown	%
Collecting speed (range)	0.2 to 0.5	m/s
Collecting efficiency	80	%
Min. collecting width (cumulative)	15	m
Max. slope (angle)	3 to 7	°

2.2.2 Blue Mining Method

A mining method is understood as the procedure, technique, or way minerals are mined. Due to the lack of details on mining methods for extracting SMnN, the concept proposed by Blue Mining is presented (Volkmann and Lehnen 2017).

Classification

At the current state, a precise classification of mining methods is lacking for SMnN. At present, the marine mining industry distinguishes between horizontal and vertical mining. In contrast to vertical mining, horizontal mining assumes that a SMT is guided over the seafloor (De Beers 2017). As in land-based mining, it is distinguished here between a continuous and a discontinuous transport of material (Niemann-Delius 2015). Although SMnN mining will not be stationary due to the spatial extent of the deposit, a platform or vessel may be relocated after a certain area has been mined (Section 3.5.4), or it might be continuously in motion following the SMTs. A criterion could be the frequency with which the infrastructure and mining equipment are relocated to proceed in the mine plan. A more precise classification still needs to be elaborated.

Strip Mining

Strip mining is a proposed mining method (Figure 2.4), which is inspired by routines applied in today's high-tech farming industry (Volkmann and Lehnen 2017). Strip-mining can be classified as a horizontal, continuous, and nonstationary mining method envisaged for SMnN. Given its name, the main characteristic is the striplike mining pattern. The concept assumes that, based on the exploration data and project-specific planning parameters, a license area would be divided into several mine sites and mining fields (Figure 3.3). A mining field would be partitioned into strips using SMTs to collect the SMnN from the top sediment layer. The mine design would depend on many factors, including "the Mining Code" and the site-specific characteristics of the seafloor as well as on project-specific technical and economic factors.

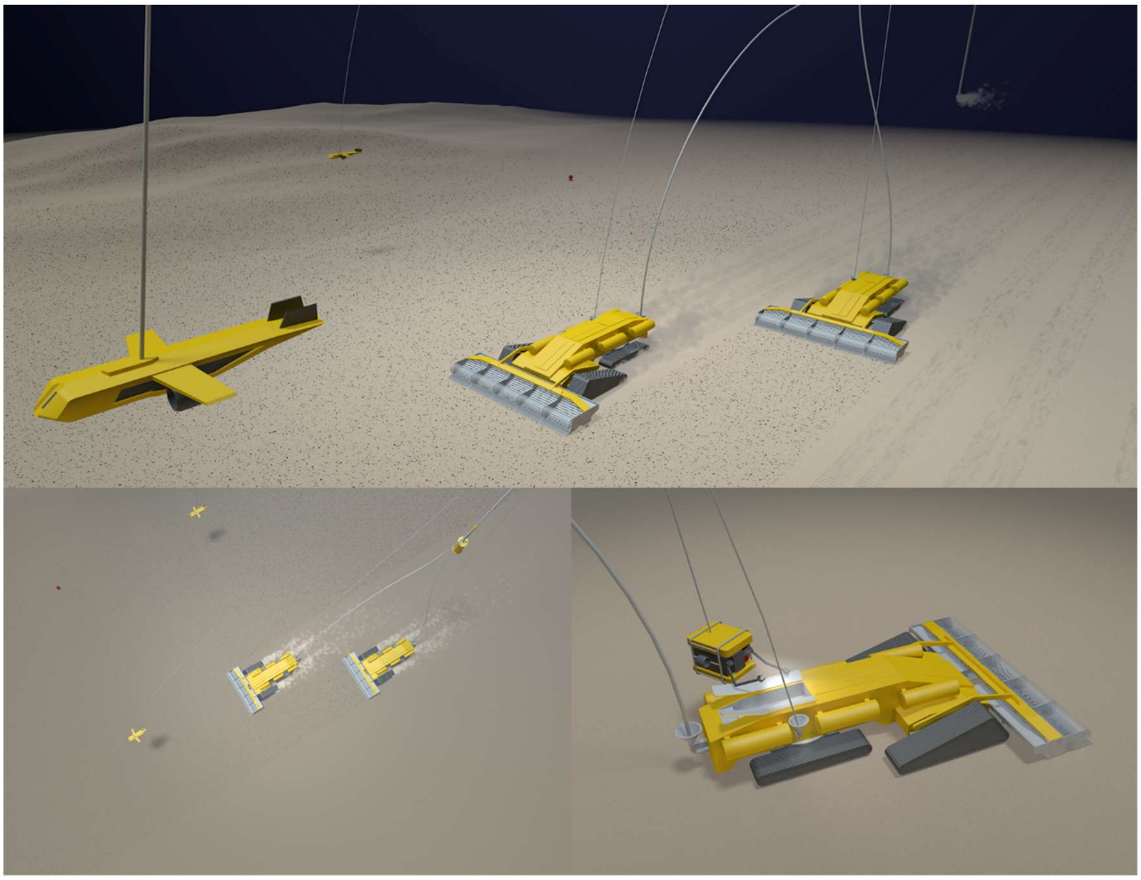


Figure 2.4. An artist's rendering on what deep-sea mining might look like. SMnN are collected by using one or two crawler-type SMTs. Several types of AUVs/ROVs assist the mining operation (e.g., by gathering high-resolution information on the characteristics of the seafloor).

The seafloor is anything but flat, and not all seafloor areas would be eligible for mining (Volkmann and Lehnen 2017). Where in agriculture in-field obstacles are constructions, trees, and infertile soil or rocks, in SMnN mining these would be, for instance, underwater mountains, cliffs, or potholes (Figure 2.5). Unlike in farming, where the soil is cultivated, the operator would have to accept the environment. Generally, the harvest would be carried out in areas where mining would be legally, technically, and economically feasible (Volkmann and Lehnen 2017; Volkmann et al. 2018a). Due to their low growth rate, SMnN can only be mined once per million years, whereby these mining areas may be revisited or remined to improve resource utilization (Chapter 6).

A detailed planning of mining activities is currently not possible from the exploration data available. Exploration surveys, which would provide a resolution of up to a few meters, and a sufficient geological confidence (indicated resource; error 10%–20%) are expensive. The exploration of an area corresponding to the size of the study area (approximately 1,000 km²; Figure 5.2) would take about 30 days and would cost around EUR 1 to 2 million in total (BGR unpublished data). It is therefore assumed that the seafloor would be mapped in high resolution during operation used to update mine plans and routes.

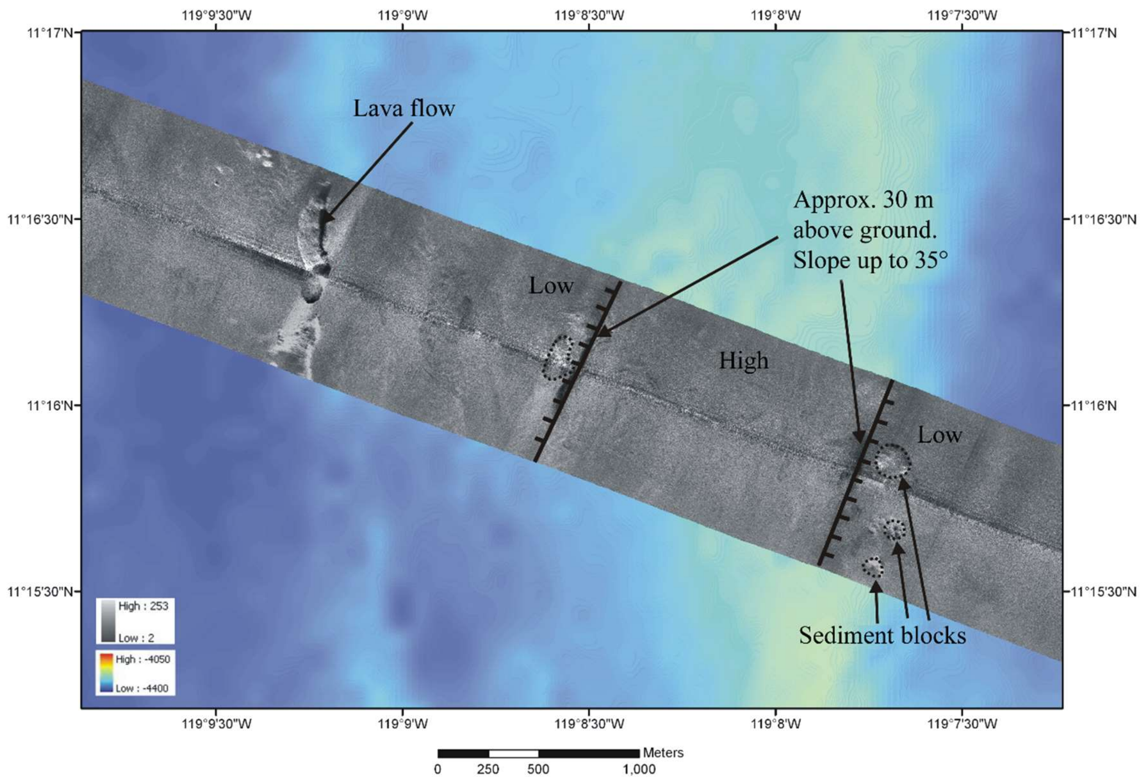


Figure 2.5. High-resolution backscatter image showing the bathymetry of the seafloor taken in the eastern German license area E1 (courtesy of BGR).

Future SMP will have to deal with activities such as the definition of mine sites, mining fields, and mining routes. Although the investigation of mining routes is not a focus of the current work, it is proposed that the mineable area serves as a basis for subsequent planning (Figure 2.6). The mining route is assumed to be projected into a two-dimensional mine plan (Volkmann and Lehnen 2017). As in farming (Poncet et al. 2016), the route is expected to be influenced by site- and field-specific factors, including the shape and size of a field, the number, size, and spatial distribution of in-field obstacles, and the nodule abundance, among other factors (Volkmann and Lehnen 2017; Volkmann et al. 2018a). Metal grades can be neglected during mining, whereas nodule abundance can vary over a few hundred meters (Volkmann and Lehnen 2017).

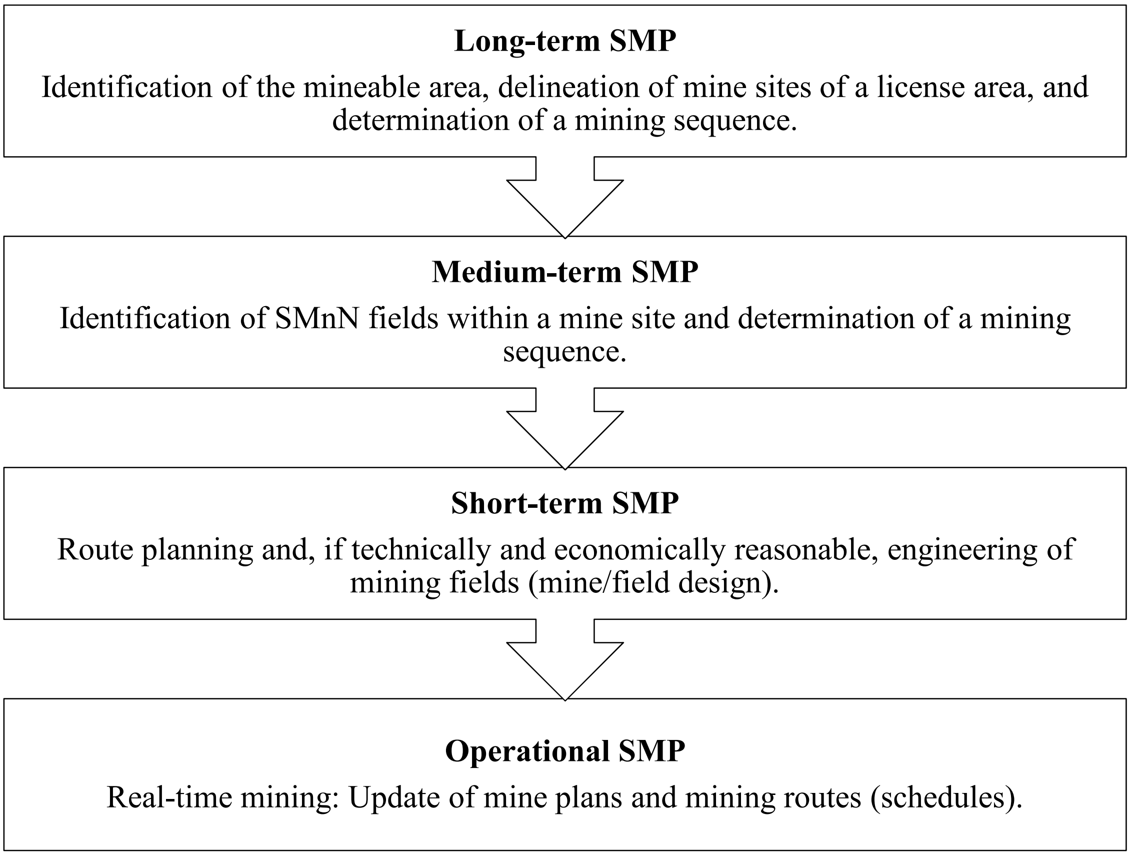


Figure 2.6. Proposed classification concept of spatial mine planning for SMnN mining.

In this thesis, a mining field is assumed to be bulk-mined[9] before moving to another field (Volkmann and Lehnen 2017). SMnN may be harvested by starting at one site of a field developing forward to another (Appendix; Figure A.7.1). A sweep is a main min-

[9] In SMnN mining, bulk mining refers to harvesting in contiguous areas without attempting to selectively mine their high-value parts; see Volkmann and Lehnen (2017).

ing direction obeyed in a field. A strip follows a sweep and is characterized by a path, turning points, and a certain width, which depends on the collecting width (Volkmann and Lehnen 2017). The SMTs would travel around obstacles, diverging from the sweep direction for the duration of the maneuver. Situationally, areas might be bypassed even though technically and legally mineable—for example, if they do not provide sufficient nodule abundance or mining rates that lead to a poor production (Volkmann and Lehnen 2017; Volkmann et al. 2018a). Field boundaries could serve as an orientation for the operator and for the determination of the in-field reserve and in-field mining efficiency (Volkmann and Lehnen 2017).

2.3 Conclusions

SMP is a multidisciplinary research that bridges technologies and sciences. Different uncertainties arise from different scientific areas that must be considered. In addition to the lack of regulations for the exploitation of SMnN in international waters as a basis for planning and mining, there are uncertainties regarding the environmental impacts and the protection of nature at the present planning stage. Although the technologies for using SMnN deposits have been continuously developed since the first PMTs in the 1970s, their economic and technical feasibility and environmental compatibility must be tested on an industrial scale and in a realistic environment. In addition, the resolution of exploration maps available today does not allow carrying out detailed mine planning (e.g., long-, medium-, short-term or production planning). In summary, assumptions concerning, for example, the mining method and mine design still need to be confirmed or refuted through research and testing of proper mining technologies and methods.

3 Production Key Figures for Planning the Mining of Seafloor Manganese Nodules

A version of this chapter has been published in Marine Georesources & Geotechnology *and is referred to as Volkmann and Lehnen (2017).*

3.1 Introduction

Even if 70% of our world's surface is covered by water, the deep sea is in many ways the last great unexplored frontier on Earth. However, the oceans hold a veritable treasure of valuable resources. Vast areas of ocean seafloor are covered by loose, metal-bearing nodules about the size of potatoes. Although seafloor manganese nodules (SMnN) were discovered by scientists of the HMS Challenger expedition (1872–1876), it was Mero who advocated these deposits as a possible commercial source of metals in the early 1950s (Mero 1977). Since then, SMnN have been in the focus of numerous research projects especially in the 1970s and 1980s (Knodt et al. 2016). "The first attempt to exploit deep-sea manganese nodules ended in failure as a result of the collapse of world metal prices, the onerous provisions imposed by the *U.N. Convention on the Law of the Sea* (UNCLOS), and the overoptimistic assumptions about the viability of nodule mining" (Glasby 2002). With rising metal prices in the years 2006–2012, the interest in deep-sea mineral resources experienced a renaissance.

Seafloor manganese nodules contain primarily manganese, but also nickel, cobalt, copper, and rare earth elements (Hein 2016). Those deposits may be an important future source of supply for the Western European automotive, metal, and electrical industries to support the expansion of renewable energies and thus contribute to climate protection (Wiedicke et al. 2015; Hein 2016; Marscheider-Weidemann et al. 2016). The International Seabed Authority (ISA) is the organ that is entitled to act on behalf of mankind, having the responsibility to organize and control all mineral-related activities and resources in "the Area" beyond the limits of national jurisdiction (UNCLOS 1994). In that time the EU funded several projects related to deep-sea mining as part of their research and technological development program. The most recent projects are MIDAS (2013–2016), Blue Mining (2014–2018), and Blue Nodules (2016–2020).

While today's mine planning of land-based ore deposits follows methods that are well established (Darling 2011), mining standards for the deep sea have not yet been established. The identification of (potentially) mineable seafloor area is reliant to a project's exploration data. Kuhn et al. (2012) "[…] suggest that hydroacoustic backscatter data in conjunction with slopes less than 3° are indicative of prospective Mn nodule fields." This approach is further developed and refined to identify potentially mineable areas and to define mining fields. Inspired by the high-tech farming industry, additional information is derived regarding mineable proportions, field sizes, and field characteristics. Suitable mining patterns can then be assessed by using production key figures (PKFs). Thus, this paper contributes to the setting of requirements and the validation of assumptions for future mine planning in the deep sea.

3.2 Background

This paper uses background information of the Blue Mining project, which received funding from the European Commission (EC) as part of the 7th Framework Programme for Research and Technological Development. The Blue Mining deposit model for SMnN was prepared by Rahn (2016) on the basis of exploration data provided by the Federal Institute for Geosciences and Natural Resources (BGR).

3.2.1 Blue Mining Concept

Started in February 2014, the EC-funded Blue Mining project (breakthrough solutions for the sustainable exploration and extraction of deep-sea mineral resources) addresses all aspects of the value chain in this field, from resource discovery to production assessment and from exploitation technologies to the legal and regulatory framework. An international European consortium of 19 enterprises and research organizations out of various maritime fields of expertise is jointly investigating sustainable approaches. In the technical part, Blue Mining is focusing on the development of a vertical transport system (VTS). Two different technologies are considered: an airlift and a serial centrifugal pump system. In the case of the airlift system, compressed air is injected at one (or more) points of the vertical riser to reduce the density of the slurry, containing SMnN. Instead of booster stations, as are used for the hydraulic pump system, compressors are installed on deck of the mining support vessel (MSV) to generate compressed air. The VTS is designed for production rates of up to 150 kg/s (dry solids). This should enable annual production rates of up to 2 million dry metric tons of ore.

The Blue Mining concept (Figure 3.1) is based on routines used in the high-tech farming industry. The concept was jointly developed by the following entities: RWTH Aachen University, Royal IHC, MTI, Dredging International (DEME), Ramboll IMS, and MH Wirth.

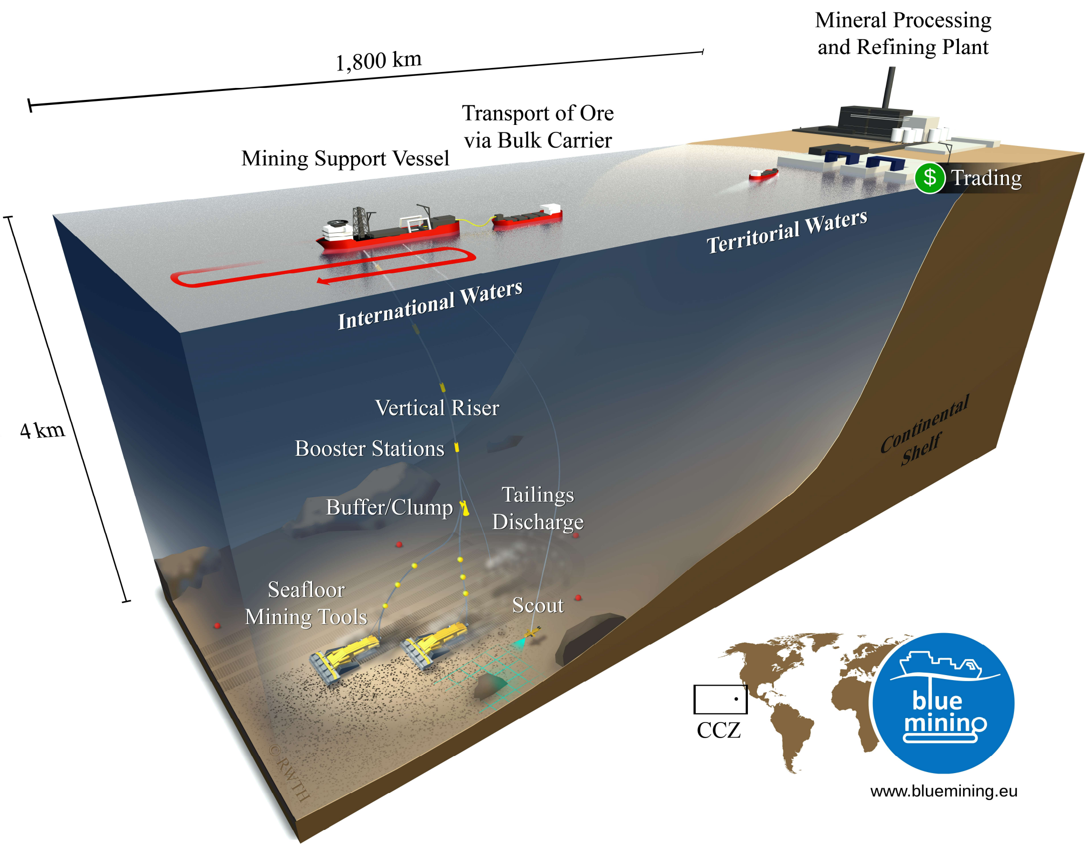


Figure 3.1. Strip-mining concept for SMnN proposed by Blue Mining.

The proposed mining system composes of one or two self-propelled, crawler-type seafloor mining tools SMT(s) and different types of underwater vehicles. Autonomously and remotely operated vehicles (AUVs, ROVs) will be required to execute specific tasks such as salvage of equipment, repair, and maintenance as well as for exploration and environmental monitoring. Mining is planned in designated areas. A striplike mining pattern is considered whereby the MSV follows the mining route of the SMT. SMnN are picked up by the SMT, freed from sediments, and sized. The ore is then hydraulically lifted on board of the MSV as a mixture of seawater and broken SMnN, diluted by a smaller amount of fine sediment. Onboard the MSV, the slurry is dewatered, bunkered, and discharged onto bulk carriers for shipment to the purchaser. Seawater and residual particles from the dewatering process are pumped back close to the ocean floor to reduce the spread of particle-laden plumes and thus environmental impact. The processing and refining of ore is not subject to Blue Mining research.

3.2.2 Deposit Characteristics

The German license area in the eastern part of the Clarion Clipperton Zone (CCZ; 11°00′N, 118°00′W; Figure 3.1) encompasses a total of 75,000 km². The license area is divided into two regions, with 17,000 km² in the central part and 58,000 km² in the eastern part of the Pacific Nodule Belt (Rühlemann et al. 2011). For spatial analysis exploration, data of the eastern German exploration license (E1) have been used. A vessel-based bathymetric survey was executed by the BGR using the swath echo sounding system EM 120 to receive information on the geological properties[10] of the seafloor (Kuhn et al. 2012). "The seafloor is characterized by extensive deep-sea plains interspersed with elongated [NNE-SSW] NNW-SSE oriented horst and graben structures that are several kilometers wide, tens of kilometers long and on the order of hundred meters high […] An analysis of the topography shows that in ~80% of the license area the slope of the seafloor does not exceed 3°" (Rühlemann et al. 2009).

In the framework of the Blue Mining project, a potential mine site within E1 was studied (Rahn 2016). Due to its size (255 km²), the exemplary mine site is assumed to represent the characteristics of a potential mining field (Table 3.1). "The study area is dominantly flat, 94% of the area exhibit a slope of less than 3°, only 6% of the area has a slope larger than 3° with a maximum of 29.86°. The nodule coverage is on average 16.51 kg/m² with a minimum of 10.29 kg/m² and maximum of 21.31 kg/m² (dry weight). The total tonnage of nodules is about 4 Mt with 113,812 t for copper, nickel and cobalt tonnage and 1,171,000 t for manganese" (Rahn 2016).

[10] In the context of marine geology, deposit characteristics are, for instance, the nodule abundance, the metal grades, the slope angle, and water depth.

Table 3.1. Characteristics of E1 (BGR) and of the exemplary mine site of the Blue Mining project (Rahn 2016).

Item	Values		Unit
	German exploration area E1	Exemplary mine site within E1	
Area	58,000	255	km²
Depth	4,200 to 4,300	3,987 to 4,022	m
Nodule abundance[a]	0 to 23.6 (13.7)	10.3 to 21.3 (16.5)	kg/m², dry
Copper, nickel and cobalt grades[a]	1.22 to 3.45 (2.75)	2.58 to 3.13 (2.84)	%
Manganese grade[a]	20.5 to 40.3 (31.3)	- (29.3)	%
Total tonnage of nodules	560	4	Mt, dry
Copper, nickel, and cobalt tonnage	14	0.11	Mt
Manganese tonnage	159	1.17	Mt

[a]Arithmetic mean (average value) in brackets.

Ordinary kriging interpolation was applied to predict nodule abundances on the basis of box core sample data provided by the BGR (Rahn 2016). The created prediction map (Figure 3.2) indicates large continuous areas of nodule abundances between 14 to 16 kg/m² and 16 to 18 kg/m². The chemical composition of the SMnN is relatively constant. The coefficient of variation for nodule abundance is about 7 times higher (0.25) than compared to the coefficient of variation for the combined grade (Co+Cu+Ni) (Rahn 2016). At this planning stage, it is considered to bulk-mine a field irrespective of metal grades.

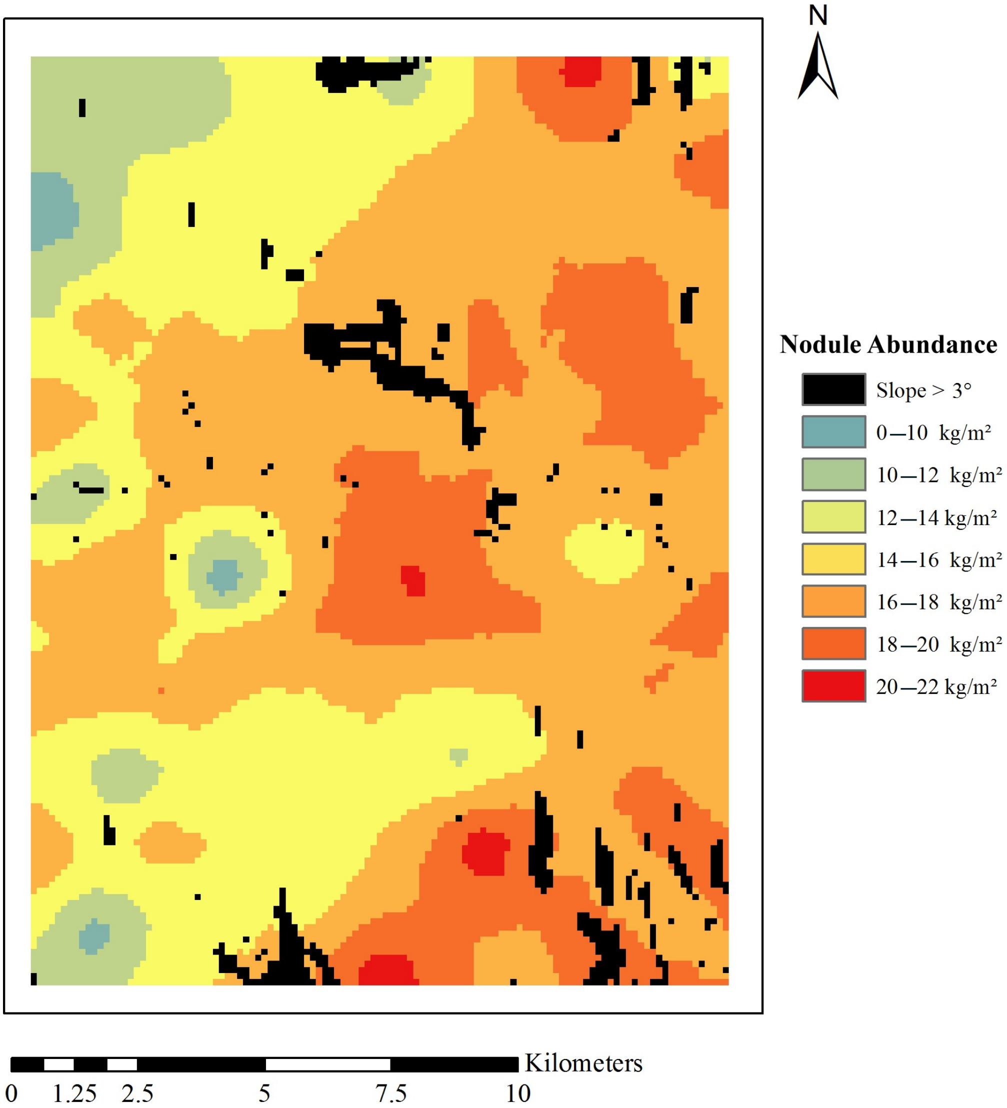


Figure 3.2. Prediction map on nodule abundance after Rahn (2016).

3.3 Methodology

This section provides definitions and develops formulas for the proposed mining concept and production key figures (PKFs) as well as definitions pertaining to spatial (image) analysis. Definitions on the mining capacity, rate, and field efficiency were adopted from the agriculture and high-tech farming industry (Grisso et al. 2000; Hunt and Wilson 2015; Hanna 2016). The approach was then tested for a part of the eastern German license area (E1) in which context PKFs were estimated.

3.3.1 Definitions

Out of the previously described mining concept, certain definitions can be derived. Accordingly, a definition of resources and reserves is formulated. Both groups of definitions are then processed within the calculation of PKFs.

Mining Concept

“Strip-mining” is a proposed mining method for deep-sea mining that involves mining a field partitioned into long, narrow strips, similar to practices in farming as described by Hunt and Wilson (2015). A striplike mining pattern is suggested for harvesting SMnN.

The **“mine plan”** is considered as a map, which shows all relevant information to execute a mining project. Details of the seafloor (e.g., on nodule abundance and grades) are stored as raster data. Accordingly, the seafloor is divided into several raster units. Besides geological information, mine sites, mining fields, and mining routes are outlined (Figure 3.3).

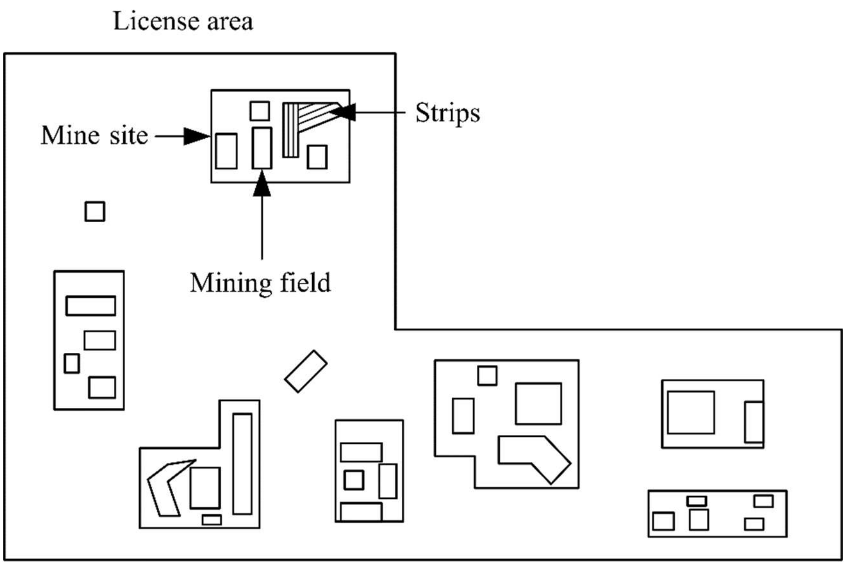


Figure 3.3. Schematic illustration of a mine design for SMnN.

A **“mine site”** is defined as an area on the ocean floor where, under specific geological, technical, and economic conditions, a single SMnN mining operation (one MSV) can be performed for a period of time (UNOET 1987).

A **"mining field"** is defined as the next smaller unit in a mine site. It refers to a continuous mineable area described by a boundary, which defines the "in-field" reserve. Thus, a mine site may contain several mining fields.

A **"strip"** is defined as the next smaller unit within in a mining field. It is characterized by width and a path with a starting point and an end point, representing turning or field entry and exit points of the SMT. SMTs are navigated along predefined mining routes, which reflect the mining pattern (Figure 3.1).

A **"raster unit"** is defined as a quadratic cell of a grid into which the seafloor is divided. It contains information on the area (e.g., obtained from vessel-based bathymetric and near seafloor AUV-based surveys). In this study, grid spacing is restricted by the spatial resolution. Raster units are hereinafter represented by image pixels.

Resources and Reserves

To dimension a corresponding mining system that would best utilize the mineral deposit, SMnN in the potentially mineable area are qualified as potential reserves. However, none of the known SMnN resources has reached the status of a reserve yet. This is due to the lack of economic technological readiness and a missing legal and regulatory framework for the exploitation of SMnN ("the Mining Code"). If not stated otherwise, nodule abundance and metal grades refer to the dry weight. Occasionally nodule abundance is expressed in wet weight per unit surface area. The reduction factor used to arrive at the former is approximately 0.7 (UNOET 1987). Average values refer to the arithmetic mean.

The **"resource"** (RSC) is defined as the quantity of SMnN contained in a particular area (A_{TOT}) with prospect for eventual economic extraction. In general, mineral resources are subdivided into inferred, indicated, and measured resources in order of increasing geological confidence (Rendu and Miskelly 2013). The quantity of SMnN in the area is estimated on the basis of the average nodule abundance and size of the area (Formula 3.1).

$$\boldsymbol{RSC = NA_{TOT} \times A_{TOT} \times 10^3} \qquad 3.1$$

Where:

RSC	= Resource [t, dry]
NA_{TOT}	= Average nodule abundance in the total area [kg/m², dry]
A_{TOT}	= Total area [km²]
10^3	= Conversion from kg to t and from km² to m²

The **"reserve"** (RSV) is defined as the quantity of SMnN contained in the mineable proportion of a particular area (A_{TOT}). In general, a reserve represents the probable or proven mineable share of a mineral resource "[…] taking into account all relevant metallurgical, economic, marketing, legal, environmental, social and governmental factors" (Rendu and Miskelly 2013). Beside general criteria, area-specific criteria apply, distinguishing between mineable and nonmineable seafloor area (Formula 3.5). The quantity of SMnN in the potentially mineable area is again estimated on basis of the average nodule abundance and size of the area (Formula 3.2).

$$\boldsymbol{RSV = NA_M \times A_M \times 10^3} \qquad 3.2$$

Where:

RSV	= Reserve [t, dry]
NA_M	= Average nodule abundance in the mineable area [kg/m², dry]
A_M	= Mineable area [km²]

The **"in-field reserve"** (RSV_F) is defined as the quantity of SMnN contained in the mining fields (A_F). Mining fields are those fields of the mineable area that are actually mined. Expecting a field to be bulk-mined, it is assumed that the average nodule abundance in the field is equal to the abundance in the covered area. The quantity of SMnN in the fields is estimated on basis of the average nodule abundance and the total size of the fields (Formula 3.3).

$$\boldsymbol{RSV_F = NA_F \times A_F \times 10^3} \qquad 3.3$$

Where:

RSV_F	= In-field reserve [t, dry weight]
NA_F	= Average nodule abundance in mining fields [kg/m², dry weight]
A_F	= Area of mining fields [km²]

The **"gross mineable proportion"** (α) is defined as the percentage of the seafloor (A_{TOT}) that meets all criteria of being mineable (Formula 3.4). In image or spatial analysis, the gross mineable proportion is estimated by dividing the number of mineable raster units (cells or image pixels) by the total number of units in the particular area.

$$\boldsymbol{\alpha = \frac{A_M}{A_{TOT}} \times 100\%} \qquad 3.4$$

Where:

α = Gross mineable proportion [%]

The **"mineable area"** (A_M) corresponds to the former definition but is expressed in square kilometers. A raster unit (cell or pixel) may not be mineable due to its economic value, environmental protection, or inaccessibility (water depth, slope or obstacles in that area like cliffs, pot holes and scarps). The approach (Formula 3.5) can be found in another form at UNOET (1987). In this study, exclusion criteria ($Crit\ i$) are based on backscatter data, slope angles, and calculated density values. To avoid multiple counting, the set union is used here instead of the sum of areas fulfilling criteria:

$$\boldsymbol{A_M = A_{TOT} - \bigcup_{i=1}^{n} A_{Crit\ i}} \qquad 3.5$$

Where:

n = Number of exclusion criteria

$A_{Crit\ i}$ = Area excluded from mining by criterion i [km²]

The **"net mineable proportion"** (β) is defined as the percentage of seafloor (A_{TOT}) where mining would actually be performed (A_F; Formula 3.6). In image or spatial analyses, the net mineable proportion is estimated by dividing the number of raster units (cells or image pixels) planned to be mined by the total number in the area.

$$\boldsymbol{\beta = \frac{A_F}{A_{TOT}} \times 100\%} \qquad 3.6$$

Where:

β = Net mineable proportion [%]

3.3.2 Development of Production Key Figures

"Production key figures are used to describe production processes (that is, how much of each component or raw material is consumed during which period, at which location, and in which production process) as well as how much output quantity is produced" (SAP 2014). PKFs considered for planning the mining of SMnN are the production rate, yield per area, duration of mining, seafloor consumption, and requirement. Time and seafloor are consumed during mining, whereas yield and production describe output quantities. Moreover, resource utilization, mining efficiency, and extraction efficiency are calculated. The latter describe how efficient the operation performs and how efficient the mineral deposit is utilized. Thus, these figures refer to key performance indicators.

The **"production rate"** (P) is defined as the dry mass of SMnN recovered per unit of time. It is expressed in kilograms dry solids per operational second. The production rate is controlled by the mining rate, nodule abundance, and collecting efficiency in the area covered (Formula 3.7). Dilution of ore with sediments and transport losses are neglected. The production rate is constrained by the mining capacity (MR_{Max}) and the production capacity (P_{Max}).

$$\boldsymbol{P = NA \times MR \times \eta_C} \qquad 3.7$$

Where:

P	= Production rate [kg/s, dry]
NA	= Nodule abundance [kg/m², dry]
MR	= Mining rate [m²/s], see Formula 3.9
η_C	= Collecting efficiency [%]

The **"production capacity"** (P_{Max}) is defined as the maximum dry mass of SMnN recovered per unit of time. It is expressed in kilograms of dry solids per operational second. It is technically constrained by the lifting capacity (VTS_{Max}) or the collecting capacity (SMT_{Max}). Hereinafter, it is assumed that production is limited by the lifting capacity of the VTS.

The **"annual production rate"** (P_A) is defined as the dry mass of SMnN, in (million) dry metric tons, recovered per calendar year. It is estimated on basis of the average nodule abundance in the mining fields, annual operating time, average mining rate, and collecting efficiency (Formula 3.8). The formula can also be used to determine the required average nodule abundance to meet the production target.

$$\boldsymbol{P_A = NA_F \times T_A \times MR_A \times \eta_C \times 3.6} \qquad 3.8$$

Where:

P_A = Annual production rate [t/a, dry weight]
T_A = Annual operating time (scheduled) [h/a]
MR_A = Annual average mining rate [m²/s], see Formula 3.10
3.6 = Conversion from kg to t and from s to a

The **"mining rate"** (MR) is defined as the effective rate of coverage in square meters per second. It is the product of the effective collecting width and collecting speed during operation (Formula 3.9).

$$\boldsymbol{MR = w \times v} \qquad 3.9$$

Where:

w = Collecting width [m]
v = Collecting speed [m/s]

The **"mining capacity"** (MR_{Max}) is defined as the maximum mining rate in square meters per second. It is obtained when operating at full capacity utilization (i.e., full operating width and full rated collecting speed).

The **"average mining rate"** (MR_A) is defined as the average area mined during the time the machine is committed to the operation. It is estimated on the basis of the mining capacity and annual time efficiency (Formula 3.10).

$$\boldsymbol{MR_A = MR_{Max} \times \eta_T} \qquad 3.10$$

Where:

MR_{Max} = Mining capacity of the SMT(s) [m²/s]
η_T = Time efficiency [%]

The **"time efficiency"** (η_T) "[…] is a percentage reporting the ratio of the time a machine is effectively operating to the total time the machine is committed to the operation" (Hunt and Wilson 2015). Hereinafter, it is referring to the ratio of the annual operating time at full mining capacity to the scheduled operating time (Formula 3.11). Field-to-field travel is counted as productive time when collecting ore.[11]

$$\boldsymbol{\eta_T = \frac{T_{A\,MC}}{T_A} \times 100\%} \qquad 3.11$$

Where:

$T_{A\,MC}$ = Annual operating time at mining capacity (i.e., maximum mining rate; measured) [h/a]

The **"resource utilization"** (RU) is defined as the percentage of SMnN recovered from an area (Formula 3.12).

$$\boldsymbol{RU = \frac{RSV}{RSC} \times e = \frac{Y}{RSC} \times 100\%} \qquad 3.12$$

Where:

RU = Resource utilization [%]

Y = Yield of SMnN [t, dry], see Formula 3.13

e = Extraction efficiency [%], see Formula 3.15

The **"theoretical resource utilization"** (RU_{Max}) is defined and calculated accordingly, assuming an ideal extraction efficiency ($e = 100\%$). It is used in assessing the potential of a given resource against an envisaged production and mining rate.

The **"yield"** (Y) is defined as the quantity of SMnN recovered from an area, expressed in dry metric tons. In agriculture, yield is a measure that refers to the yield of crop per unit of land (Hunt and Wilson 2015). It is here estimated on the basis of the average nodule abundance, size of area, net mineable proportion, and in-field mining efficiency (Formula 3.13). Alternatively, latter could be replaced by the gross mineable proportion and overall mining efficiency.

$$\boldsymbol{Y = NA_F \times A_{TOT} \times \beta \times \eta_{MF} \times 10^3} \qquad 3.13$$

Where:

η_{MF} = In-field mining efficiency [%], see Formula 3.16

[11] The demarcation between field and time efficiency is described in more detail in the Appendix (Additional Contents of Chapter 3: Field Efficiency).

The **"duration of mining"** (D) in one operation is estimated on the basis of the estimated yield and envisaged annual production rate (Formula 3.14).

$$\boldsymbol{D = \frac{Y}{P_A}} \qquad 3.14$$

Where:

D = Duration of mining operation [a]

The **"extraction efficiency"** (e) is defined as the percentage of SMnN recovered from the mineable area. It is thus the relation of yield and reserve. Alternatively, it can be calculated on the basis of the overall mining efficiency, average nodule abundance in the mineable area and in the mining fields (Formula 3.15).

$$\boldsymbol{e = \frac{Y}{RSV} \times 100\% = \frac{NA_F}{NA_M} \times \eta_M} \qquad 3.15$$

Where:

η_M = Overall mining efficiency [%], see Formula 3.17

The **"in-field mining efficiency"** (η_{MF}) is defined as the mining efficiency, in percent, achieved in the mining fields (A_F). It is the product of the area coverage performance and collecting efficiency (Formula 3.16). It indicates the technical and operational efficiency of the extraction process in the mining fields. As a field is intended to be bulk-mined, it is equal to the extraction efficiency in a field.

$$\boldsymbol{\eta_{MF} = \eta_C \times \eta_A} \qquad 3.16$$

Where:

η_A = Area coverage performance [%]

The **"overall mining efficiency"** (η_M) is defined as the product of the technical collecting efficiency, the operational area coverage performance, and the spatial utilization of mineable area (Formula 3.17). Unlike the extraction efficiency (e), it indicates the overall efficiency of the mining process in the mineable area, but independent of where mining is performed and regardless of nodule abundance.

$$\boldsymbol{\eta_M = \eta_C \times \eta_A \times \varphi} \quad 3.17$$

Where:

φ = Utilization of mineable area [%], see Formula 3.18

The **“collecting efficiency”** (η_C) or “pick-up efficiency” is defined as the percentage of SMnN recovered from the seafloor. It is primarily a technical parameter that depends on, among other things, the collecting technique, collecting speed, size, and burry depth of the SMnN (Hong et al. 1999; Yamazaki 2008). The collecting efficiency is assumed to be constant for the scope of this study.

The **“area coverage performance”** (η_A) is defined as the percentage of a designed field actually covered by the SMT. It reflects the accuracy of the operator and the SMT(s) in covering all margins of the planned field while harvesting.

The **“utilization of mineable area”** (φ) is defined as the share of actual mining fields in a generally mineable area. Thus, it indicates the percentage of a mineable area being utilized, taking into account the engineered field design of the mine plan. Accordingly, φ can be calculated as the ratio of the net mineable to the gross mineable proportion (Formula 3.18).

$$\boldsymbol{\varphi = \frac{\beta}{\alpha} \times 100\%} \quad 3.18$$

The **“annual consumption of seafloor”** ($A_M{}^*$) is defined as the required area to yield in a certain annual production rate. It is estimated on the basis of annual production rate (target value), average nodule abundance in the mining fields, and collecting efficiency (Formula 3.19).

$$\boldsymbol{A_M{}^* = \frac{P_A}{NA_F \times \eta_C \times 10^3}} \quad 3.19$$

Where:

$A_M{}^*$ = Annual consumption of seafloor [km²/a]

The **“total seafloor requirement”** ($A_{TOT}{}^*$) is defined as the total area required for carrying out a single mining operation. It is estimated on the basis of the annual production (target) rate, envisaged life of mine, average nodule abundance in the mining fields, net mineable proportion, and in-field mining efficiency (Formula 3.20). Alternatively, the latter could be replaced by the gross mineable proportion and overall mining efficiency. The formula has already been published in a different form (UNOET 1987).

$$A_{TOT}^{*} = \frac{P_A \times D}{NA_F \times \beta \times \eta_{MF} \times 10^3} \qquad 3.20$$

Where:

A_{TOT}^{*} = Total seafloor requirement [km²]

3.3.3 Computational Image Analysis

GIS software applications already provide a wide spectrum of tools to perform spatial analysis, but they do not always allow for modification or require expertise. In this paper, spatial analysis is performed via image analysis of GIS-data. The authors present their own programmed tools—that is, filters involving spatial analysis of an (image) area. The identification of mineable areas and fields follow these steps.

Creating a Binary Image

The presented mapping approach was adopted from methods proposed by Rühlemann et al. (2013) and Kuhn et al. (2012). "High-resolution side-scan sonar data, seafloor photographs as well as box core sampling proved that manganese nodule fields with an abundance of > 10 kg/m² can be distinguished from sediment-covered seafloor areas devoid of nodules using backscatter data" (Kuhn et al. 2012). The "seafloor backscatter" "[…] is defined as the amount of acoustic energy being received by the sonar after a complex interaction with the seafloor. This information can be used to determine bottom type, because different bottom types 'scatter' sound energy differently" (Stuart 2011).

Kuhn et al. (2012) created a binary image on basis of hydro-acoustic backscatter data and slope angles for a part of E1 (Figure 3.4). A "binary image" is a digital black-and-white image. This requires that raster data is translated into binary information. Hereinafter, a valid (white) image pixel represents a mineable raster unit, whereas a non-mineable raster unit is represented by an invalid (black) image pixel. A valid pixel (white; mineable) refers to a backscatter value between 70 and 140 (> 10 kg/m², wet weight) and a slope ≤ 3°. An invalid pixel (black; non-mineable) is outside this range and/or > 3° (Kuhn et al. 2012). The slope angle (in degrees) is derived from raster bathymetry data.

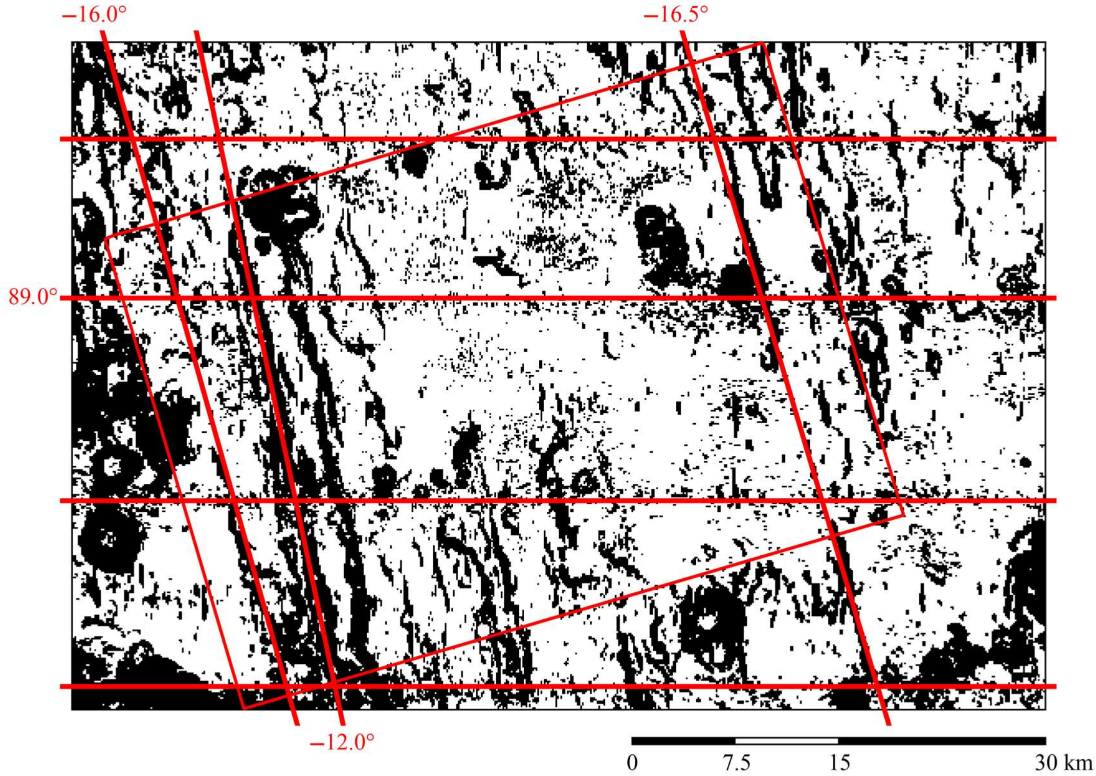


Figure 3.4. Binary image of the bathymetry of the seafloor in a part of E1 analyzed by Kuhn et al. (2012). The inner rectangle indicates the analyzed area. Lines represent interpreted horizontal and vertical image structures.

Within the scope of this study, a part of this area was analyzed (Figure 3.4). The cropped image consists of 416 × 298 pixels, equivalent to approximately 1,800 km². The spatial resolution is given with 120 m × 120 m per pixel. The ore layer is assumed to be uniformly graded.

Image Filtering

The Blue Mining concept requires that continuous areas be identified that would allow mining for a period of time. For this purpose, so-called neighborhood filters were applied to the binary image. In image processing, filtering is a technique for modifying or enhancing an image. Within the scope of this study, custom-made filters were programmed to determine the concentration of valid pixels: A "neighborhood filter" is a moving, overlapping statistical analysis method. A density value is calculated for each valid image pixel, which falls into the search area. Values are translated into grayscale color values. The "search area" is thus the neighborhood of an image pixel and is described by the search distance. The "search distance" is again the distance (DIST) originating from the center pixel to the border pixel (Figure 3.5). The center pixel is not considered in the distance value.

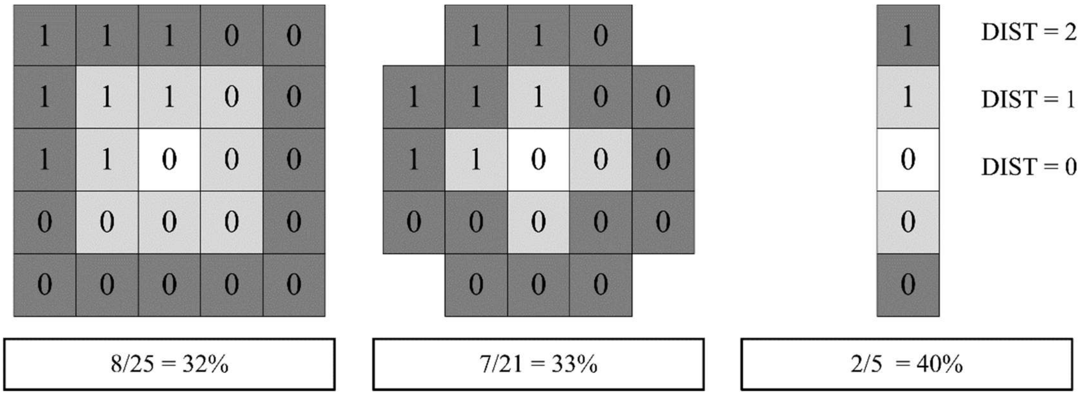


Figure 3.5. Schematic illustration on the calculation of the density value for a rectangular, circular and vertical filter shape.

The (CIR-) filter is the simplest filter, which uses a circular search area. In addition to the latter, a bidirectional (VER-) filter was developed to simulate a striplike mining pattern, portioning the area into narrow strips. Using this filter, the search distance that originates in backward and forward direction from the center pixel and the rotation angle theta (ϑ) must be parameterized. The "angle theta" is the angle from the y-axis winding clockwise in screen space. It is oriented to the main structures interpreted from the original binary image (Figure 3.4) and is −16.5°.

Strictly speaking, the filter works only in vertical direction (DIST-V) as the background image is rotated relative to the search direction. To consider mine planning, it is assumed that nonmineable areas (i.e., pixels) must be bypassed by the SMT(s). To take this into account, a search in the horizontal direction (DIST-H) was implemented. Furthermore, the circular (CIR-) filter and the bidirectional (VER-) filter were combined. This is hereinafter referred to as a combined (MIX-) filter.

A grayscale image is created from the binary image. A pixel remains mineable if a certain percentage of neighboring pixels are mineable. The mineable area is subdivided into two types of areas by defining two threshold values (TRH1, TRH2). Light gray (LGY) pixels represent density values ≥ TRH1 and < TRH2, whereas white (WT) pixels refer to values > TRH1 and ≤ 100%. It is assumed that the mining operation would be performed in core areas with a high density of valid pixels (WT), whereas secondary areas (LGY) are considered for maneuvering and/or may serve as buffer zones. Black pixels (BK) are assumed to be nonmineable. A TRH1-value of 80% and a TRH2-value of 90% are considered to best reflect the requirements and risks of a pioneer deep-sea mining operation.

Field Design

Field design is only merely hinted at because the planning of a field is not within the scope of this study. The color transitions in the processed images outline the contours of potentially mineable fields before field design. It was assumed that a mining field would be portioned into narrow, mostly longish strips to reduce the number of turnings. To take this into account, field boundaries are described by a simple geometry.

3.4 Results

Production key figures are now exemplarily calculated on assumptions made by the Blue Mining concept and the area (E1) studied (Table 3.2). The same applies for the image analysis, which has been applied to actual data out of E1.

Table 3.2. Key assumptions for the calculation of production key figures.

Item	**Value**	**Unit**
Annual production rate (P_A)	1.5 to 2	Mt/a, dry
Operating time (T_A)	5,000	h/a
Mining capacity (MR_{Max})	9	m²/s
Collecting efficiency (η_C)	80	%
Area coverage performance (η_A)	75 to 95	%
Lifting capacity (VTS_{Max})	150	kg/s, dry
Average abundance in the mineable area (NA_M)	13.7	kg/m², dry
Average abundance in the mining fields (NA_F)	13.7 to 16.5	kg/m², dry

3.4.1 Spatial Analysis

Processed images were analyzed for different filter settings, computing the gross and net mineable proportion by counting the total, the valid, and nonvalid number of pixels contained in the image. Early results indicated that a value of $-16.5°$ for ϑ was already an appropriate approximation to obtain the maximum mineable proportion and was therefore retained. The secondary area is only indicated in processed images. In all other cases, TRH2 is equal to TRH1. Processed images are presented to allow a visual comparison of different filter settings. A red rectangle indicates the area where confident density values can be expected. For pixels outside the rectangle, not all neighboring pixels are defined as out of the image and were excluded from calculation. Uncertainty was not quantified.

Results of the image analysis show that 70% (α) of the analyzed area is potentially mineable (Figure 3.6). In general, one can state: the higher the threshold level, the lower the mineable proportion and vice versa. The circular filter (Figure 3.6A) is not efficient compared to the other filters. This is in particular evident for larger vertical search distances (V-DIST). The highest values are obtained by application of the bidirectional filter (Figure 3.6B) and the combined (MIX-) filter (Figure 3.6D).

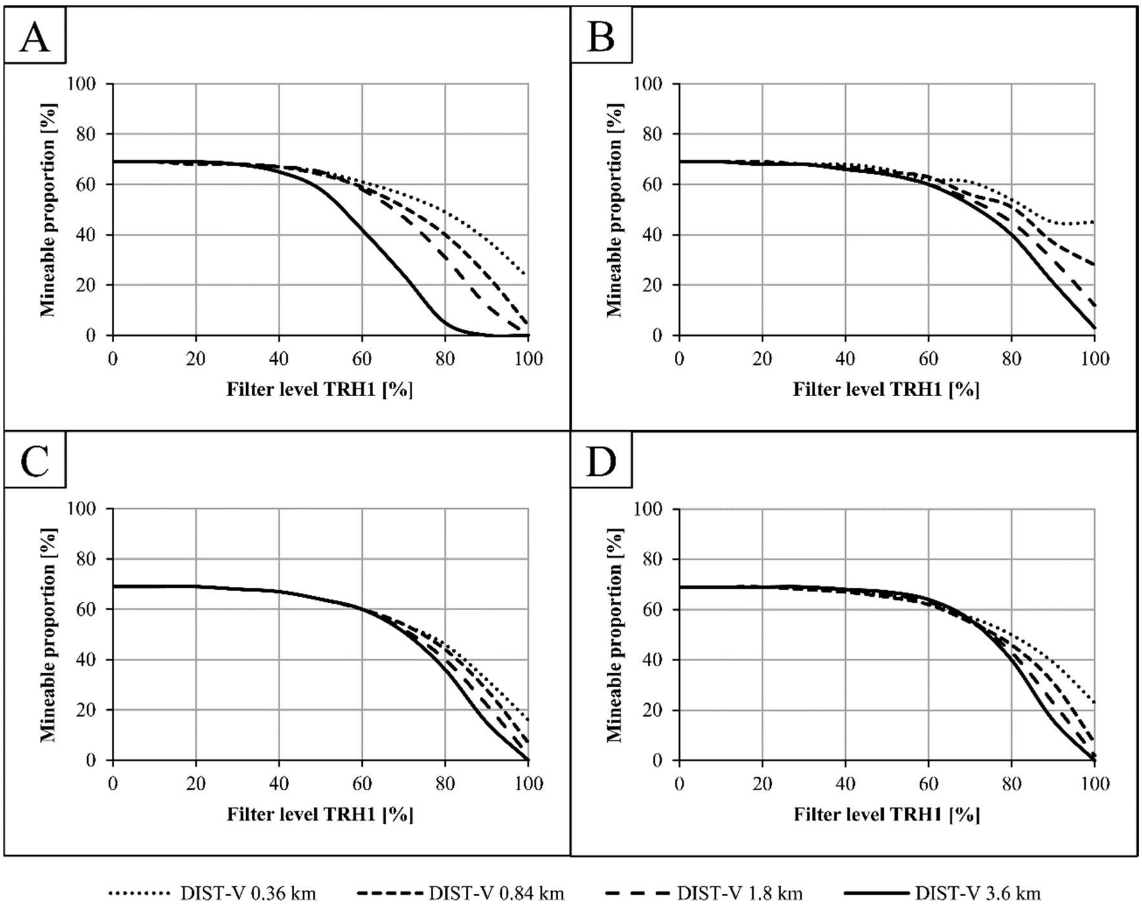


Figure 3.6. Potentially mineable proportion computed for the study area. A: Radial filter. B: Bidirectional filter. C: Bidirectional filter with a horizontal distance of 0.36 km. D: Mixture of a radial and bidirectional filter (for all: $\vartheta = -16.5°$, TRH2 =TRH1, DIST-V is the vertical filter distance).

Processed images (Figure 3.7) indicate potentially mineable areas, filtered by using a circular (CIR-) filter, a bidirectional (VER-) filter, and a combined (MIX-) filter. The mineable proportion ranges between values of 30% and 45% (Figure 3.7A). The mineable area is less fringed the higher the horizontal search distance is (Figure 3.7B, C). The image created by applying the combined filter (Figure 3.7D) is like the first one but shows narrow details. As determined for the combined (MIX-) filter, the core area increases by a factor of 2, whereas the secondary area remains almost the same.

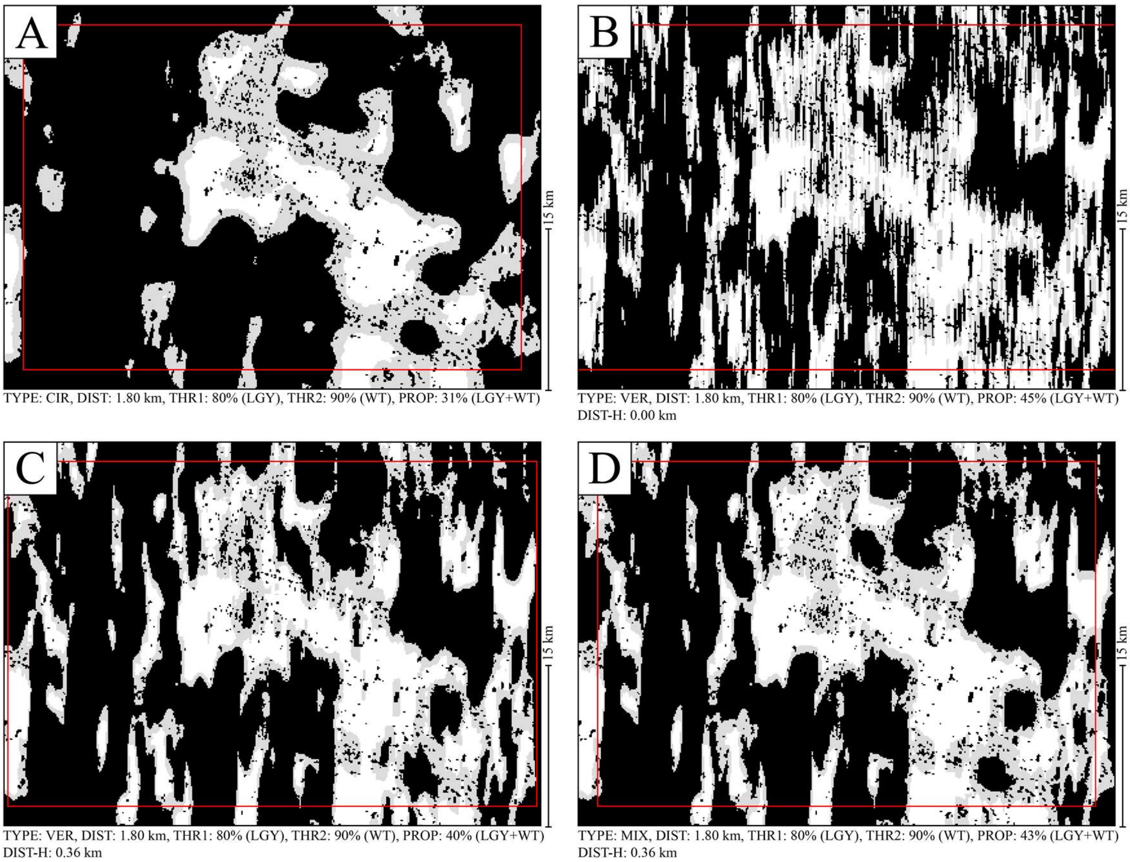


Figure 3.7. Potentially mineable area computed for the study area. A: Radial filter. B: Bidirectional filter. C: Bidirectional filter with a horizontal distance of 0.36 km. D: Mixture of a radial and bidirectional filter (for all: $\vartheta = -16.5°$, TRH2 = TRH1). Black (BK): Nonmineable area. Light gray (LGY): 80%–89% of the surrounding area is mineable; white (WT) if higher. The inner rectangle indicates the effective filter area.

Within the analyzed area, 28 potential mining fields were identified, covering 36% (β) of the total area (Figure 3.8). The typical size of a potential mining field would be about 25 km². These fields would be 1 to 4 km wide and 5 to 14 km long (average value ± the standard deviation), north-south orientated. The biggest field would cover an area of 114 km² and would sustain mining for almost 1 year, assuming 250 days of operation per calendar year.

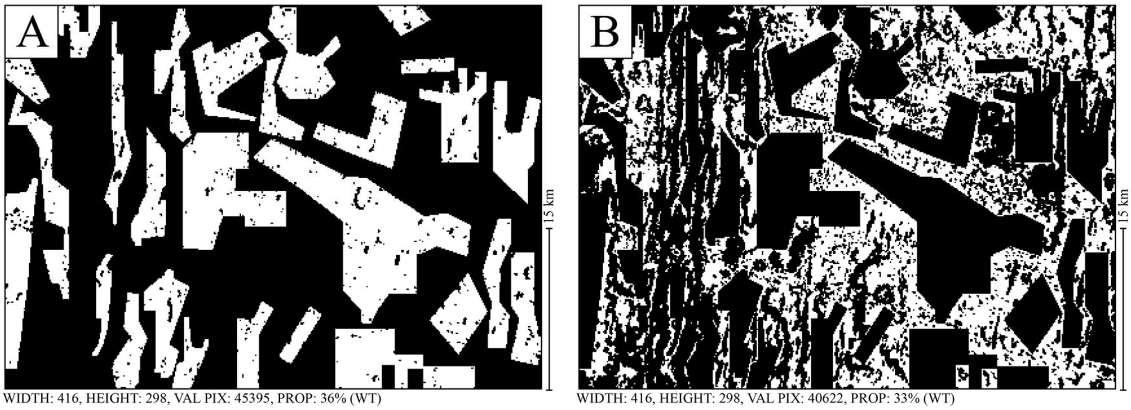


Figure 3.8. Area before (A) and after mining (B) computed for the study area. A: Mineable area inside the fields in white (WT). Nonmineable area inside and areas outside the fields in black (BK). B: Extraction losses in white (WT). Nonmineable area and fields mined in black (BK).

3.4.2 Production Key Figures

Production

Blue Mining aims for an annual production of 1.5 up to 2 Mt SMnN (P_A). PKFs can be derived accordingly. Mining is scheduled for 250 days and for 20 hours per day. Planning with 5,000 operating hours per year (T), 400 dry metric tons of SMnN must be collected on average per operating hour (P) to realize 2 Mt/a. The lifting capacity (VTS_{Max}) considered by Blue Mining is 150 kg/s. Full capacity utilization would be achieved by operating at 10 m²/s and 19 kg/m², 8 m²/s and 24 kg/m² or 6 m²/s and 24 kg/m² (Figure 3.9). Average mining rates (MR_A) of at least 6–10 m²/s must be achieved when mining average nodule abundances of 13.7–16.5 kg/m² to realize 1.5–2 Mt/a (Figure 3.10).

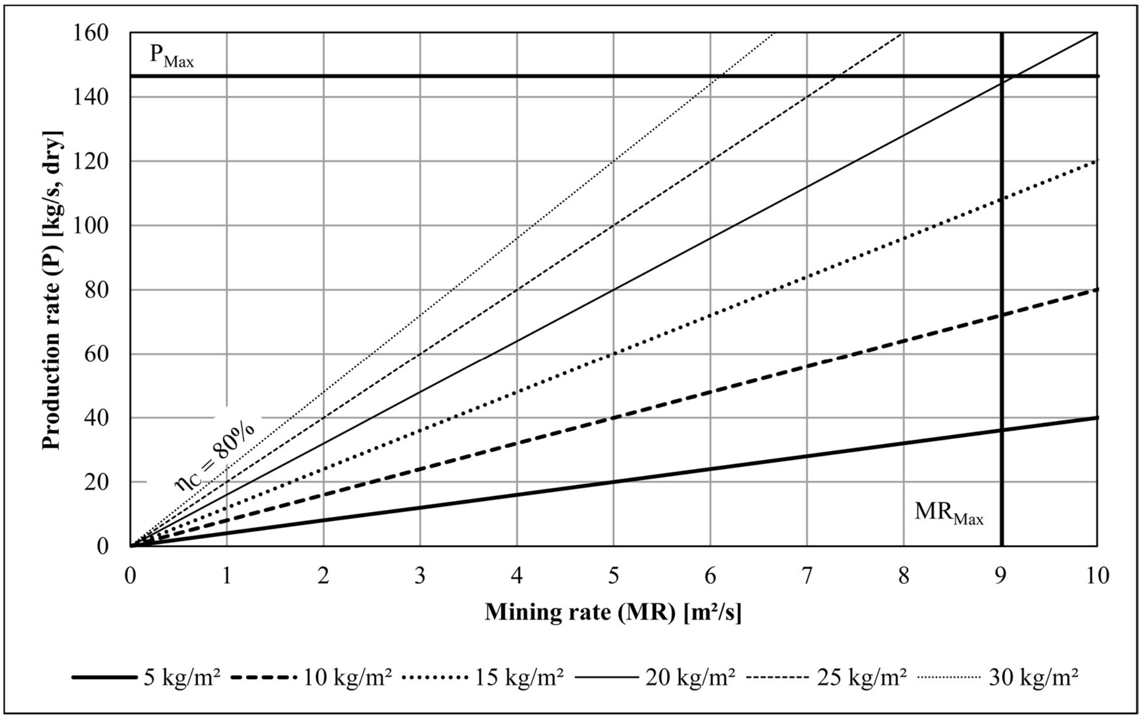


Figure 3.9. Production rate (P) as a function of nodule abundance (NA) and mining rate (MR) at a constant collecting efficiency (η_C) of 80%. Production is limited by the production capacity (P_{Max}) and mining capacity (MR_{Max}) exemplary for the Blue Mining project.

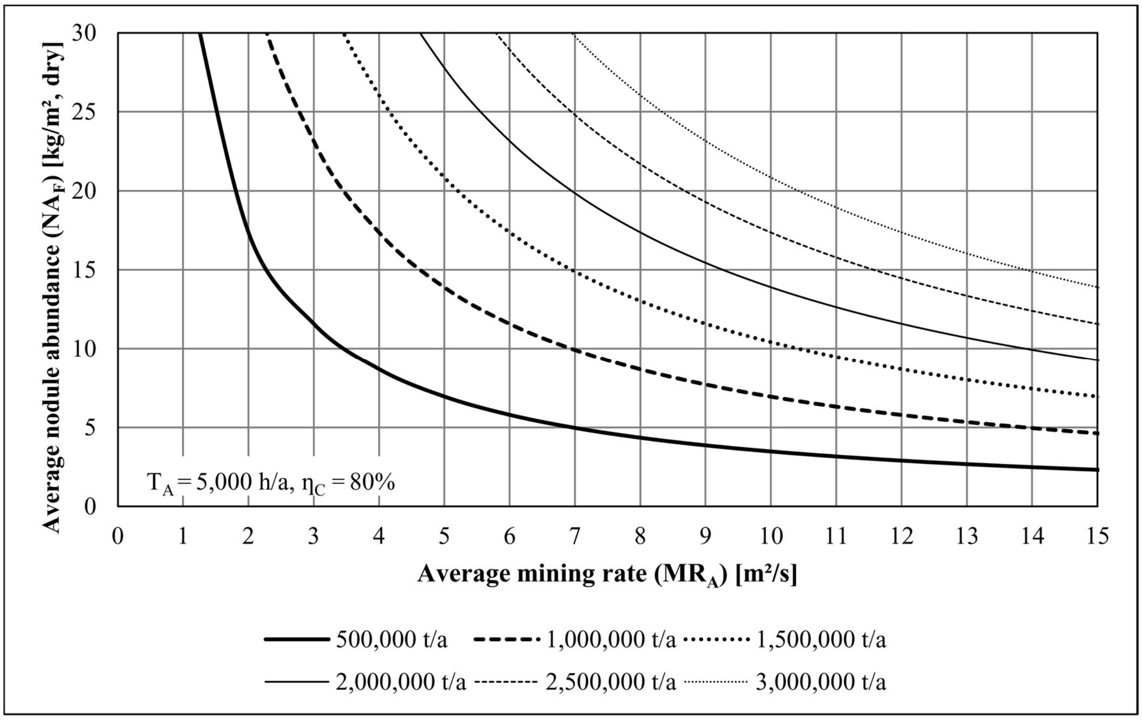


Figure 3.10. Annual production rate (P_A) as a function of the average mining rate (MR_A) and average abundance (NA_F) at a constant collecting efficiency (η_C) of 80% and 5,000 operating hours (T_A) exemplary for the Blue Mining project.

Resource Utilization

The theoretical resource utilization (RU_{Max}) is dependent on the set cutoff nodule abundance, here shown as exemplary for the area studied by Rahn (2016). A decrease in resource utilization from about 90% to 20% can be seen when increasing the cutoff value from 14 to 18 kg/m² (Figure 3.11).

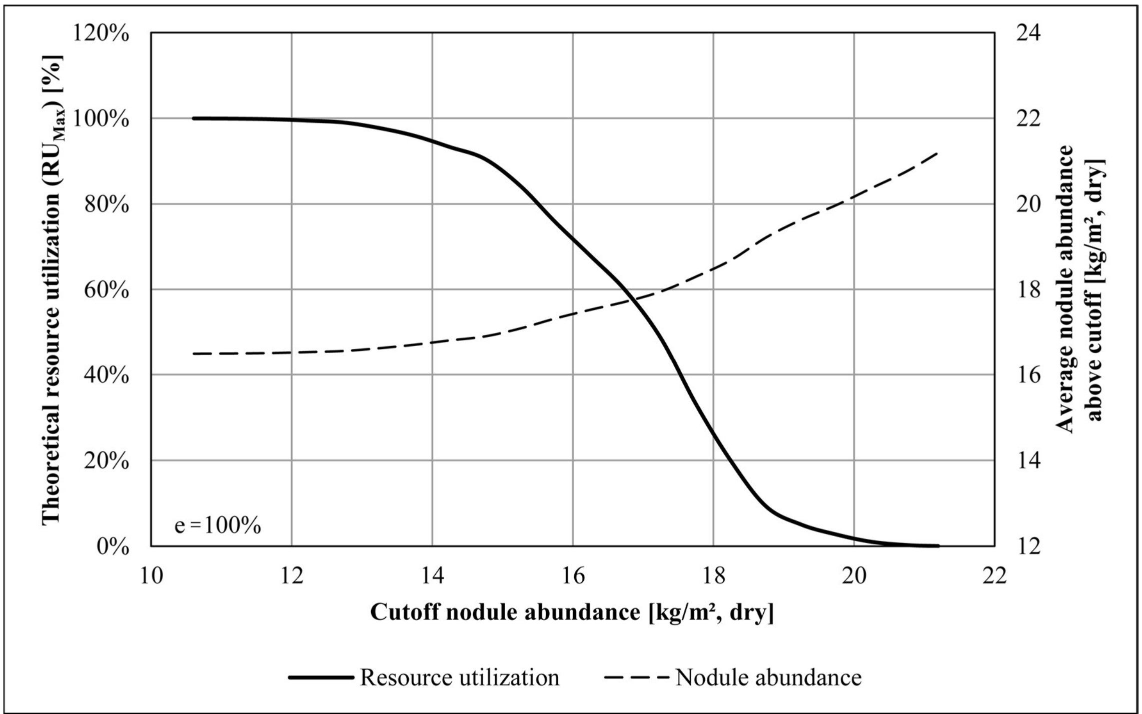


Figure 3.11. Theoretical resource utilization (RU_{Max}) as a function of the cutoff nodule abundance and the average nodule abundance above cutoff exemplary for the exemplary mine site of the Blue Mining project (Rahn 2016).

The higher the cutoff nodule abundance, the more areas are not mined. Considering the assumptions made (upper abundance of 16.5 kg/m²) a cutoff of about 10.3 kg/m² would apply, leading to a theoretical RU of 100%. To meet production requirements, mining must focus on areas of adequate average nodule abundance. For scenarios of different average abundances, RU_{Max} can be derived accordingly (Table 3.3). Figures of nodule abundances are labeled with the symbols A*, A, B, and C, which reflect the likeliness of occurrence, based on literature and Blue Mining results (Rahn 2016).

Table 3.3. Likelihood of occurrence of areas of adequate nodule abundances estimated for different annual production rates and mining rates.

Annual production rate (P_A) [Mt/a]	**Mining rate (MR_A)[1] [m²/s]**					
	10		8		6	
0.5	A*	(3; 100%)	A*	(4; 100%)	A*	(6; 100%)
1.0	A*	(7; 100%)	A	(9; 100%)	A	(12; 100%)
1.5	A	(10; 100%)	A	(13; 100%)	B	(17; 90%)
2.0	A	(14; 100%)	B	(17; 90%)	C	(23; 0%)
2.5	B	(17; 90%)	C	(22; 0%)	C	(29; 0%)
3.0	C	(19; 10%)	C	(26; 0%)	C	(35; 0%)

Classification: A* (most likely); A (likely); B (less likely); C (unlikely). In brackets the required nodule abundance in the mining fields (NA_F; kg/m² dry) and the corresponding theoretical resource utilization (RU_{Max}) for the exemplary mine site studied by Rahn (2016).[1] Average mining rate (MR_A) based on 5,000 operating hours per year (T_A) and a collecting efficiency of 80%.

Mining and Extraction Efficiency

The gross mineable proportion (α) is computed to be 70%, whereas the net mineable proportion (β) is 36% in cases where all mining fields are mined. It is shown how mining efficiency would change if strips were intentionally left unmined (Table 3.4).

Table 3.4. Mining efficiencies estimated for the study area.

Item		Derivation	**Values** Base case	Lower coverage	**Unit**
A	Gross mineable proportion (α)	Computed	70	70	%
B	Net mineable proportion (β)	Computed	36	36	%
C	Utilization of mineable area (φ)	(B / A)	51	51	%
D	Area coverage performance (η_A)	Assumed	95	75	%
E	Collecting efficiency (η_C)	Assumed	80	80	%
F	In-field mining efficiency (η_{MF})	D x E	76	60	%
G	Overall mining efficiency (η_M)	C x F	39	31	%

Such zones may provide connectivity of habitat for native species or be unintentionally left unmined due to imprecise navigation of the SMT(s). In the base case, the coverage performance (η_A) is assumed to be 95%. Leaving a 5-m-wide strip unmined next to each strip mined, this would reduce area coverage by approximately 20%. The strip width is assumed to be 20 m. This corresponds to the collecting width of the SMT(s) considered by Blue Mining. A collecting efficiency (η_C) of 80% is assumed.

The mining efficiency (η_{MF}) is estimated to be about 60%–76% in the fields and approximately 30%–40% in total (η_M). Based on the assumption that the average nodule abundance in the mineable area (NA_M) would be 13.7 kg/m² and 16.5 kg/m² in the fields (NA_F) at best, the extraction efficiency (e) is estimated to be slightly higher: approximately 30%–50%.

Yield and Duration of Mining

The total area of the analyzed part of E1 (A_{TOT}) amounts to almost 1.800 km². Assuming the average nodule abundance in the fields (NA_F) to range between 13.7 and 16.5 kg/m², about 5–8 Mt of SMnN could be recovered (Y). Thus, the area may provide enough SMnN to sustain mining for approximately 2½ to 5½ years (D), entailing production rates (P_A) of 1.5–2 Mt per year and overall mining efficiencies (η_M) between about 30%–40%.

Seafloor Consumption and Requirement

Seafloor consumption (${A_M}^*$) depends on the average abundance in the mining fields harvested by the miner. A higher average abundance leads to lower consumption and vice versa (Table 3.5).

Table 3.5. Seafloor consumption and requirement estimated for different annual production rates and average nodule abundances.

Item	**Values**				**Unit**
Annual production rate (P_A)	1.5	1.5	2.0	2 .0	Mt/a, dry
Average nodule abundance (NA_F)	13.7	16.5	13.7	16.5	kg/m², dry
Area consumption ($A_M{}^*$)	137	114	182	152	km²/a
… over 20 years (D)	2,700	2,300	3,600	3,000	km²
… soccer fields per day	76	64	102	85	fields
Total seafloor requirement ($A_{TOT}{}^*$) for a duration (D) of 20 years, where η_M = 30% and α = 70%	10,400	8,700	13,900	11,500	km²
Total seafloor requirement ($A_{TOT}{}^*$) for a duration (D) of 20 years, where η_M = 40% and α = 70%	7,800	6,500	10,400	8,700	km²

To achieve a production of 1.5–2 Mt per year, it is estimated that approximately 114–182 km² would have to be mined per year. Planning with 250 days per year, about 64–102 soccer fields (68 m × 105 m) would have to be mined per day. The area mined in a period of 20 years is estimated to be about 2,300 km² to 3,600 km². This is about the size of Luxembourg and represents only about 4%–6% of E1. The total seafloor requirement ($A_{TOT}{}^*$) is estimated to make up between 12% and 24% of E1. Absolute values may range between 6,500 and 14,100 km², entailing 20 years of production at annual rates between 1.5 and 2 Mt.

3.5 Discussion

This section discusses the validity of the methodology developed for estimating production key figures (PKFs). The discussion aims to clarify the framework conditions of SMnN mining. Although the case study is hypothetical and based on estimates and assumptions applicable to the Blue Mining case study, the methodology and estimated PKFs may be helpful in planning future SMnN mining projects.

3.5.1 Spatial Analysis

A strip-mining concept requires the identification of continuously mineable areas. Most software applications already provide comparable filters for this purpose (e.g., ArcGIS). Developed filters already assume a striplike mining pattern. This is inspired by traffic patterns of farming machines (Grisso et al. 2002; Poncet et al. 2016). The intention here is not to result in an optimal field design and mining route but to identify continuous areas that would favor mining long, narrow strips. A circular (CIR-) filter (Figure 3.7A) has not been proven to be efficient as narrow areas, which are potentially mineable, are not detected. The bidirectional (VER-) filter (Figure 3.7B) is also unsuitable as it would be too restrictive for future mine planning. The combined (MIX-) filter (Figure 3.7D) seems to be the most suitable as the advantages of both filters are combined. Although filter settings must be further fine-tuned, it can be pointed out that the geology favors a striplike mining pattern. Sound criteria to differentiate nonmineable from mineable areas have still to be investigated.

Comparable to agriculture, there might be “profitable” and “non/less profitable” fields based on the operating profit generated during the time spent in a field. The authors expect that shape, number, size, and spatial distribution of obstacles among other factors have effect on time efficiency as known from agriculture (Grisso et al. 2000; Hunt and Wilson 2015). A mining field is expected to be shaped through the field planning process involving route planning. Field planning is only hinted at in this paper. The presented mapping technique is adjusted to the expectation of the authors that pilot mining would take place in areas with a high mineable proportion (≥ 90%), while more disturbed areas (≥ 80%) may be used for turning or serve as a safety distance to threats (e.g. cliffs) or protected areas of environmental interest. Further research is required concerning field planning to determine the exact shape of a mining field, mining pattern, and time to mine it. Much of this is already described for farming machines (Hunt and Wilson 2015).

Preliminary results of this paper have already given an impression of how the seafloor may look like after mining takes place (Figure 3.8). Mining would leave patchy areas scattered on the ocean seafloor (Kuhn et al. 2012). Potential mining fields are embedded in horst and graben structures and are predefined by geology (Rühlemann et al. 2009). Considering that horizontal structures visible in the processed (filter-) images are artifacts as assumed by Rahn (2016), there may be fewer but longer fields. This cannot be clarified with the underlying data. Moreover, only about 3% of E1 was analyzed, which may not be representative for other regions inside or outside the license area. The factsheet on polymetallic nodules published by the ISA, referring to results of J. P. Lenoble for the French pioneer area, states: “In the best areas, they would be 1 to 5 km wide and

10 to 18 km long, with a north-south orientation. They might cover 35% of the bottom with a nodule abundance of 15 kg/m²" (ISA n.d.). These dimensions are comparable to those determined in the scope of this study.

Furthermore, black pixels of the binary images may be traversable, other than assumed in this study. In addition, due to the relatively low resolution of the seafloor data, raster units can consist of nonmineable parts and vice versa. Mine planning will require a more precise prediction of seafloor properties (e.g., on nodule abundance and grades). A new approach to increase prediction confidence has been investigated by the BGR in collaboration with Beak Consultants GmbH using an algorithm of artificial neural network (ANN) to compile predictive maps for SMnN coverage. Based on the prediction results, mineral resources of manganese, copper, nickel, cobalt, molybdenum, vanadium, titan, zinc, and rare earth elements were estimated at different cutoff grades (Beak 2015). In addition to exploration, it is considered that AUVs/ROVs scout the seafloor during mining to update the mine plan with a spatial resolution of a few meters (Kuhn et al. 2011).

3.5.2 Production Key Figures

Results shown in this paper may not be representative for other areas or projects due to legal, economic, and technical uncertainties (Ecorys 2014). Furthermore, the analyzed area (about 1,800 km²) accounts for only about 3% of the entire eastern German license area E1. Characteristics of the exemplary mine site differ significantly (Table 3.1).

Production

To achieve a certain production target, mining must focus on areas of adequate abundance (Figure 3.10). Besides geological and technical reasons, production and thus the required abundance is also influenced by the mining rate. The annual average mining rate depends on the mining capacity provided by the SMT(s) as well as on the time the operation is performed at full mining capacity (Formula 3.10). Technical figures are closely related to those used in agricultural engineering (Grisso et al. 2000; Hunt and Wilson 2015; Hanna 2016). With the provided formula (Formula 3.8), one could determine the necessary average abundance to realize a certain annual production rate. Then it might be possible to map out the appropriate areas on the seafloor meeting the requirements. On the other hand, based on a given annual production rate and a given abundance, one could determine the necessary mining rate (i.e., the needed technical layout and capacity of a SMT).

With respect to dimensioning, the lifting capacity of the VTS must fit to the mining capacity and peaks in nodule abundance (Figure 3.9). Dilution of ore with sediments and transport losses are not considered. According to the current-state-of-the-art, SMnN are freed from sediments inside the SMT (Ecorys 2014). To dimension the SMT(s), the annual operating time and time efficiency i.e. time mining at full rated speed and full width utilization must be investigated (Formula 3.11). While the annual operating time (5,000 operating hours) is an experience-based figure from dredging, time efficiency is a largely unknown factor because of the lack of experience. In agriculture, field efficiencies of farming machines typically range between 50 and 80% (Grisso et al. 2000). Achieving similar performance as in farming will be an ambitious challenge.

As shown, average mining rates of 6–10 m²/s would be required to recover 1.5–2 Mt SMnN per year. The Blue Mining reference of 2 Mt SMnN per year is based on an early economic assessment. Although a collecting efficiency of 80% was assumed, it is not a constant. It depends, among other things, on the colleting speed, nodule abundance, and collecting technology (Handschuh et al. 2001).

Adopting the mentioned time efficiencies to SMnN mining, a total capacity of about 7.5 –20 m²/s would be required. In contrast to this wide range, a mining capacity of 9 m²/s is considered by Blue Mining (Table 3.2). The MH Wirth concept is similar to the proposed Blue Mining concept and consists of two SMTs (Kuhn et al. 2011). Their SMTs are equipped with two drums, each 6 m in width. The nominal (conceptual) operating speed is 0.5 m/s. In comparison, the Claas Lexion 780, one of the world's biggest combine harvesters, is equipped with six drums, each 1.7 m in width (Claas 2017). The nominal operating speed according to data specifications is 3 m/s.

Although small-scale and prototype tests were carried out in the past in shallow waters (Deepak et al. 2001; Hong et al. 2010). Further research and tests are necessary to resolve uncertainties. It has yet to be investigated whether mining rates can be achieved, which would ensure carrying out SMnN mining in a balanced manner, ensuring profitability at acceptable resource utilization and reasonable seafloor consumption. In the opinion of the authors, an annual production rate of 2 Mt or higher seems to be too optimistic to expect from a pioneer mining operation, mainly due to geological, technical, and operational reasons.

Resource Utilization

Resource utilization is dependent on the annual production rate and the average mining rate (Table 3.3). Within the scope of this paper, the theoretical resource utilization (RU_{Max}) was estimated for an exemplary area, indicating the mining potential. In practice, the resource utilization is probably lower due to mining losses (considered in the extraction efficiency). According to Kuhn et al. (2012), E1 has proven to consist of at least 10 kg/m² (wet weight). This corresponds to a dry weight of about 7 kg/m². The letter A (likely) indicates that the required average abundance is less than or equal to 14 kg/m² (dry weight). This value refers to an average abundance of 13.7 kg/m² assessed for E1 (Rühlemann et al. 2011). Feasibility studies carried out in the 1970s and 1980s used similar nodule abundances for their calculations (Nyhart et al. 1978; Hillman and Gosling 1985). The letter B (less likely) is referring to average abundances between 14 and 17 kg/m². Large continuous areas with abundances in this range are expected to be representative for future mining fields (Figure 3.2). All values above 17 kg/m² are marked with a C (unlikely), expecting that only a small proportion of the seafloor contains abundances in this range. Only mining nodule-rich parts of a mineral deposit, labeled with C, is expected to result in poor resource utilization.

Resource utilization as the share of the deposit actually used can be applied as an indicator to assess the sustainability of a mining operation. Without legal regulations, high production requirements and mining rates below expectations could foster cherry-picking, mining only the favorable parts of a deposit, not utilizing the mineral resource well. Since metals grades have shown to be relatively constant, these parts would be nodule-rich areas and thus easy to mine, therefore resulting in higher average mining rates. Since the spatial distribution of SMnN is site-specific, the classification matrix (Table 3.3) may not apply for other areas. However, it may be useful to get first a general idea of what can be expected with regard to the spatial distribution in the CCZ (ISA 2010).

Mining and Extraction Efficiency

According to UNOET (1987), ”mining efficiency” or “overall efficiency” is the product of the collecting efficiency (originally referred to “dredge efficiency”) and area coverage performance (originally referred to “sweep efficiency”). At that time, a dredge head was expected to be dragged over the seafloor to collect SMnN. The overall efficiency was estimated to range most likely between values of 10% and 40% (UNOET 1987). In comparison to their concept, the Blue Mining approach is inspired by the potato harvest on land. One or several self-propelled, crawler-type SMTs are planned to be navigated along predefined routes as state of the art (Ecorys 2014). However, in both cases the mineable area must be defined in a first instance. Other than assumed for the former mine-site concept, the mineable proportion is expected to be narrowed down due to field design. Therefore, it is suggested to consider the degree of utilization and to differentiate between in-field and overall mining efficiency to consider field design.

Field design is a subsequent planning process, closely related to route planning. An area (referring to a specific raster unit) can meet the criteria of being mineable, but it may not be mined. Path planning is the subject of many scientific papers and is related to coverage problems (Huang 2001; Galceran and Carreras 2012). However, the main objective is not only to best cover the mineable area but to result in a (most) economic route i.e. mining pattern, while considering the affected area (to be explained). Although, if a “good utilization” is the aim, it is not yet certain if a striplike mining pattern is realizable. It might be the case that the SMT cannot be navigated as precise as known from precision-farming operations in agriculture, resulting in a poor area coverage performance. In conclusion, a pilot-mining test has yet to demonstrate the technical feasibility of strip-mining and SMnN mining in general.

The extraction efficiency or extraction efficiency or ratio is an established term in mining, which is commonly used in room-and-pillar mining (Darling 2011). Room-and-pillar mining is an underground mining method that is usually used for flat-lying deposits. The material is extracted across a horizontal plane, whereby pillars are left in place to support the roof. SMnN can be considered a thin layer of ore covering vast areas of seafloor. Although the reasons for not mining valuable material are different, deep-sea strip-mining and terrestrial room-and-pillar mining have in common that the mine design has an effect on extraction efficiency. In SMnN mining, the extraction efficiency is defined to be the ratio of the quantity of SMnN mined to the reserve. Cherry-picking only nodule-rich parts of a mine site could result in poor mining efficiency but sufficient (higher) extraction efficiency at the same time. For the exemplary area, extraction efficiency was estimated to be 30%–50%, while the overall mining efficiency was computed to be 40% at the best. However, the difference is insignificant in cases where the mineable area is utilized most efficiently.

Reserve Estimation

In this paper, SMnN contained in the mineable area are qualified as potential reserves. The purpose was to investigate the requirements and dimensions of a future SMnN system that would utilize the deposit in the best possible manner. None of the known SMnN resources has yet reached the status of a reserve. This is mainly due the absence of a regulatory framework and poor technical readiness level (Ecorys 2014). A standard to report SMnN reserves has not been established yet. For the mining entrepreneur, it will be important to validate if a field generates enough profit in adequate time, taking into account technical feasibility and field characteristics. Still, that does not exclude a field from turning into a reserve at some later point in time. Therefore, it is suggested to report the quantity of SMnN in the mineable area and additionally the quantity of SMnN in the mining fields, after field design and economic assessment.

Duration of Mining

The analyzed part of E1 (about 1.800 km²) may already provide enough SMnN to sustain mining for maybe 2½–5½ years. Planning with at least 20 years of production, another three to seven areas would be required of similar characteristics. Under the premise that the area is representative for the entire license area E1 (Table 3.1), one mining operation (one MSV) could be carried out for maybe 84 to 186 years under the assumption that 30%–50% of the resource is recovered. However, these figures are very speculative. Kuhn et al. (2012) identified 10 prospective fields in E1, which "[…] cover 18% of the total area and contain nodule reserves that sustain at least 40 years of seabed mining." The term field refers here to the potentially mineable area, not considering extraction efficiency. In conclusion, results indicate that extraction efficiency and thus field design will have effect on the life of the mine and the number of mining projects per license area and thus needs to be thoroughly studied.

Seafloor Consumption and Requirement

The terms land (seafloor) consumption and requirement are common terms in agriculture (Hunt and Wilson 2015). The formula provided to estimate the seafloor requirement (Formula 3.20) is similar to the one proposed by the UNOET (1987). They estimated that mining would require approximately 15,300 km²–125,000 km² over a period of 20 to 40 years at a production of 3 Mt per year. "The wide range in the estimates is primarily due to the different perceptions of the risk factors involved" (UNOET 1987). In comparison, E1 is about 58,000 km² in size. Own estimations indicate that about

6,500 to 13,900 km² of seafloor would be needed to sustain a single mining operation of 20 years at 1.5–2 Mt SMnN per year. Even if the annual production rate and overall mining efficiency are marked by uncertainty, a requirement of 125,000 km² of seafloor cannot be expected for E1: 80% of the exploration area is of flat terrain (≤ 3°) and the average nodule abundance is 13.7 kg/m² (dry; Rühlemann et al. 2009).

3.5.3 Environmental Aspects

SMnN mining is predicted to disturb vast areas of seafloor (Thiel and Schriever 1993). Simulations have shown that sediment particles can settle over distances of several to hundreds of kilometers and may form a thin sediment layer that can overlap and suppress the benthic ecosystem (MIDAS 2016b). Sediment is expected to be swirled up by the SMT(s). Another source is the return line ("downer"). Seawater and residue from the dewatering process on board of the MSV, basically undersized particles, are rejected into the sea (Oebius et al. 2001). Beside plume generation, the seafloor is likely to be disturbed due to the removal of SMnN and compaction of soil, which functions as habitat for sessile organisms (Valsangkar 2003; Sharma 2013). The "affected seafloor area" is a possible indicator to take the environmental footprint into consideration. It is defined as the by deep-sea mining disturbed seafloor implying an as-yet-undefined severity of impact (Volkmann 2014). At present there are no environmental provisions due to the absence of a regulatory framework. Also, there is still a lack in understanding the large-scale and long-time environmental impact of deep-sea mining. In conclusion, the affected area cannot be quantified yet.

3.5.4 Other Mining Concepts

Besides the Blue Mining concept, there are other—due to the absence of regulations—not yet competing mining concepts, such as the Indian, for instance. The University of Siegen, Germany, proposed in collaboration with the National Institute of Ocean Technology (NIOT), India, a concept for deep-sea mining based on a flexible riser and self-propelled mining machines (Handschuh et al. 2001). In contrast to the Blue Mining concept, the Indian system operates (semi-) stationary. Instead of a continuously moving mining support vessel, platforms are considered from which numerous smaller SMT(s) are operated at speeds of 0.2 m/s and collecting efficiencies of 70%. The platform would have to be moved by 2 km approximately every 6 weeks. In the beginning four to five platforms would be required to lift 1 million wet metric tons of nodules. It is considered that production could be increased to one million tons per platform. Today, no statement can be made of which mentioned concept is the better one, considering environmental, technical, and economic aspects. An Environmental Impact Assessment (EIA) through a pilot-mining test could provide that (ISA 2013).

3.6 Conclusions

Potential mining fields can be found in plain areas embedded in horst and graben structures. Bulk mining would leave patchy areas scattered on the seafloor. In case of the eastern German license area, the geology favors a striplike mining pattern in NNW-SSE[12] direction. Production from a single Blue Mining or comparable system is likely limited to 1.5 to 2 Mt SMnN per year, mainly due to geological, technical, and operational reasons. Time efficiency (i.e., annual operating time at full mining capacity) has emerged to be the largest unknown factor to assess future mining systems. Further research and pilot-mining tests are necessary to gain a better understanding of the geology, technical, and economic feasibility and environmental footprint of SMnN mining. Although results are marked by uncertainty, the presented mapping technique and provided formulas to calculate production key figures are a step forward to technically and economically dimension a SMnN mining system. Parallels to agricultural engineering regarding machine, land and resource management become obvious.

[12] In the paper article it read NNE-SSW according to the original BGR source.

4 Estimating the Economics of a Mining Project on Seafloor Manganese Nodules

A version of this chapter has been submitted for publication and is referred to as Volkmann et al. (2018b).

4.1 Introduction

Mineral resources are a key factor of successful economies and societal progress. To minimize supply risks for import dependent countries such as Germany, unhindered access to strategical important metals must be ensured. Today, large quantities of manganese (Mn; 100%), cobalt (Co; 90%) and copper (Cu; 50%) are imported by Germany from non-European countries (Kausch et al. 2016). Besides their application as alloying elements in steelmaking, Ni, Co, and Mn become increasingly important due to their application in high and green technologies (Hein et al. 2013; Marscheider-Weidemann et al. 2016). In the event of the market penetration of electric cars with lithium-ion technology, the metal demand for the German automotive industry is estimated at 110,000 metric tons of Co, 188,000 tons of Ni, 194,000 tons of Mn, and 110,000 tons of Li in the year 2035 (Marscheider-Weidemann et al. 2016).

Seafloor manganese nodules (SMnN), about potato-sized, polymetallic rock concretions covering vast areas of the Earth's ocean floor (Mero 1962; Hein and Koschinsky 2014; Petersen et al. 2016), might be a source of future supply (Table 4.1). The occurrences with the highest economic potential according to their abundances and metal grades occur in areas beyond national jurisdiction—for example, the Clarion-Clipperton Zone (CCZ), Indian Ocean, Penrhyn Basin, and in the Peru Basin (Figure 4.1; Hein and Koschinsky 2014). The global resource potential is estimated to be about 500 billion dry metric tons of SMnN (Archer 1981). However, global abundance is far from certain as many areas have never been sampled adequately (Hannington and Petersen 2016), while regulations for the exploitation of SMnN in international waters are under development (ISA 2017b). Moreover, SMnN have not yet proven to be economically minable with current technology and economic conditions (Ecorys 2014).

Table 4.1. Estimated metal production of a future SMnN mine compared to the world mine production, the apparent consumption of Germany of year 2014 and compared to the estimated metal tonnages of SMnN resources of the CCZ and global land-based reserves.

Item	Nickel	Cobalt	Copper	Manganese	Unit
Mine production[1]	12,500 to 25,000	1,500 to 3,000	9,500 to 19,000	250,000 to 500,000	t/a
% of world mine production 2014	0.6 to 1.2	1.7 to 3.3	0.1 or less	1.5 to 2.9	%
% of apparent consumption of Germany 2014[2]	30 to 60	63 to 127	1 to 2	171 to 341	%
Resource estimates CCZ (SMnN)[3]	280	40	220	5,900	Mt
Global land-based reserves[3]	80	7.5	700	800	Mt
Global land-based reserves base[3]	150	13	1,000	5,200	Mt

[1] Estimates are based on Blue Mining data (rounded production figures). Production figures of the world mine production of manganese correspond to figures reported by the U.S. Geological Survey; cf. USGS (2016).[2] The apparent consumption calculates as the production + imports – exports (stock changes are not considered). Typical metal contents and import quantities are based on figures provided by the British Geological Survey (BGS); cf. Brown et al. (2016).[3] Metal tonnages reported in SPC (2013).

Focused here, the CCZ represents the largest occurrence with the highest economic potential (Hein and Koschinsky 2014). The so-called Manganese Nodule Belt of the Pacific Ocean stretches from the west coast of Mexico to Hawaii and encompasses an area of ~5.2 million km², including an area of ~4.2 million km² of commercial interest (ISA 2010). The average nodule abundance is about 15 kg/m² (wet weight); however, it varies from 0 to ~30 kg/m² within only a few hundreds of meters (SPC 2013). Metal grades are relatively constant over wide areas of the CCZ (ISA 2010). The conservatively estimated quantity of SMnN amounts to ~21 billion dry metric tons (ISA 2010). Compared to global land-based reserves the estimated metal tonnages are indeed remarkable (Table 4.1). However, only a small fraction of the reported SMnN resource might be mined under current assumptions and estimates on the resource utilization are yet highly speculative (Volkmann and Lehnen 2017; Volkmann et al. 2018a).

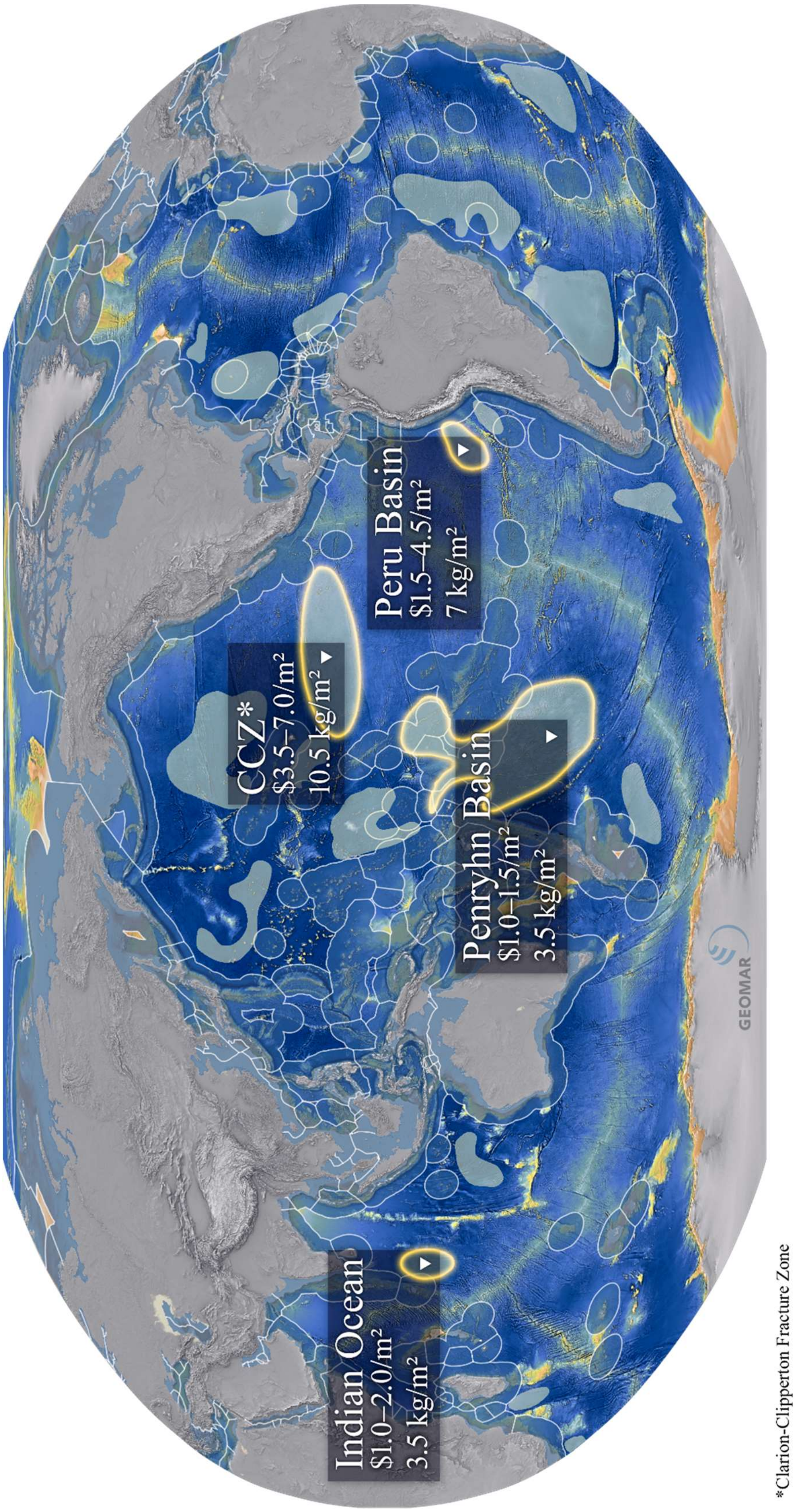


Figure 4.1. Global occurrences of SMnN (courtesy of GEOMAR; edited). Cash values refer to the mean value (2015-US$ per sqm.) of the years 1970 to 2015; estimated according to the methodology and data published by Volkmann et al. (2018a). The lower cash value refers to 3-metal recovery (Ni, Co, Cu), the upper cash value to 4-metal recovery (+Mn). Nodule abundance (kg/m²; dry weight) and metal grades (wt%) according to data published by Hein and Koschinsky (2014) and SPC (2013). Rounded figures.

Focus of this research is the investigation of economic conditions needed to invest into a commercial SMnN project. The European research project Blue Mining (2014–2018) serves as a specific case study. Past and future cost and price trends are considered. Although the investigation of the economic viability of SMnN mining has been intensively studied since the 1970s, the transfer of evaluation tools from land-based mining has not yet been completed. This contribution offers methods to evaluate the profitability of a mining project on SMnN. Besides the net present value (NPV) or the internal rate of return (IRR), an additional approach is presented to assess the "early feasibility" of a SMnN mining project. Using this approach, a spatial planning tool is developed (Volkmann et al. 2018a). Moreover, a further approach is discussed, which allows one to include route planning in the economic evaluation at a more advanced technological readiness. Thus, this paper contributes to the setting of requirements and the validation of assumptions for future mine planning.

4.2 Background

This study uses background information of the Blue Mining research project (2014–2018), funded by the European Commission (GA-no. 604500). Assumptions and estimates used for the economic project evaluation are subject to uncertainty. Figures reported by Blue Mining apply (Volkmann and Osterholt 2017). The geological and technical part has been covered in an earlier publication with focus on the determination of production key figures (Volkmann and Lehnen 2017). Geological data relate to the eastern German license area E1, located in the CCZ (Rühlemann et al. 2011).

4.2.1 Definitions

SMnN mining will mostly take place in international waters, on the seabed and ocean floor and the subsoil thereof beyond the limits of national jurisdiction termed "the Area" (Jenisch 2013). According to the *United Nations Convention on the Law of the Sea* (UNCLOS 1994), the International Seabed Authority (ISA or "the Authority") is obliged to organize, regulate, and control all activities in the Area (Jaeckel et al. 2017). To plan future mining activities, clear definitions and demarcations are needed:

The **"miner"** is a generic term for the entity conducting all offshore mining processes. In the scope of this study, this includes the delivery (shipping and over-land transport) of SMnN to the processing and refining plant operated by "the processor."

The **"processor"** is a generic term for the entity covering all subsequent processes that take place after the extraction and transportation (i.e. beneficiation, hydro- and pyro-metallurgical processing and refining of ore). The expression "processing and refining" is used to describe the processes.

A **"mining project"** encompasses the whole mine value chain from the exploration to the refining of the metals, although the project is planned from the miner's perspective.

4.2.2 Proposed Mine Value Chain

"In general, [a] deep sea mining value chain is similar to the structure of activities performed in land-based mining. […] The biggest challenge when planning deep sea mining enterprise activities and business models is a proper value chain analysis" (Abramowski 2016). According to the activities, it is differentiated from the sectors "mining and transportation," managed by the miner, and "processing and refining," outsourced to the processor (Figure 4.2).

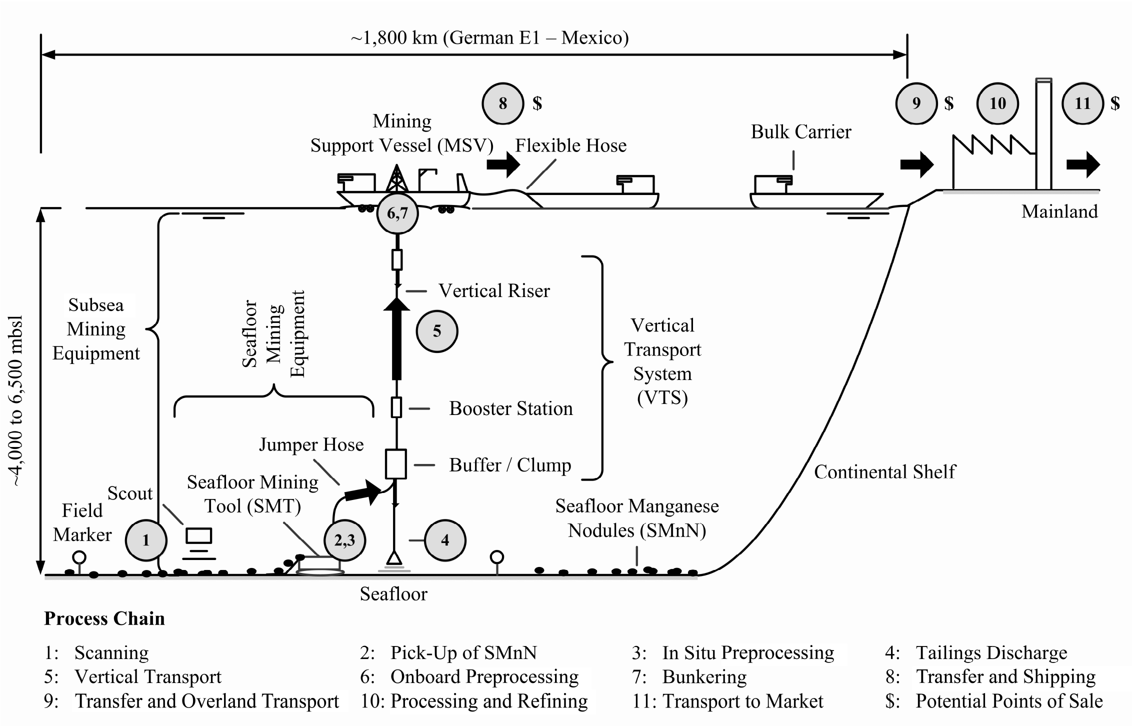


Figure 4.2. Proposed concept and activities related to a SMnN mining project.

According to the proposed mining concept, the harvest of SMnN involves mining a field partitioned into long, narrow strips (Volkmann and Lehnen 2017). The mining support vessel (MSV) follows the mining route of one or two seafloor mining tools

(SMTs), picking up the SMnN. SMnN are sized and freed from sediments before being lifted onboard the MSV, where the ore is dewatered and stored. Seawater and residue particles from the dewatering process are pumped back to the seafloor. Bulk carriers are chartered, which arrive at the mine site every 5 to 7 days. The ore is shipped and transported overland to a processing and refining plant.

4.2.3 Data Collection and Analysis

Model parameters for the economic evaluation of the Blue Mining case study (Table 4.2) were determined through a GAP analysis (good, average, poor) to take uncertainties into account. This included the statistical analysis of selected studies. Economic and financial figures given relate to year-end 2015 values. Further breakdown is not possible due to confidentiality of additional details. Three cases consider the feasibility of manganese (Mn) extraction in the processing and refining of SMnN, while another moderate case covers the scenario of only three metals (Ni, Co, Cu) being extracted.

Table 4.2. Assumptions and estimates related to the Blue Mining case study. Figures are based on economic factors of year-end 2015. Excerpts published in Volkmann and Osterholt (2017).

Item	**Good-Case Scenario**	**Moderate (Average)-Case Scenario**		**Poor-Case Scenario**	**Unit**
Process route Key elements	Four-metal Ni, Co, Cu, Mn	Four-metal Ni, Co, Cu, Mn	Three-metal Ni, Co, Cu	Four-metal Ni, Co, Cu, Mn	
Sales value[1]	732	649	304	493	$/dmt
Capacity	2	1.5	1.5	1	Mt/a
Life of Mine	20	20	20	20	a
CAPEX	1.5	1.43	1.22	1.32	$BN
Miner	596	560	560	511	$M
Processor	907	874	662	805	$M
OPEX	234	270	197	337	$/dmt
Miner	76	96	96	129	$/dmt
Processor	159	175	101	208	$/dmt
NSR-Royalty[2]	4	6	6	8	%
Corporate Tax	30	30	30	30	%
Discount Rate	15	20	20	25	%

[1] Hypothetical value of ore considering the recovery of Ni (95%), Co (90%), Cu (94%), and Mn (85%) at constant grades Ni (1.3%), Co (0.17%), Cu (1.1%), Mn (29.2%) in US$ per dry metric ton (dmt).[2] Royalty based on the net smelter return (NSR).

Selected Studies

Assumptions and estimates are partly based on Blue Mining background data. Since the processing and refining is outside the scope of Blue Mining research, data were derived from selected studies. The first comprehensive studies on the economic feasibility of SMnN mining this study is based on were carried out in the 1970s and 1980s (Arthur D. Little Inc. 1977; Nyhart et al. 1978; Andrews et al. 1983; Hillman and Gosling 1985). Furthermore, later studies were included in the study (Charles C. et al. 1990; Lenoble 1992; Ham 1997; Søreide et al. 2001) as well as information reported by the ISA (2008a). The assumptions and estimates of these studies have been widely reused (Dick 1985; Yamazaki 2008; SPC 2016). Recent studies carried out by the German Federal Ministry of Economics and Energy (BMWi 2016), for instance, were not included in the GAP analysis and are used for comparison purposes (Section 4.5.1).

Value of Ore

The value of ore is based on the sales value of SMnN. Since no market and no established processing technology for SMnN exist (Ecorys 2014), figures are hypothetical. The profitability will rely on the metals Ni, Co, Cu, and optionally Mn, although other metals may be of economic interest as well (Martino and Parson 2013; Hein 2016; SPC 2016). It is distinguished between three-metal (3M; Ni, Co, Cu) and four-metal (4M; +Mn) processing. Ni, Co, and Cu are assumed to be sold as pure metals (electro-refined 99.9%), while Mn is sold as ferromanganese (FeMn). FeMn is a ferroalloy with a high Mn content (here: ~75 wt.% Mn), which is used, for example, in steel production. Recovery rates reported by the ISA (2008a) and metal grades published by Rühlemann et al. (2011) for the eastern German license area E1 apply. Historical metal prices were used (USGS 2016) and adjusted for inflation effects (Appendix; Table A.7.3). The time series for Mn ore was scaled up to match with the 2015 price of FeMn. The sales value of the good-case scenario refers to the upper quartile, the average case to the mean value and the poor-case scenario to the lower quartile of constant 2015 prices (1970 to 2015).

Production

Mine production has shown to be likely limited to about 1.5 to 2 Mt/a (dry weight) due to geological, technical, and operational constraints, mainly (Volkmann and Lehnen 2017). Full capacity utilization is assumed at constant rates over 20 years, while tests still have to demonstrate the techno-economic feasibility. The life of mine (LOM) corresponds to the minimum life, specified by Blue Mining, which would also be applied to financial models of typical land-based mining projects.

Costs

Costs have only been partly published for the Blue Mining project (Volkmann and Osterholt 2017). Capital expenditures (CAPEX; miner and processor) range between about \$1.2 and \$1.5 billion and operative expenditures (OPEX) between about \$200 and 340/dmt. Possible costs of a pilot mining test (PMT) and (yet uncertain) environmental costs, e.g., to minimize mining-related environmental impacts in the deep sea and on land (Thiel and Schriever 1993; Sharma 2013; MIDAS 2016a,b), are not included. Costs allocated to the mining and transport sector are based on Blue Mining estimates (Appendix; Figure A.7.2), whereas the processing and refining costs were derived from a statistical analysis of the selected studies. Costs were re-allocated, scaled to a capacity of 1.5 Mt/a (dry; per MSV) and indexed to year-end 2015 US dollars (\$). As of limited data, the 3M average-case scenario is based on the 4M average-case scenario. The percentage ratio was derived from an updated cost model (Hillman and Gosling 1985). As for the sales values, the upper quartile applies for the good case, the mean for the average and the lower quartile for the poor case GAP scenario (Figure 4.3).

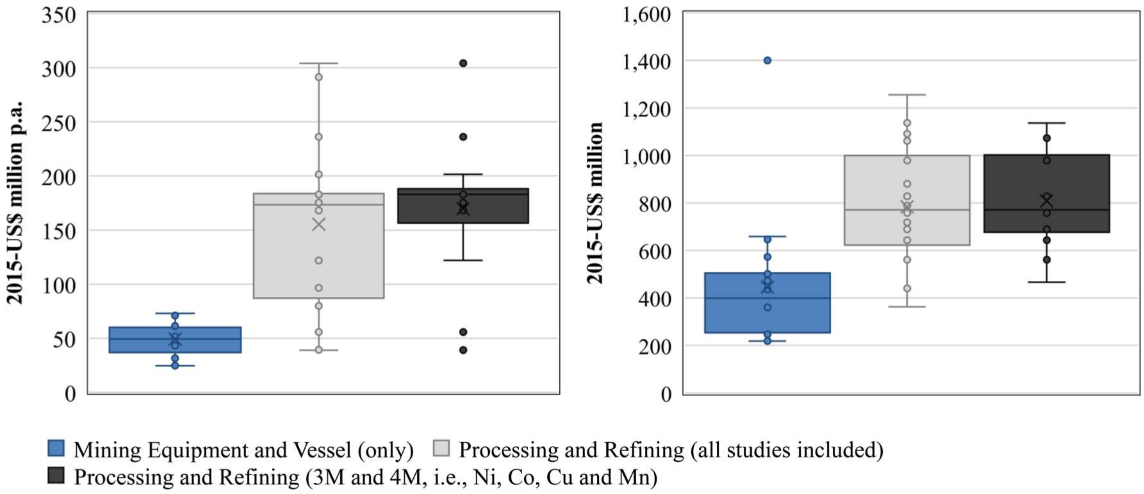


Figure 4.3. OPEX (left) and CAPEX (right) for the mining and processing of SMnN. The costs are based on selected studies, indexed to 2015-\$ and scaled to a capacity of 1.5 Mt/a (dry weight; one MSV). Note that not all costs incurred in a SMnN project are included. References to the studies are given in the text.

Taxation

The corporate tax, which is country-specific, amounts to about 30% for Germany and for Mexico, where the processing plant is considered to be located (KPMG 2015). The royalty is assumed to be imposed by the ISA and is applied on the net smelter return (NSR). As there is no tax regulation yet, conventional royalty and tax rates are assumed to be adequate for SMnN mining as they are also accepted as a fair compromise for land-based operations (Otto 2006).

Financing

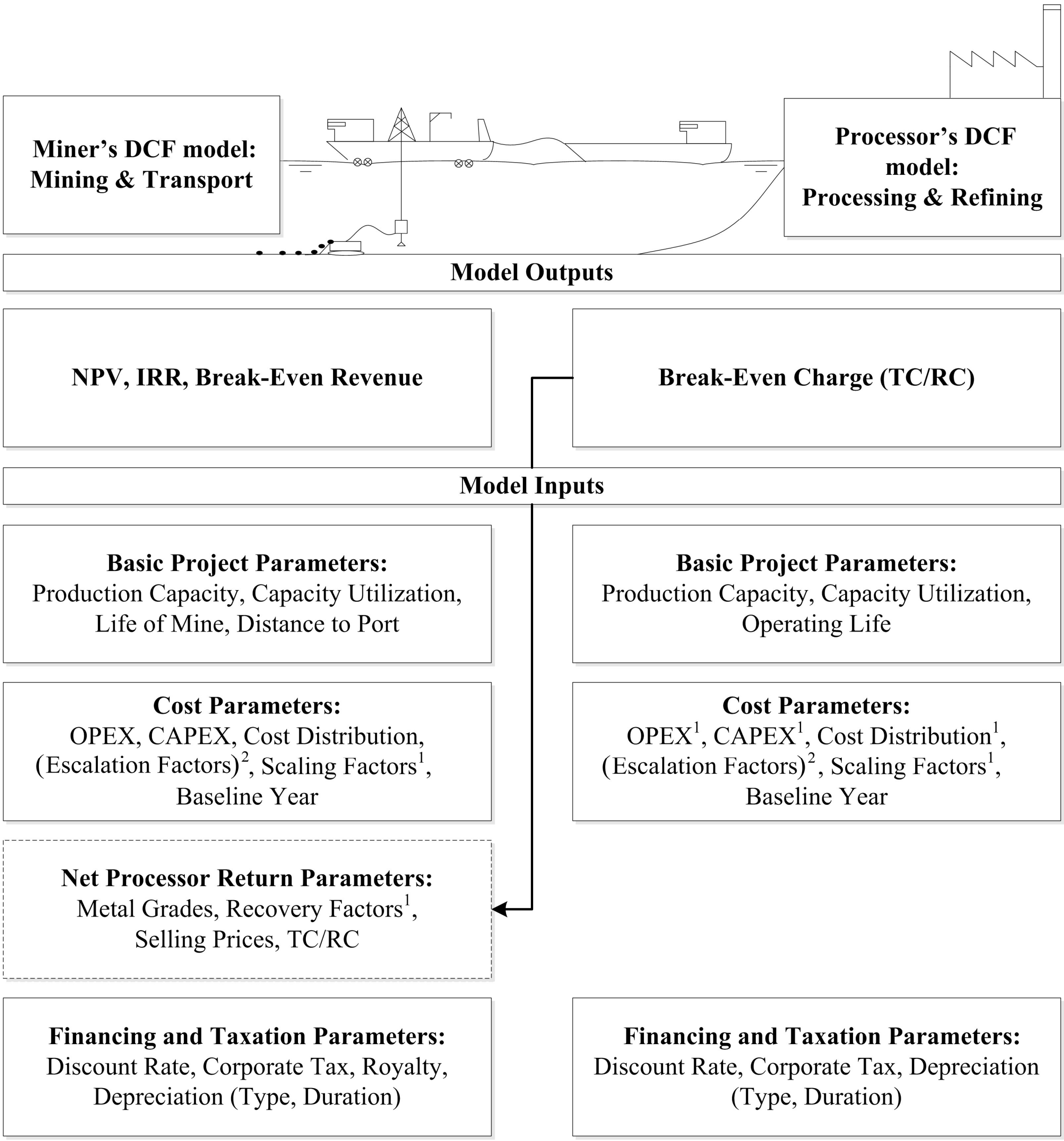
The discount rate (DR) used in the scenarios of this study is the minimum IRR required to invest in a DSM project. Even if no SMnN mine is yet in operation, these projects are considered as high-risk investments due to technological, geological and legal uncertainties, among other aspects. Therefore, DRs of 15% to 25% apply in the GAP analysis (Table 4.2). An IRR of around 30% is anticipated to be commensurate with the level of risk currently associated with the first SMnN projects (Arthur D. Little Inc. 1977; Hoagland et al. 2010; Kuhn et al. 2011; Martino and Parson 2013). ISA states that a SMnN mining project would require 5 to 10 extra percent compared to land-based mining projects of the same order of magnitude to compensate the increased risk (ISA 2013).

4.3 Methodology

This section presents methods and procedures for economic analysis of the Blue Mining case study, which are widely used in the evaluation of land-based mining projects. A sensitivity analysis is carried out to identify the most influencing factors on the profitability of a SMnN mining project. The economic feasibility of the Blue Mining case study is analyzed against past and future cost and price trends.

4.3.1 Development of Economic Key Figures

Traditionally, the NPV and the IRR are guiding factors in investment decision for new mining projects (Wellmer et al. 2008). In this study, the net profit (NP) is used as a further indicator of profitability. The calculation of the economic key figures is subject to financial modeling based on a simplified discounted cash flow method (DCF) and assuming constant annual net cash flows. The CAPEX is depreciated over 20 years using the straight-line method. Assumptions and estimates of the GAP scenarios apply (Table 4.2). A deterministic DCF model is used (Figure 4.4). The mining and transport and the processing and refining of SMnN are considered as separate model units. The project is evaluated from the miner's perspective. The output variable of the processor's model unit is the treatment and refining charge (TC/RC) to be paid by the miner.



[1] Parameters derived from a statistical evaluation of SMnN studies. [2] Inflation is not considered in the simplified model.

Figure 4.4. Parameters of the economic/financial model.

Net Present Value

In this study, the **"net present value"** (NPV[13]) calculates as the product of the annual constant net cash flow (after tax and royalty) and the present value annuity factor (PVAF), less the initial investment (Wellmer et al. 2008). A project is accepted for positive NPVs only. The NPV is derived from the miner's DCF model unit. This requires

[13] The NPV is the present estimated dollar value of an investment/project based on future net cash flows adjusted for interest rates and the initial investment. When the net cash flows are even, the NPV can be calculated by using the present value formula of annuity (Wellmer et al. 2008).

the determination of the net processor return—in this context referred to the common "NSR."

The **"net smelter return"** (NSR) "[…] is defined as the proceeds from the sale of mineral products after deducting all off-mine costs relating to the transportation, treatment and sale of those products" (Goldie and Tredger 1991). The miner's NSR (R'_{NSR}) is determined by the sales value and accordingly revenue (R'), which is offset against the TC/RC (Formula 4.1). Hereinafter, the (for the processor) minimum acceptable TC/RC ($\hat{R}'_{TC/RC}$) applies. Off-mine costs other than the TC/RC are neglected (and are not included in the formula) for reasons of simplicity.

$$\boldsymbol{R'_{NSR} = R' - \hat{R}'_{TC/RC}} \qquad 4.1$$

Where:

R'_{NSR}	= NSR per dmt SMnN [$/t]
R'	= Revenue per dmt SMnN (sales value) [$/t]
$\hat{R}'_{TC/RC}$	= Break-even TC/RC per dmt SMnN [$/t]

Internal Rate of Return

The **"internal rate of return"** (IRR) is the DR at which the NPV is nil (Wellmer et al. 2008). The IRR is solved iteratively by recalculating the break-even TC/RC and NSR for different DRs. In the base case, the same DR applies for the miner as for the processor. In this case the TC/RC is variable (assuming a profit/risk-sharing between miner and processor). Alternatively, a fixed TC/RC is assumed. A project is accepted if the IRR is not less the DR specified for the respective case scenario (Table 4.2).

Net Profit

The **"net profit"** (NP) is a measure of the profitability of a venture after deducting all costs from the total revenue (Farris et al. 2010). Other than to its common definition in accounting, the (NP') is defined as the remaining value after deducting the break-even value from the sales value (of ore) from which revenues are generated (Formula 4.2). It is expressed in $ per dry metric ton of SMnN recovered from the seafloor. The break-even calculation is based on a method of investment appraisal. Accordingly, a mining project is accepted for positive values ($NP' > 0$).

$$\boldsymbol{NP' = R' - \hat{R}'} \qquad 4.2$$

Where:

NP'	= NP per dmt SMnN (after tax and royalty) [\$/t]
R'	= Revenue per dmt SMnN (sales value) [\$/t]
$\hat{R}'$	= Break-even revenue per dmt SMnN (sales value) [\$/t]

The **"sales value"** (R') indicates the value of ore (SMnN), expressed in \$ per dry metric ton of SMnN. In the model, revenues from a single SMnN mining operation are generated from the sale of Ni, Co, Co, and optionally FeMn. Due to the polymetallic composition of SMnN, the sales value will depend on the selling price of the respective product and the metal content recovered from the ore, which in turn depends on the recovery rate and metal grade (Formula 4.3).

$$\boldsymbol{R' = \sum_{m=1}^{k} p_m \times (\eta_{R\,m} \times g_m)} \qquad 4.3$$

Where:

R'	= Miner's revenue (sales value) [\$/t]
p_m	= Selling price of product containing metal m [\$/t]
g_m	= Average grade of metal m in ore [%]
$\eta_{R\,m}$	= Average recovery rate for metal m [%]
$\eta_{R\,m} \times g_m$	= Recoverable metal content (M'_m) [%]
k	= Number of metals recovered (here three or four metals)
m	= Ni (1), Co (2), Cu (3), and optionally Mn sold as FeMn (4)

The **"break-even sales value"** ($\hat{R}'$) is the economic minimum value of ore that is required to provide the miner and the processor (and if applicable, other entities) with adequate revenue (Formula 4.4). From the miner's perspective, the break-even value is the minimum sales value and accordingly revenue required to cover all costs of launching and running a SMnN project, including the TC/RC. Break-even figures can be considered as both, costs and minimum revenues required to cover costs.

$$\boldsymbol{\hat{R}' = \hat{R}'_{NSR} + \hat{R}'_{TC/RC}} \qquad 4.4$$

Where:

$\hat{R}'$	= Break-even revenue (sales value) [\$/t]

$\hat{R}'_{NSR}$ = Break-even NSR (after tax and royalty) [$/t]

$\hat{R}'_{TC/RC}$ = Break-even TC/RC (after tax) [$/t]

The **"break-even NSR"** is the minimum revenue (sales) for the miner ($\hat{R}'_{NSR}$) required to cover all costs, less the TC/RC. In this contribution, the break-even value is the NSR at which the NPV of the miner's model unit is nil (Appendix; Table A.7.1), expressed in $ per dry metric ton of SMnN recovered.

Accordingly, the **"break-even TC/RC"** is the minimum revenue for the processor ($\hat{R}'_{TC/RC}$) to cover all costs related to the processing and refining of SMnN. In this contribution, the break-even value is the TC/RC at which the NPV of the processor's model unit is nil (Appendix; Table A.7.2), expressed in $ per dry metric ton of SMnN processed.

4.3.2 Evaluation of Cost and Price Trends

The "US-Producer Price Index" (PPI) is used as a deflator (US Bureau of Statistics 2016). Break-even figures of the year-end 2015 are translated to the value of money in the respective year. A linear trend line is derived from that historic data and is extended to the year 2025. In contrast, constant break-even values of the respective scenarios (Table 4.2) are compared to a time series (1970 to 2015) of calculated sales values, showing the development of the value of ore over time (Formula 4.3). The sales value (i.e., revenue per dmt) is based on metal prices (Section 4.2.3) and is expressed as constant 2015-$. Due to fluctuating metal prices, the moving average method is applied to smoothen the data set (Wellmer et al. 2008). A linear trend line is derived from the series of 5-year moving averages (5-YR MA) and is extended to the year 2025. Referenced forecasts are deflated to year 2015 using the "Manufactures Unit Value Index" (MUV). Indices forecasted by the World Bank Group (2016) apply.

4.4 Results

In the following section, the results of the GAP and sensitivity analyses are shown with focus on the IRR, NPV, and NP. Break-even figures are opposed to past and future cost and price trends. Price and cost changes as well as forecasts become part of the discussion (Section 4.5).

4.4.1 Economic Key Figures

NPVs and IRRs are shown for the different GAP scenarios (Table 4.3). The hypothetical Blue Mining project settings would be most promising in combination with four-metal (4M) recovery under good or even average conditions (Table 4.2). The NPV (before tax and royalty) is estimated to range between US$1 and US$4.4 billion before tax and to range between $0.5 and $2.8 billion after tax and royalty. Under poor conditions or average conditions implying three metal (3M) recovery, a project is not attractive for investment. The NPVs are negative, whereas the IRRs of the respective scenarios are lower than the assumed DRs (Table 4.2). Tax revenues of about $0 to $5 billion and royalty revenues of about $0 to $0.8 billion would be generated over 20 years.

IRRs range from 6% to 45%, after interest, tax and royalty, if the TC/RC is variable and adapts to the (overall) economic viability of the venture. The 4M average-case scenario results in an IRR of 28% (after tax and royalty), 8% above the (hurdle) rate by which future cash flows are discounted (20%; Table 4.2). IRRs below 7% are far below the DR set for the 4M poor or 3M average-case scenario. A fixed TC/RC would be advantageous for the miner under good and average conditions, resulting in higher after-tax IRRs of 38% to 91% but would be to its own detriment under worse conditions. Due to the strong dependency between miner and processor to be expected at the beginning of DSM, it can be assumed that no constant TC/RC will be negotiated under the assumption that processing plants for SMnN have yet to be built (Ecorys 2014).

Table 4.3. Figures on NPV and IRR estimated for the respective GAP-scenarios specified for the Blue Mining case study at economic factors of year-end 2015.

Item	**Good**	**Average**		**Poor**	**Unit**
	4M	4M	3M	4M	
NPV before tax and royalty	4,437	1,032	−662	−983	$M
NPV after tax and royalty	2,812	496	−698	−985	$M
IRR[1] before tax and royalty	135 | 53	58 | 32	− | 9	− | 8	%
IRR[1] after tax and royalty	91 | 45	38 | 28	− | 7	− | 6	%

[1] The first figure refers to the IRR assuming a fixed TC/RC (Section 4.3.1). The second figure refers to the IRR if the same DR applies for the processor as for the miner. In this case, the TC/RC is variable and adapts to the (overall) economic viability of the venture. If no positive rate or no valid result was determined, this is indicated by a hyphen.

Sensitivity is shown for different input parameters of the 4M average-case scenario on the NPV (Figure 4.5). The value of ore (i.e., sales value), the TC/RC and the DR, and the annual production are the most decisive factors from the miner's perspective. In detail, the sales value (and thus revenue per dmt) would be most sensitive toward price changes for FeMn and Ni, which is consistent to their share on the gross annual sales. In this study, about 53% of the revenue would be generated by the sale of FeMn, about 27% by the sale of Ni, about 13% by the sale of Co, and only 7% by the sale of Cu. The value of ore must not derivate by more than −16% from its baseline value (i.e., amounting to \$546/dmt; Table 4.2). The production must not deviate by more than approximately −40%, the TC/RC +30%, and costs by not more than +80% from the baseline value when considered individually.

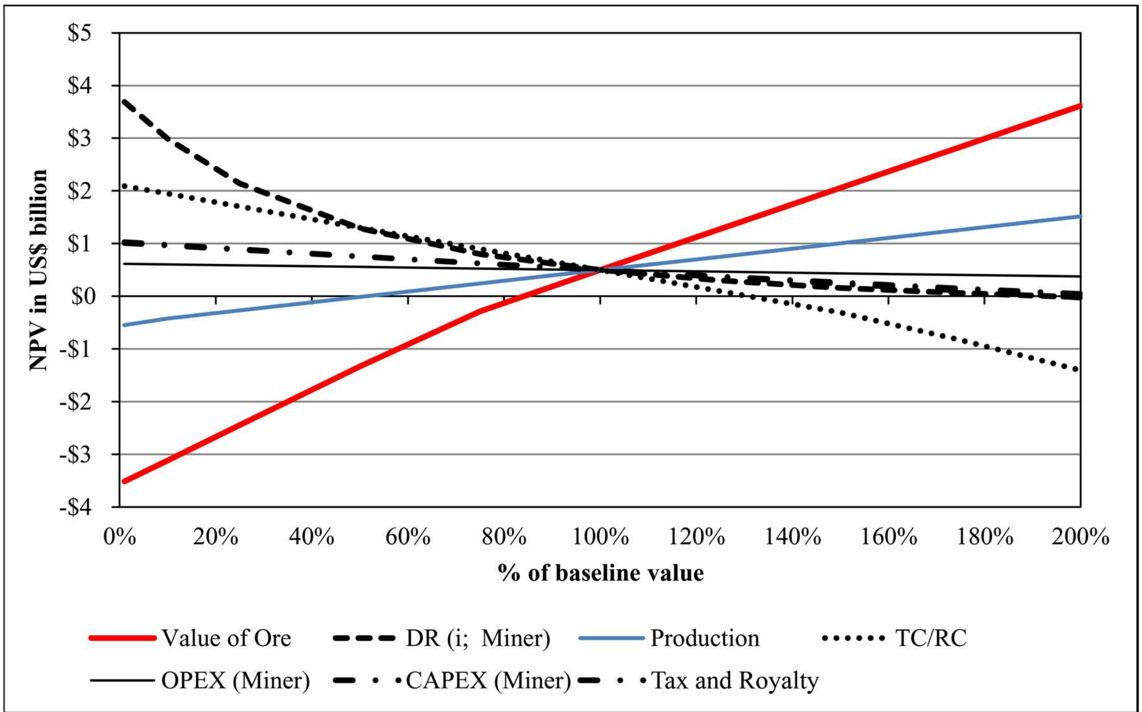


Figure 4.5. Sensitivity of selected input parameters on NPV estimated for the four-metal (4M) average-case GAP scenario of the Blue Mining case study, with economic factors from year-end 2015.

The TC/RC is estimated to be higher than the required NSR under which the investment would be attractive for the miner (Figure 4.6). This is primarily due to the higher costs for the processing and refining of SMnN (Table 4.2). The comparison of the 3M with the 4M average scenario shows that the recovery of FeMn should be aimed to make the project economically viable. The DR has significant influence on the profitability as it inflates the break-even sales values (= costs; Figure 4.7). For example, the minimum sales value (accordingly revenue per dmt), which must be obtained at a DR of 1%, is almost half as would be required at a DR of 30%.

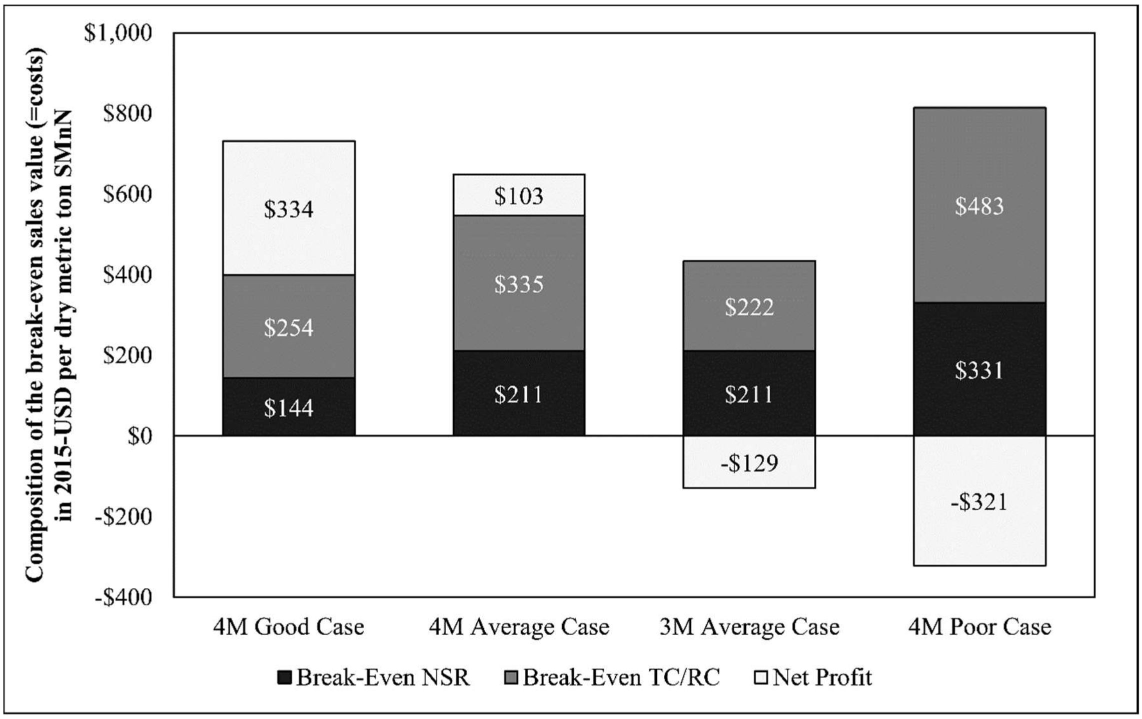


Figure 4.6. Break-even sales value estimated for the GAP scenarios. The net profit is the difference between the sales value and the break-even value (= costs).

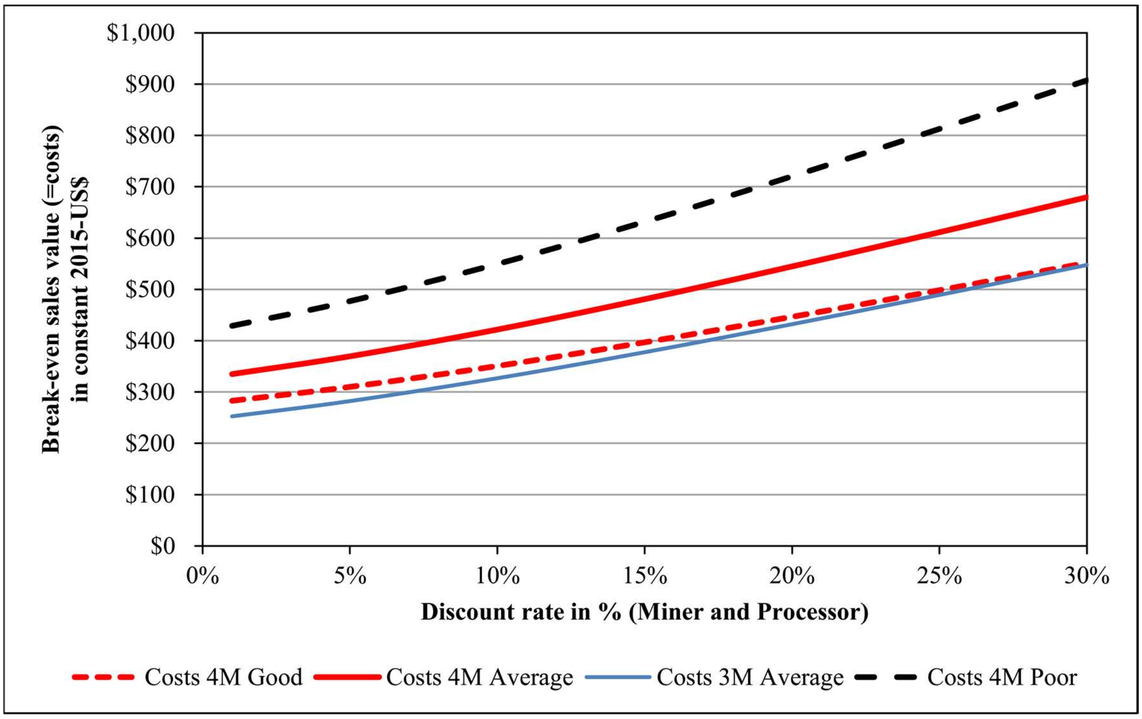


Figure 4.7. Break-even sales value (= costs) estimated for the GAP scenarios of the Blue Mining case study.

4.4.2 Cost and Price Trends

The break-even sales value can be considered as a cost figure. It thus depends on the development of costs arising for the miner and processor (Figure 4.8). Apart from minor fluctuations, a moderate but steady increase of costs can be observed. In the past, prices of mineral commodities were significantly influenced by the effects of the oil crisis (1981–1987) or by the global financial crisis in the new millennium (Bräuninger et al. 2013).

The average annual increase of value during the years 1970 and 2015 amounts to about 3%. Extending the trend line to the year 2025, minimum sales values of approximately \$1,000 (4M poor), \$700 (4M average), and \$300/dmt SMnN (4M good-case scenario) should be obtained to attract investors for SMnN mining. Sales and accordingly revenues of at least about \$750/dmt must be generated in the average case of 3M recovery.

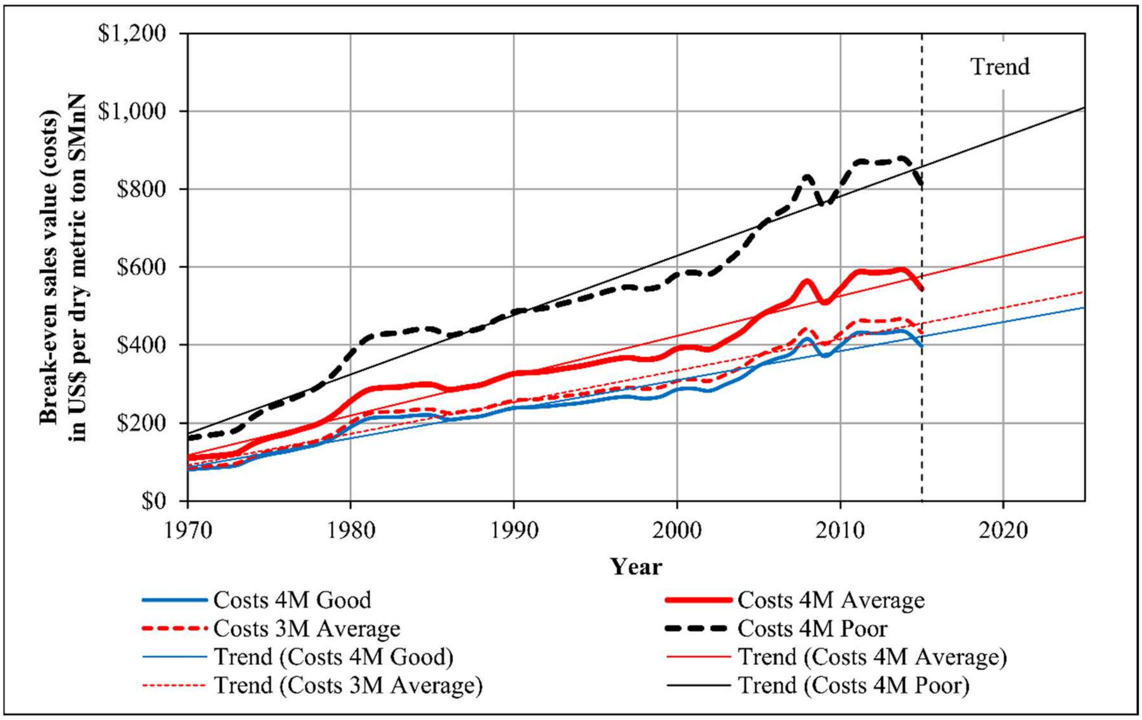


Figure 4.8. Past and future development of the hypothetical break-even sales value of SMnN expressed in US\$/dmt, determined for the GAP scenarios using data from the US Bureau of Statistics (2016).

Revenues generated from the sale of metals are subject to major fluctuation (Figure 4.9; Figure 4.10). The impacts of the oil crisis and the global financial crisis are more evident when compared to estimated costs (break-even sales values). Since 2002, metals have shown a price increase due to increasing production costs in land-based mining, an increased demand and partly a limited supply (Bräuninger et al. 2013). Since their peak in 2011, metal prices have been on a downward trend resulting from global economic recession. Prices fell to about \$530/dmt in 2016.

In case of 4M recovery, the average sales value of ore would have amounted to about \$580 during the years 1970 and 2000 and to around \$760/dmt during the years 2000 and 2015 (Figure 4.9). In comparison to the time series of revenues, the estimated break-even sales values (minimum revenues per dmt) required to cover costs are estimated to be about \$400 for the good, \$550 for the average, and \$820/dmt for the poor-case scenario. It is evident that the good-case scenario shows highest attractiveness for investment only with minor time frames of deficits during the 1980s. Even under moderate conditions, only short periods (1981–1987, 1998–2003, and 2016) would have brought costs (break-even sales values) above the value of ore. In contrast, high metal prices as seen in 2006 and 2012 would be required for profitable DSM under conditions of the poor-case scenario.

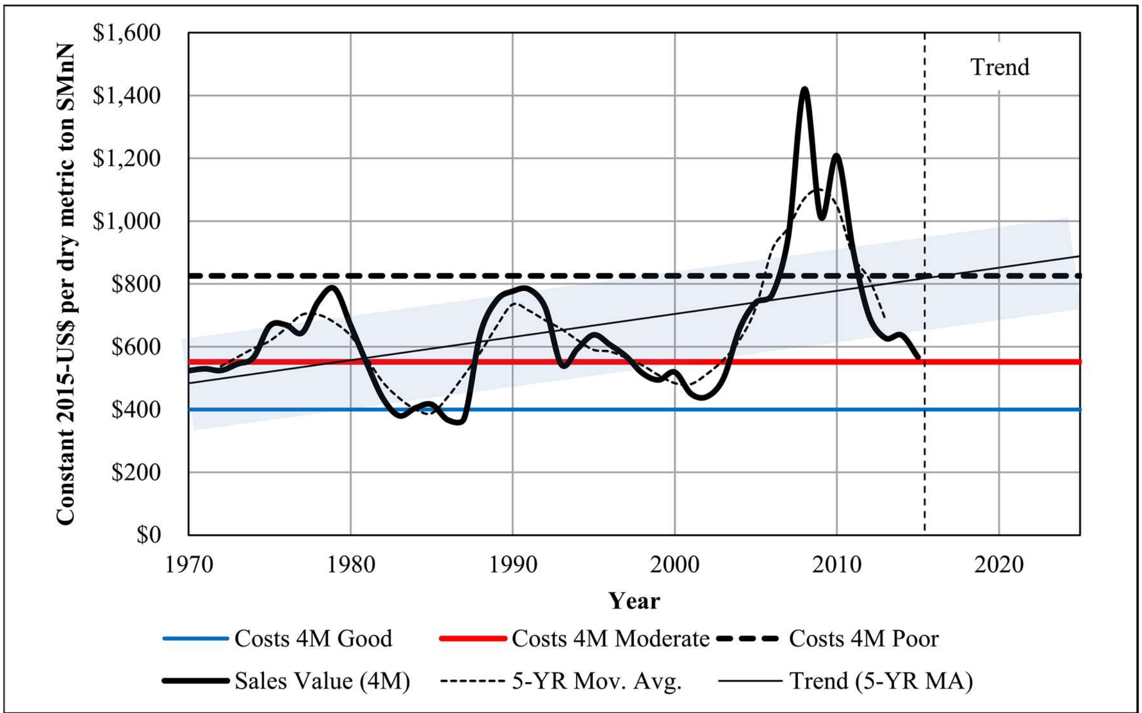


Figure 4.9. Past and future development of the sales value expressed in constant 2015-\$/dmt SMnN considering the recovery of Ni (95%), Co (90%), Cu (94%), and Mn (85%) at constant grades Ni (1.3%), Co (0.17%), Cu (1.1%), Mn (29.2%). The gray bar indicates the standard deviation from the trend line. Sales values are based on data reported by the USGS (2016), ISA (2008a) and Rühlemann et al. (2011).

With outlook to year 2025, a growth rate of the sales value of ore of about 1.9% per annum (starting in 2015) would be required to make SMnN mining attractive under poor conditions (costs). Considering the historical long-term trend (5-YR MA; 1.6%

real growth; standard deviation of +/− $150/dmt), the sales value and accordingly revenue could range between $740 to $1,040/dmt in 2025.

In case of 3M recovery, the average sales value and accordingly revenue would have amounted to about $280 between 1970 and 2000 and to about $340/dmt until 2015 (Figure 4.10). In comparison, the revenue generated from the sales must be minimum $430/dmt SMnN (average-case scenario). Based on this estimate, mining would have been attractive only at peaks of the years 1979 and 2006 to 2008.

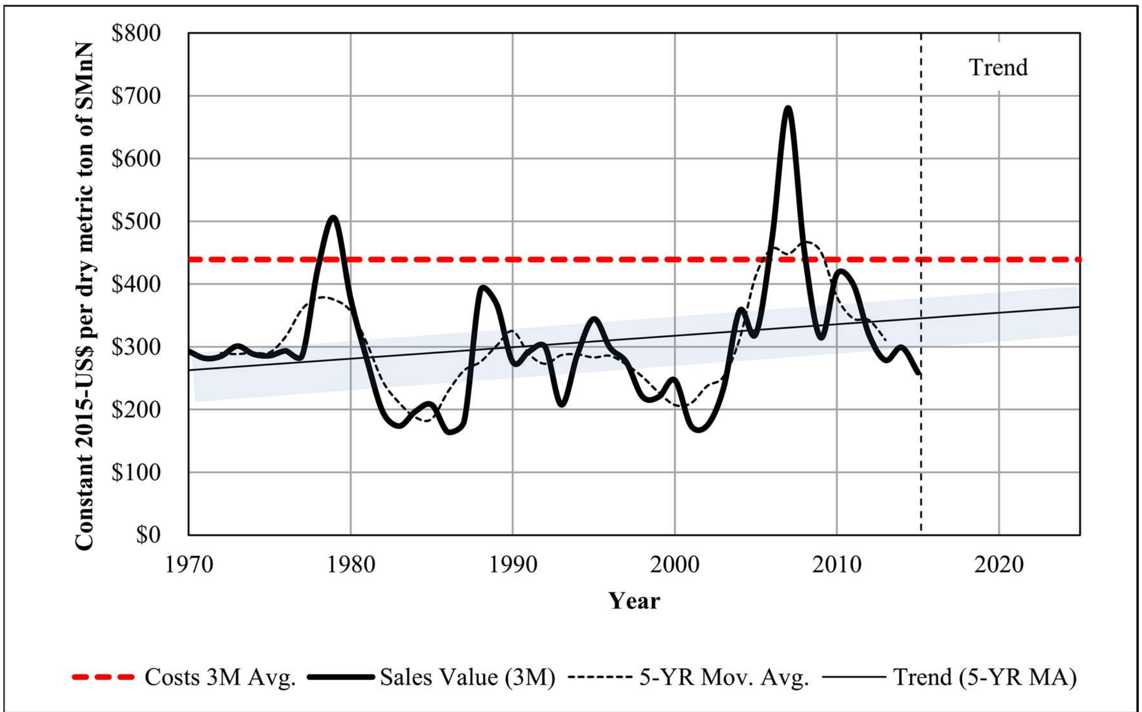


Figure 4.10. Past and future development of the sales value per expressed in constant 2015-$/dmt SMnN considering 3-metal recovery of Ni (95%), Co (90%) and Cu (94%) at constant grades Ni (1.3%), Co (0.17%), Cu (1.1%). The grey bar indicates the standard deviation from the trend line. Sales values are based on data reported by the USGS (2016), ISA (2008a) and Rühlemann et al. (2011).

With outlook to 2025, a growth rate of 2.7% per annum (starting in 2015) would be required to turn SMnN mining attractive, recovering Ni, Co, and Cu, only. Considering the historical long-term trend (5-YR MA; 0.7% real growth; standard deviation of +/− $70/dmt), the sales value and accordingly revenue could range between $296 to 434/dmt in 2025.

4.5 Discussion

This section discusses the validity of the methods used to determine the profitability of SMnN projects and the results of the Blue Mining case study. The discussion aims to clarify the economic framework conditions for the start of SMnN projects in the foreseeable future. The discussion includes the background to the research (i.e., the assumptions and estimates) in connection with the financial analysis.

4.5.1 Critical Review of the Methodology

Data Accuracy

Mining engineers are accustomed to dealing with uncertainties and risks, especially when facing mineral projects in new environments (e.g., in space; Gertsch and Gertsch 2005). At the current stage of technological readiness, it is inevitable for the estimate of the economics of a DSM project to rely on assumptions and information from published studies (Section 4.2.3). In particular, environmental costs and TC/RCs (i.e., the processing and refining costs) are uncertain and difficult to estimate. Therefore, environmental costs were not considered. Also, the TC/RCs shown in this study are based on (prepared) data from earlier DSM cost studies as the metal recovery processes for SMnN differ from those known in land-based mining (Pophanken et al. 2013).

However, inaccuracies occur in the data preparation of studies. These include the allocation, indexation, and scaling of costs that are necessary to make costs comparable. The problem is that the selected studies (Section 4.2.3) differ in date and level of detail; the large spread of costs (Figure 4.3) is due to different technologies and different scientific knowledge at the time. A comparison with current studies—for example, SPC (2016) or BMWi (2016)—shows that the identified costs (Table 4.2) are quite similar or even slightly higher for the same capacity (van Nijen et al. 2018). The (indexed) 2015 costs of the 1970s and 80s studies (Arthur D. Little Inc. 1977; Nyhart et al. 1978; Andrews et al. 1983; Hillman and Gosling 1985) are significantly higher (Volkmann 2014).

It should also be emphasized that the assumptions of the Blue Mining case study are project-specific and may only apply to pioneer projects. The first pioneers will have to develop the full mining technology chain and may experience technical and operational difficulties with no precedents to learn from (Reydellet and Volkmann 2017). For example, a processing plant could also be supplied by more than one mining company and would be more economic due to economies of scale (Wellmer et al. 2008). Conservatively, the construction of one new plant per mining operation (one MSV) is to be assumed. According to Volkmann and Lehnen (2017), the plant's capacity would be restricted by the mining operation. A production in the range of 1.5 to 2 Mt/a is considered realistic, but most studies assume 1.5 Mt/a in their calculations (SPC 2016).

A DR of up to 25% or higher may apply to safeguard a project against uncertainties and project risks (Table 4.2). The expectations of the required IRR are company-specific. In addition to legal and geological certainties, mining tests are required to demonstrate technical and economic feasibility and to assess the minimum acceptable IRR. In addition, it should be considered that commercial ventures must make a profit, while governments and their agencies may not (Gertsch and Gertsch 2005). In addition, tax payments have a significant impact on profitability (Volkmann and Osterholt 2017). However, a tax regime and regulations for the exploitation of SMnN are under development. Fiscal incentives were proposed (Reydellet and Volkmann 2017), which could stimulate DSM and contribute to sustainable development (Volkmann 2014).

Analytic Approach

Given the prevailing uncertainties, a DCF method was used. DCF methods are used in 75% of the mining companies, although other valuation methods allow for better consideration of uncertainties (Kulatilaka and Marcus 1992; Mirakovski et al. 2009). The advantage is that the figures are relatively easy to calculate and do not require deep economic knowledge. A stochastic economic evaluation is reasonable when a more detailed analysis is required and possible with the underlying data (van Nijen et al. 2018). It is also common in the financial modeling of mining projects to build on historical price/cost data when planning with time horizons of several decades. Costs and prices were indexed using the PPI for the sake of simplification—"only in a complete feasibility study would one work with differently inflated prices and costs" (Wellmer et al. 2008).

Facing erratic price fluctuations of metals, mining companies employ different methods for price assumptions. An established method is to derive minimum or break-even prices from cash cost curves that, among other things, require cost data from all producing mines (Wellmer et al. 2008). At that time, the economic viability of SMnN mining depends on more than one metal (Volkmann and Osterholt 2017). This makes a cost comparison with land-based projects complicated, even if bringing costs down to a common denominator (e.g., costs per metal-equivalent unit; Dick 1985). Therefore, it is suggested to compare sales with break-even sales values (= costs) derived from the financial models, using the NP criterion for an investment decision (Formula 4.2). A strict separation between financial modeling and price forecasting is not possible as both the value of ore and costs depend on the processing and refining technology.

Considering the time value of money, high expectations on the IRR artificially inflate the break-even sales value, making a project technologically and operationally more difficult (Figure 4.8). Despite the use of constant cash flows and the neglect of inflation, the major advantage of the presented approach lies in the separation of costs and prices. Although the approach is used for investment calculation and relies on the NPV criterion, the break-even sales value might be defined and used differently. In certain cases—for example, when comparing different projects—it may be reasonable to choose the IRR. Prediction methods could be applied to estimate future price and costs (Costa Lima and Suslick 2006; Bernard et al. 2008). Also, price forecasts should take into account the possibility of price changes induced by DSM (Martino and Parson 2013).

Applicability of the Key Figures

The methodology presented in this study can be used to assess the feasibility of DSM projects. Although the applicability is limited, it can be useful for investment decisions. For example, the NP as an economic key figure has proven helpful in identifying areas of potential economic interest (Volkmann et al. 2018a). However, to allow for a more accurate estimate of the profitability of a project, cash flows could be derived from production simulations—using other methods and key figures. It is expected that, among other factors, the shape and size of a mining field as well as site and field conditions (i.e., the size, number, and spatial distribution of in-field obstacles and nodule abundance) will influence the mining route and thus the economic performance of the operation (Volkmann and Lehnen 2017; Volkmann et al. 2018a).

It is proposed that a field should be mined if a sufficient cash flow is provided over a certain period of time. For this purpose, average daily profits could be estimated (Formula 4.5). Accordingly, mining routes and field layouts/designs could be determined that, for example, result in the maximum daily profit. To maximize the NPV, a field below an as yet undefined cutoff daily profit may not be mined or postponed. A dynamic approach must consider field-to-field travel and associated production and therefore the mining sequence. In a more general approach, or if mining is not moving from one field to another, the respective figures could be replaced by the quantity of SMnN in the mineable area, the overall mining efficiency, total operating costs, and also by time efficiency (Volkmann and Lehnen 2017). In order to determine mining routes, operating costs and mining and time/field efficiencies must be determined first (Volkmann and Lehnen 2017).

$$\boldsymbol{DP_i} = \frac{\left(\boldsymbol{R'} \times \boldsymbol{RSV_{F_i}} \times \boldsymbol{\eta_{MF_i}}\right) - \boldsymbol{C'_i}}{\boldsymbol{T_{MC_i}} \times \boldsymbol{\eta_{T_i}}} \quad (4.5)$$

Where:

DP_i	= Daily profit of field i [\$/d]
R'	= Sales value SMnN [\$/dmt]
RSV_{F_i}	= Reserve of field i [dmt]
η_{MF_i}	= Mining efficiency achieved in field i [%]
C'_i	= Operating costs to mine field i [\$]
T_{MC_i}	= Theoretical time (max. mining capacity) to mine field i [d]
η_{T_i}	= Time efficiency achieved in field i [%]

However, societal (resource-related) and environmental objectives should be integrated in future concepts. In that case, the ambition may not be to maximize the NPV only. However, further research is required on how the sustainability performance could be measured and integrated into the assessment of SMnN projects and deposits.

4.5.2 Validity of the Results and Outlook

Validity of the Key Figures

According to the findings of this study, SMnN mining could be an attractive investment opportunity if conditions of the good- or average-case scenario apply (Table 4.2). A project would be economically viable if focusing on the metals Ni, Co, Cu, and Mn. In this event, a project could easily shoulder additional costs of ~$500 million under assumed moderate conditions, resulting in an acceptable IRR (Table 4.3). That could act as an additional buffer for uncertainties and risks. Assuming a production of 20 years or longer, the value of SMnN at that time should exceed $550/dmt (break-even point; 4M average-case scenario). Even though the techno-economic feasibility and the environmental requirements need to be assessed through DSM tests and environmental impact studies, it is expected that a pioneer project would require financial support.

The profitability figures of the Blue Mining case study (IRRs) are broadly comparable to the results of recent studies (BMWi 2016; SPC 2016; van Nijen et al. 2018). The results seem to be slightly overly optimistic when compared to updated financial figures (Volkmann 2014) of the studies carried out in the 1970s and 1980s (Arthur D. Little Inc. 1977; Nyhart et al. 1978; Andrews et al. 1983; Hillman and Gosling 1985). However, it is generally recognized that 3M recovery is less profitable compared to 4M recovery (Arthur D. Little Inc. 1977; Hillman and Gosling 1985; SPC 2016). Although rare earth elements, lithium, and other elements have become increasingly important for future high- and green-tech applications (Hein et al. 2013), their distribution behavior, as well as their extraction, has hardly been investigated (Pophanken et al. 2013). According to SPC (2016), the extraction of these (trace) elements is not feasible at the present time.

Outlook on SMnN Mining

The launch of a DSM project will rely on the forecast of future revenues and projected profitability (Hoagland 1993; Martino and Parson 2013). Costs—notably OPEX for fuel, related products, and power—are anticipated to be crucial elements for launching an SMnN mining project. Given the assumption that these costs might have a share of up to 80% (Kuhn et al. 2011), price changes might be even more decisive. Metal but also fuel or fuel-based prices are subject to strong, often difficult-to-predict fluctuations. Volatility can be traced back to sudden and unforeseeable incidents that are unpredictable, such as natural hazards, worker protests, the burst of speculation bubbles, and the outbreak of other crises. To some extent, developments follow long-term trends—for example, technological developments, which can be derived from historical data as shown (Figure 4.8). However, these trends may not be linear as assumed in this study.

The economic performance of a DSM project—as exemplified by the Blue Mining case study—would chiefly depend on the revenues obtained from the sales of Ni and FeMn (estimated at 27% or 53% of the total sales value; 4M average-case scenario). The TC/RC would be the main cost driver (Figure 4.5). The profitability of a mine would therefore depend on price developments and technical progress in processing and refining. There is a mutual dependency between the steel price and metal prices of the alloying elements Mn, Co, and Ni used to produce stainless steel and other alloy steels. The steel industry has in a major way influenced the price development of these metals in the past (Bräuninger et al. 2013). Main consumers of steel are the construction and the automotive industries, which are expected to grow in the future (Gajigo et al. 2011).

The future of SMnN mining is expected to depend on the development of electromobility, as Mn, Co, and Ni are used in Li-ion batteries. In light of increasing global demand for these metals (Marscheider-Weidemann et al. 2016; Tisserant and Pauliuk 2016), it is reasonable to assume that the hypothetical value of ore (SMnN) will recover after 2016 (this was the case for 2017). This would also correspond to linear long-term trends (Figure 4.9; Figure 4.10).

Although Co may not add much to a company's revenue (estimated at 13%; 4M average-case scenario), it might be the decisive factor for governments in whether to support SMnN mining. The European Commission has classified Co as critical in terms of economic importance and supply risk (EC 2017). In the past, production restrictions imposed by the government of the Democratic Republic of Congo and political instabilities have been the main reason for supply shortages and increases in price (Bräuninger et al. 2013). In contrast to the former metals, Cu is of minor importance for the economic feasibility of a project (estimated at 7%; 4M average-case scenario).

Based on recent forecasts (long-term 2025), the value of SMnN may range between \$600 to \$650/dmt in the event of 4M recovery (Consensus Economics, Inc. 2015; World Bank Group 2016). In the event of 3M recovery, the hypothetical sales value may range between \$280 and \$330/dmt SMnN (World Bank Group 2016). At this time and for the foreseeable future, SMnN mining projects would be launched at the verge of profitability, while they would probably not be profitable in the event of 3M recovery (Figure 4.9; Figure 4.10). Despite speculation about future metal prices and the value of SMnN, legal developments and environmental requirements are critical to the economics of a DSM project and must therefore be seriously considered in future economic studies.

Although not within the scope of this study, a detailed market study must be conducted when seeking to invest in SMnN mining. It is as yet uncertain at which price and in what quantity FeMn as well as other products could be produced and sold. As pointed out by Martino and Parson (2013), mining companies with assets (mines) on land could see price reductions as an effective measure to hinder SMnN ventures to enter the market (Marvasti 1998, 2000). A single SMnN mine could put a large amount of FeMn on the market (Table 4.1), and the high sensitivity to profitability (Figure 4.5) could be a threat with increasing activity in the fields of DSM.

Despite the predicted increase in demand for high- and green-tech elements contained in SMnN (Hein et al. 2013)—in particular Co—developments in land-based exploration, and mining (Bleischwitz and Bringezu 2009; Hermanus 2017) as well as circular economy concepts (Antikainen et al. 2018) may render DSM unnecessary or uneconomic. Apart from that, as yet undiscovered resources may be identified on land in addition to those becoming reserves (Meinert et al. 2016). The competitiveness of DSM compared to land-based mining must be examined in more detail (Dick 1985).

Environmental Considerations

Besides economic aspects, it is important to emphasize the environmental problems of SMnN mining. Two major environmental problems can be recognized in the proposed concept (Figure 4.2):

1) The greatest unknown and the greatest potential hazard is the behavior and effects of sediment plumes at the bottom of the ocean, within the water column, and at the surface (MIDAS 2016a,b). Effective regulations, measures, and costs for environmental protection and the return of the mine site to an "acceptable state"—still to be defined—have yet to be determined (e.g., through mining tests and environmental impact studies).

2) In this study, only small quantities of metal were recovered (Table 4.2), and little is known about the rest products formed in the process (Pophanken et al. 2013). SMnN mining may cause a costly waste problem, as known from land-based mining (Lottermoser 2007). Research is currently being carried out into processing methods that aim to significantly reduce the amount of waste. In particular, the extraction of Mn from SMnN would reduce the amount of waste due to the high metal content (~30 wt% Mn; Friedrich and Friedmann 2017).

As the environmental costs are unknown and difficult to estimate, these costs have not been estimated but are reflected in the DRs. It has been shown that under moderate and good conditions, an additional financial buffer would protect the project against uncertainties and risks. However, the question is whether the DRs adopted in this study are justified to safeguard a project from adverse environmental impacts. The challenge for future studies will be to take a closer look at environmental risks and costs and include them in the calculations. The studies will depend crucially on the results of the environmental studies obtained from the mining tests. In this respect, it can be assumed that the costs for a (precommercial) pilot mining test must be included in such a study.

4.6 Conclusions

The estimated figures have proven to be largely consistent with the research results of other studies, even if they differ slightly. The calculation of break-even sales values has proven to be a simple way to investigate profitability by comparing break-even sales values with past, present, or future sales values. In contrast to NPV and IRR, the NP analysis allows the definition of requirements and the validation of assumptions for spatial mine planning. However, the analysis is inaccurate and limited in its applicability and should therefore only be used in prefeasibility studies. For an accurate economic assessment reliable models and data, proven/approved technologies, methodologies, and tools are required. A detailed study should include comprehensive market analyses that consider, among other things, forecasts on prices, costs, supply, and demand.

Although the estimates are uncertain, research has demonstrated the economic potential of SMnN mining and its associated socio-economic benefits. A project would (potentially) be economically viable if Ni, Co, Cu, and FeMn were sold under moderate and good conditions (Table 4.2). The discount rate, treatment and refining charges (TC/RC), annual production rate, and sales prices of FeMn and Ni have the greatest effect on profitability, while the figures are marked by greater uncertainty. Thus, the development of cost-effective mining systems and processing routes offers a perspective for further research and development activities. Given the financial risks associated with such a billion-dollar (investment) project, state support and fiscal incentives are seen as a necessary measure to realize DSM. Project uncertainties and risks need to be investigated—in particular with regard to the as yet unknown environmental costs.

5 A Comprehensive Approach for a Techno-Economic Assessment of Manganese Nodule Mining on the Seafloor

A version of this chapter has been published in Mineral Economics *and is referred to as Volkmann et al. (2018a).*

5.1 Introduction

The first mining activities go back to the Stone Age (Sieveking et al. 1972). Since then, technologies have evolved from manual picking to high-tech mining, from the surface to the underground, and from the land to the sea. In the future, mining operations to extract marine minerals could take place in the deep sea. Seafloor manganese nodules (SMnN) may be one target of deep-sea mining (DSM) beyond the limits of national jurisdiction (Mero 1962; Hein and Koschinsky 2014; Petersen et al. 2016). Covering vast abyssal plains, high-tech harvesters are envisaged to collect these potato-sized rock concretions in water depths between 4,000 and 6,500 m (Volkmann and Lehnen 2017). SMnN primarily contain manganese, but they are also rich in nickel, cobalt, copper, and other metals, which makes them economically interesting (Hein et al. 2013). However, the future of DSM is still uncertain. Regulations for the exploitation of SMnN are still under development (ISA 2017b). Moreover, mining technologies are yet to attain a technological readiness level (TRL) to undertake DSM operations (ISA 2008a; Ecorys 2014; Knodt et al. 2016).

Exploitation technologies and methodologies as well as tools to plan for a sustainable exploitation must be developed in parallel to current exploration activities. Otherwise, the seafloor areas and their valuable resources may not be managed in a responsible manner if market conditions allow for economic exploitation. Spatial planning tools are used today in land-based mining (Preuße et al. 2016), for marine spatial planning purposes (Stelzenmüller et al. 2013), and in many other areas to plan human activities. Despite intensive research efforts since the 1970s, approaches to assess the techno-economic requirements and implications of SMnN mining are still lacking (Abramowski 2016; Sharma 2017; Volkmann and Lehnen 2017). In this light, a spatial planning tool and a method to valuate SMnN deposits are presented here and exemplified for a part of the eastern German license area, which is located in the Clarion-

Clipperton Fracture Zone (CCZ), Pacific Ocean. The comprehensive approach covers a whole range of disciplines—from exploration through to the financing of such projects and to the study of economics. To validate the results, research findings of the European research project Blue Mining are included as a specific case study (Section 5.2).

Blue Mining research contributes to a sustainable spatial management and utilization of marine mineral resources (Volkmann 2014). Up to now, ecologic, economic, and societal aspects have been considered on a rather regional scale—that is, for the entire CZZ (Wedding et al. 2013; Lodge et al. 2014; ISA 2017c). Although considered in marine spatial planning (Ardron et al. 2008; Ehler 2008; Ehler and Douvere 2009), the development of a spatial management strategy has not yet been tackled for mining activities (Durden et al. 2017). Relating to this, the techno-economic requirements of commercial SMnN mining are assessed here, and a planning approach is proposed. Besides mine planning by future mine operators, authorities may also apply the tool to identify and assess areas of potential commercial interest. The methodology may support the study of mining-related environmental impacts (Mengerink et al. 2014; Vanreusel et al. 2016) and human "land use"[14] (Foley et al. 2005) in the deep sea—and may also be applicable to other spatially distributed marine mineral resources (e.g., phosphate nodules).

5.2 Background

This study uses background information of the Blue Mining project (2014–2018), which received funding from the European Commission (EC) in the seventh framework program. Geological and technical aspects have been covered in an earlier publication with focus on production key figures (Volkmann and Lehnen 2017). Financial key figures were investigated by the Blue Mining project but have only been partly published to date (Volkmann and Osterholt 2017). Exploration data have kindly been provided by the Federal Institute for Geosciences and Natural Resources (BGR).

5.2.1 Definitions

SMnN mining will mostly take place in international waters, on the seabed and ocean floor and the subsoil thereof beyond the limits of national jurisdiction termed "the Area" (Jenisch 2013). According to the *United Nations Convention on the Law of the Sea*

[14] The term *land use* is used here to illustrate the similarity with mining and agriculture on land, although in this context the use of the seafloor is meant.

(UNCLOS 1994), the International Seabed Authority (ISA or "the Authority") shall organize, regulate and control all activities in the Area, particularly with a view to administering its resources—the common heritage of mankind (Jaeckel et al. 2017). To plan future mining activities, clear definitions and demarcations are needed:

"Marine spatial planning" (MSP) is a "public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that are usually specified through a political process" (Ehler and Douvere 2009). MSP should be ecosystem-based, with the goal "to maintain an ecosystem in a healthy, productive and resilient condition so that it can provide the goods and services humans want and need" (Ehler and Douvere 2009).

In contrast to MSP, **"spatial mine planning"** (SMP) is a process of analyzing and allocating the spatial and temporal distribution of human activities on the seafloor, which are related to a mining project. A spatial planning and management strategy to exploit SMnN in the most sustainable manner has not yet been developed, and therefore objectives, indicators, and regulations need to be defined. One main focus of research, as an important part of SMP, is the identification of the so-called mineable area.

The **"mineable area"** is the basis for other activities related to SMP, e.g. the identification of mine sites, mining fields and routes (Volkmann and Lehnen 2017). In general, mining the seafloor area must be legally permitted and technically and economically feasible, considering site-specific conditions of the marine environment. Geological factors are, among other things, the water depth, the local bathymetry, the nodule abundance and the chemical composition. As legal and environmental aspects are not included in the spatial planning tool presented here (Section 5.3.2), and since the future of SMnN mining is still uncertain, it is referred here to area(s) of potential commercial interest.

A **"spatial (mine) planning tool"** refers to a device that is necessary to or aids in the performance of SMP. A graphical calculating device, a nomogram, has been developed to determine the techno-economic requirements of a SMnN mining project and is used to identify the areas of (potential) commercial interest. Nomograms have roots back to the 1880s and "provide engineers with fast graphical calculations of complicated formulas to a practical precision" (Doerfler 2009). A later integration of the derived algorithms into a practical mine planning or scheduling software is conceivable.

5.2.2 Characteristics of the Study Area

The case study area is located in the eastern part of the CCZ in the equatorial northeast Pacific Ocean (Figure 5.1). This area, covering about 4 million km^2, is characterized by the largest contiguous occurrence of SMnN fields in the world oceans (Kuhn et al. 2017). Moreover, this area has been extensively investigated by both academia and industry since the early 1970s. The large knowledge base, together with high occurrences of SMnN and high metal contents, are main reasons why the ISA has granted exploration licenses in this area since 2001 (a map with all license areas of the CCZ can be retrieved from *www.isa.org.jm*).

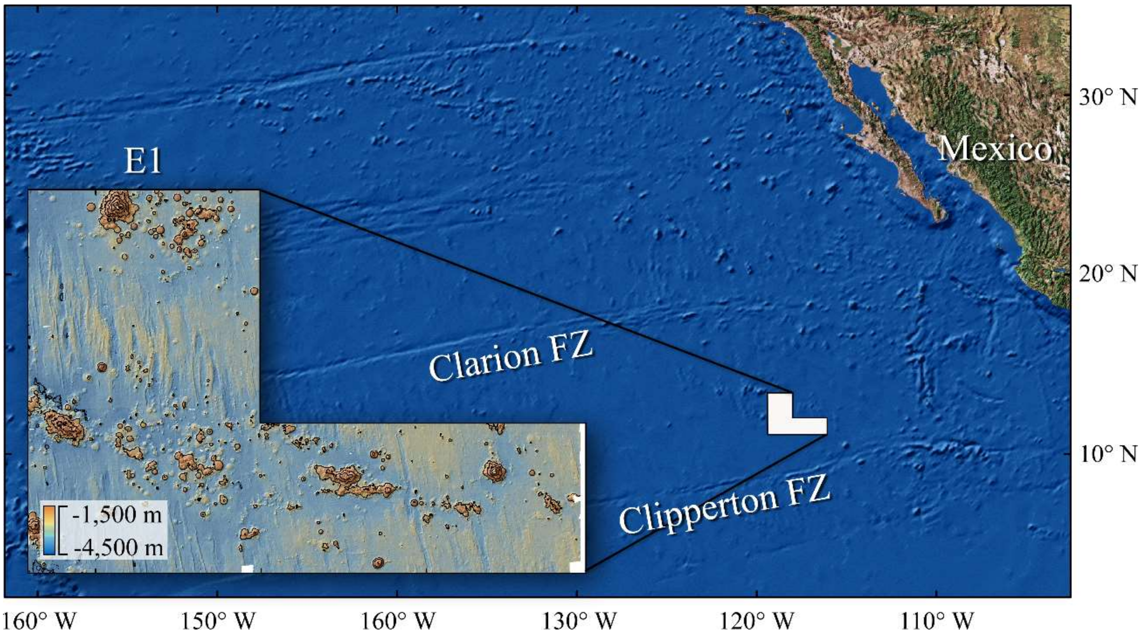


Figure 5.1. Clarion-Clipperton Fracture Zone (CCZ) bordering the area where most of the ISA exploration areas for SMnN are located. The white area indicates the eastern German license area, within which the case study area of this paper is located.

Apart from slight local variations, the chemical composition of the SMnN is relatively constant throughout the whole CCZ, especially when compared to variations in nodule abundance (in kg/m²; (Kuhn et al. 2017); the latter ranges between 0 and ~30 kg/m² (based on wet nodule weight), with an average of 15 kg/m² in the CCZ (SPC 2013). SMnN fields are not equally distributed on the seafloor within the CCZ but occur in patches. Economically interesting “patches” can cover an area of several thousand square kilometers (ISA 2010).

Water depths in the eastern German license area E1 vary from 1,460 m to 4,680 m, with an average of 4,240 m (Rühlemann et al. 2011). The seafloor of E1 is characterized by deep-sea plains interspersed with NNW-SSE–oriented horst and graben structures that are several kilometers wide, tens of kilometers long and 100–300 m high, and many extinct volcanoes (seamounts) rising a few hundred to almost 3,000 m over the surrounding abyssal plains (Rühlemann et al. 2011). Seafloor plains with slope angles less than 7° cover about 75% of the German license area and represent areas of interest with respect to future SMnN mining projects. However, due to environmental constraints, it is suggested that only about 20% of the license area may be mined in the future.

The tool developed in this paper is applied to a selected working area of exploration within E1, which is a commercially interesting area and could be a potential future mine site. This case study area has a size of 30 km (N-S) by 33 km (E-W) and is characterized by NNW-SSE oriented elevations in the central and eastern part of the area that rise about 100–150 m above the surrounding seafloor, as well as by two small seamounts in the western part (Figure 5.2a). About 97% of the area has slope angles less than 7°, whereas the slopes of the seamounts and the NNW-SSE striking elevations can reach angles up to 30° (Figure 5.2b). With this bathymetry, the case study area is representative for other potential mining areas identified in E1 (BGR, unpublished data).

By nature, SMnN are polymetallic rock concretions which are comprised of several metals of economic value (UNOET 1987). During marine exploration, though different in subsequent mine planning, it is common to sum up the grades of the key metals. The sum of the nickel, copper, and cobalt contents averages 2.73%, the manganese content averages 31.1%, and the nodule abundance ranges from 0 to 22 kg/m² (dry weight; unpublished BGR data). The nodule abundance distribution map (Figure 5.2d) indicates increased values in topographically elevated areas. Grades have not been mapped since they are relatively constant. For instance, the coefficient of variance (CoV) for the combined Co+Cu+Ni grades throughout the entire E1 area is less than 10% compared to the CoV of nodule abundance which is > 30% (Knobloch et al. 2017).

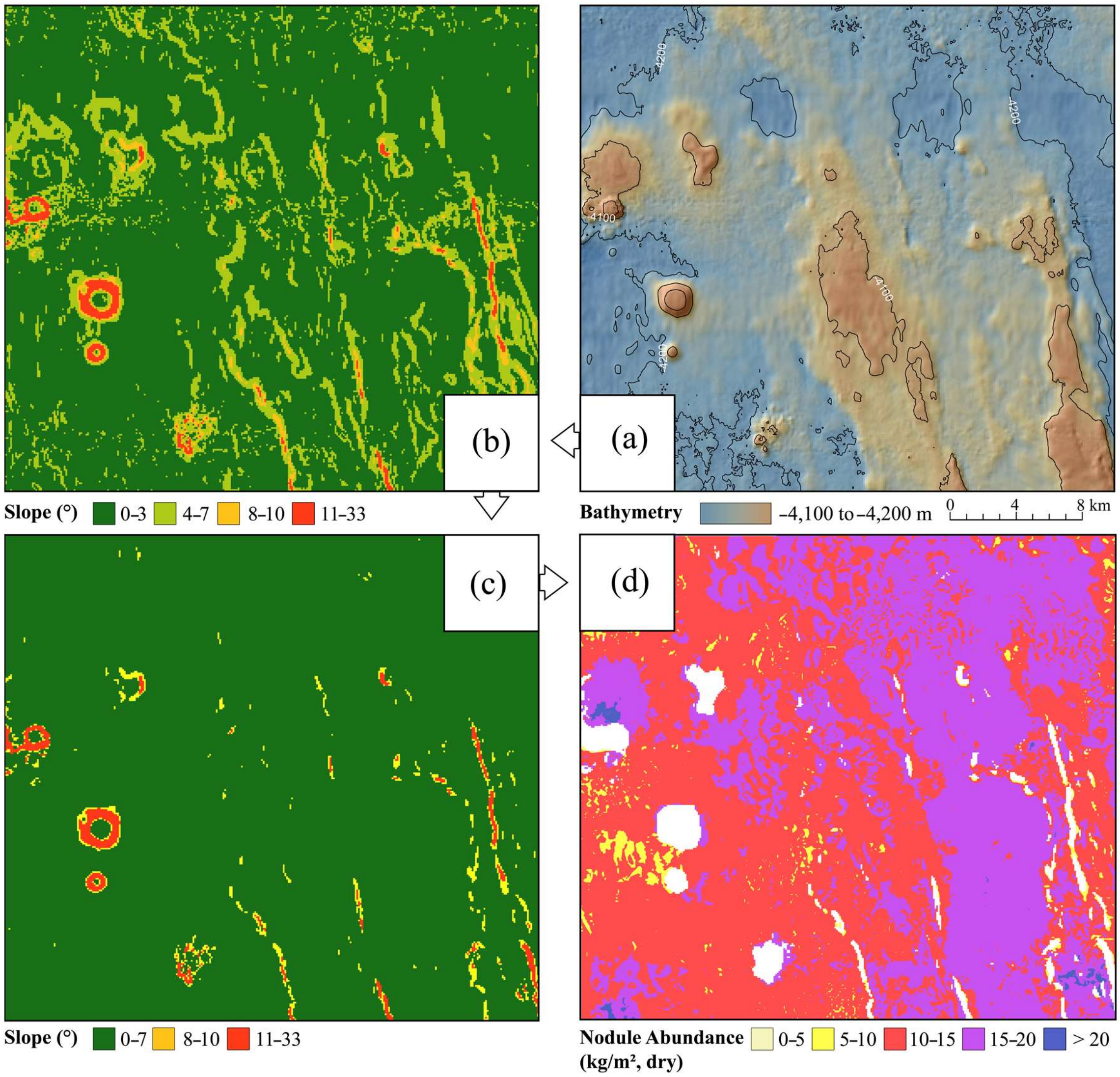


Figure 5.2. Bathymetric map (a) and slope angles (b) of the case study area in the eastern German exploration area E1. Slopes in the range of 0 to 7° are combined in map (c). Map (d) shows the predicted nodule abundance; areas with slopes exceeding 7° are excluded (white). The direction (top right to bottom right) indicates the processing/mapping sequence (Section 5.3.1).

5.2.3 Financial Key Figures of the Case Study

The launch of a DSM venture will depend on the forecast of future revenues or the predicted profitability (Hoagland 1993; Martino and Parson 2013). The net profit (NP') per unit of output is used as a measure of a project's profitability. The theoretical background is subject to financial modeling (Volkmann et al. 2018b). The project's net profit was defined as the difference between the sales value and the break-even sales value (in US$) per lifted dry metric ton of SMnN (dmt). In the spatial planning tool (Section 5.3.2), the net profit per unit of metal output is used (Formula 5.3). Different scenarios are considered that relate to the Blue Mining case study. Assumptions and estimates apply (Table 5.1), which were evaluated trough a GAP analysis (good, average, poor) as of year-end 2015.

Table 5.1. Assumptions and estimates related to the Blue Mining case study. Figures are based on economic factors of year-end 2015. Excerpts published in Volkmann and Osterholt (2017).

Item	**Good-Case scenario**	**Moderate (Average)-Case scenario**		**Poor-Case scenario**	**Unit**
Process route Key elements	Four-metal Ni, Co, Cu, Mn	Four-metal Ni, Co, Cu, Mn	Three-metal Ni, Co, Cu	Four-metal Ni, Co, Cu, Mn	
Sales Value SMnN[1]	732	649	304	493	\$/dmt
FeMn (73% Mn)	1,509	1,390	1,390	1,117	\$/t
Nickel	16,540	14,456	14,456	10,474	\$/t
Copper	5,576	4,533	4,533	3,379	\$/t
Cobalt	65,660	54,045	54,045	35,768	\$/t
Break-Even Sales Value (= Costs)	398	546	433	814	\$/dmt
Capacity	2	1.5	1.5	1	Mt/a
Life of Mine	20	20	20	20	a
CAPEX	1.5	1.43	1.22	1.32	\$BN
OPEX	234	270	197	337	\$/dmt
NSR Royalty[2]	4	6	6	8	%
Corporate Tax	30	30	30	30	%
Discount Rate	15	20	20	25	%
Net Profit[3]	334	103	−129	−321	\$/dmt

[1] Hypothetical value of ore considering the recovery of Ni (95%), Co (90%), Cu (94%) and Mn (85%) at constant grades Ni (1.3%), Co (0.17%), Cu (1.1%), Mn (29.2%) in US\$ per dry metric ton (dmt).[2] Royalty based on the net smelter return (NSR).[3] The net profit (NP') refers to the sales minus the break-even sales value per dmt of ROM (run of mine); here referring to the mine's capacity.

Revenues are generated from the sale of the metals nickel (Ni), cobalt (Co), copper (Cu), and optionally manganese (Mn), which could be sold as ferromanganese (FeMn; 73% Mn). The economic feasibility of SMnN mining will, at least for the foreseeable future, depend on these metals, even though trace metals such as the rare earth elements (REE), tellurium (Te), lithium (Li), and gallium (Ga) (Hein et al. 2013) might be of economic interest as well (Martino and Parson 2013; SPC 2016). Their prices are based on time series data sets published by the USGS (2016), which were adjusted for inflation. The good case refers to the upper quartile, the average case to the average value and the poor-case scenario to the lower quartile of constant year 2015-dollar prices (1970 to 2015). The time series data set for manganese ore was scaled up to match with the 2015 price of ferro-manganese. It is distinguished here between three-metal (Ni, Co, Cu) and four-metal (plus Mn) processing routes (SPC 2016). Recovery rates reported by the ISA (2008a) and average metal grades reported by Rühlemann et al. (2011) for E1 were used (Table 5.1).

The break-even revenue is the minimum value required to cover all costs, including interest, taxes, and depreciation. Thus, it can be considered as a cost figure. The break-even calculation is based on a discounted cash flow (DCF) analysis, using the time value of money to appraise long-term projects. SMnN and land-based mining projects share fundamental similarities: high risk and high capital cost. Capital expenditures (CAPEX) were estimated to range between about 2015-$1.2 and $1.5 billion. These costs were depreciated over 20 years using the straight-line method. Operative expenditures (OPEX) were estimated to range between $200 and $340/dmt SMnN (Volkmann and Osterholt 2017). Costs of a pilot mining test are not included. Tax and royalties are similar to rates that would be assumed for land-based mining projects. Discount rates of up to 25% apply, which are commensurate with the level of risk currently associated with the first SMnN mining projects. Production is assumed to range between 1 and 2 Mt/a (dry).

Assumptions and estimates have only been partly published for the Blue Mining project (Volkmann and Osterholt 2017). Most of these figures have yet to be validated through comprehensive studies and tests (ISA 2008a; Ecorys 2014; Knodt et al. 2016). This concerns in particular the production rate, environmental costs, and costs of processing and refining SMnN. Assumptions and estimates may be compared to figures published in recent studies, e.g. BMWi (2016), SPC (2016), or van Nijen et al. (2018).

5.3 Methodology

The case study area has been assessed from a geological (marine geology) and an economic standpoint. A spatial planning tool was developed, bringing together geological, technical, operational, financial, and economic aspects incurred in a mining project. Results of the case studies are used to investigate the techno-economic requirements—for example, the dimension and potential implications of SMnN mining on resource utilization and land use (Figure 5.3).

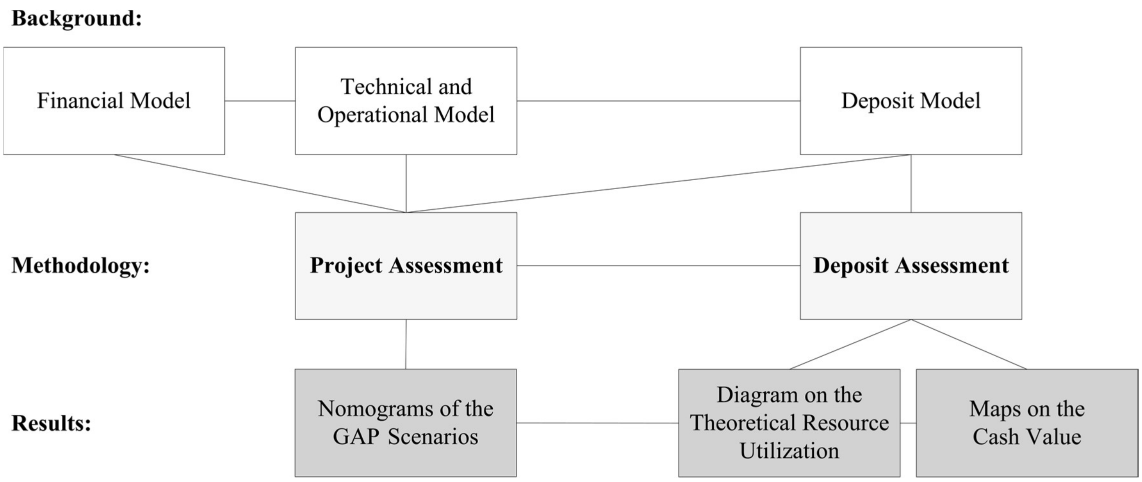


Figure 5.3. Concept of the approach to investigate the techno-economic requirements and implications of SMnN mining.

5.3.1 Development of a Valuation Technique

Although proposals for the identification of the mineable area have been made (UNOET 1979; Volkmann and Lehnen 2017), a standardized reporting code for declaring SMnN reserves does not yet exist. Recent studies consider grade, nodule abundance, and hydro-acoustic backscatter data in conjunction with slope angles to tag prospective SMnN fields (Mucha and Wasilewska-Blaszczyk 2013; Knobloch et al. 2017; Volkmann and Lehnen 2017). Relating thereto, a method for identifying the areas of (potential) commercial interest is proposed here, which—in addition to the existing approaches—takes into account the economic value of SMnN.

Mapping the Seafloor's Cash Value

To map the seafloor's cash value, information on grades, nodule abundance, metal prices, and technical parameters such as efficiencies and the climbing ability of the seafloor mining tool (SMT) are required.

The **"seafloor's cash value"** (R'') is the revenue that could be generated by mining a specific area (raster unit; i.e., pixel), in US-dollar ($) per square meter. Simplified, it is the money that can be collected from the seafloor. That is, revenue is generated by collecting SMnN and by selling the recovered metals. The cash value is the product of the metal content recovered from the area and the nickel price (Formula 5.1).

$$\boldsymbol{R''} = \boldsymbol{M''} \times \boldsymbol{p_{Ni}} = (\boldsymbol{NA_F} \times \boldsymbol{g_{NiE}} \times \boldsymbol{\eta_C}) \times \boldsymbol{p_{Ni}} \qquad 5.1$$

Where:

R''	= The seafloor's average cash value [\$/m²]
M''	= Average nickel-equivalent content, see Formula 5.6 [t/m²]
p_{Ni}	= Selling price of nickel [\$/t]
NA_F	= Average nodule abundance in the fields [t/m², dry]
g_{NiE}	= Average nickel-equivalent grade, see Formula 2 [%]
η_C	= Constant collecting efficiency [%]

Constant metal grades and metal recovery rates but variable nodule abundances (in kg/t, dry weight; Figure 5.2) and prices of the respective scenarios apply (Table 5.1). The average metal contents derive from geochemical analyses of more than 700 nodule samples (BGR data).

The **"nickel-equivalent grade"** (g_{NiE}) is defined as the percentage amount (sum) of nickel-equivalents determined for Co, Cu, and optionally Mn (sold as FeMn) with Ni as the major metal. To calculate the equivalent grade, all metals (m) are converted to a single metal based upon metal prices (p_m), grades (g_m), and recovery rates (η_m; Formula 5.2).

$$\boldsymbol{g_{NiE}} = \frac{\sum_{m=1}^{k} \boldsymbol{p_m \times \eta_{R\,m} \times g_m}}{\boldsymbol{p_{Ni}}} \qquad 5.2$$

Where:

g_{NiE}	= Average nickel-equivalent grade [%]
p_m	= Selling price of product containing metal m [\$/t, metal content]
p_{Ni}	= Selling price of nickel [\$/t]
g_m	= Average grade of metal m in ore [%]
$\eta_{R\,m}$	= Average recovery rate for metal m [%]
k	= Number of metals recovered (here three or four metals)
m	= Here: Ni (1), Co (2), Cu (3) and Mn sold as FeMn (4)

The distribution of nodule abundance per m² in the case study area (Figure 5.1) was modeled based on the neural network approach by Knobloch et al. (2017), who used bathymetry and backscatter data of the seafloor and several derived datasets as input data. Based on known nodule abundance at box corer sites, the neural network was trained to find patterns in the input data that correlate with the nodule abundance from box corers. It could be proven that such patterns exist, and thus it was possible to predict the nodule abundance at all sites where hydro-acoustic data are available (Knobloch et al. 2017). Therefore, nodule abundance values in the study area were available with a resolution of about 100 m, leading to the application of raster data with pixel sizes of about 100 m × 100 m, with one nodule abundance value per pixel (Figure 5.2) in the present study.

The distribution of cash values for each scenario in the case study area was mapped with ArcGIS™. The seafloor's cash value was then calculated by using the presented formula (Formula 5.1). Areas with slope angles above 7° were removed from the analysis (white areas in Figure 5.2d) as currently proposed mining equipment may only cope with areas inclined up to 7°—if at all (Atmanand 2011; Kuhn et al. 2011; Agarwal et al. 2012). The potentially mineable area is smaller and patchier (Figure 5.2b, c) when slopes should not exceed 3°. Cash values were filtered using a smoothing average filter to remove noisy data. An averaging filter was applied, replacing each pixel value in the image of the case study area with the mean value of its neighbors; including the central pixel of the 3 × 3 matrix.

Theoretical Resource Utilization

The theoretical resource utilization (RU_{Max}) is defined as the percentage amount of SMnN (contained in the case study area) that could be recovered by assuming an ideal extraction process (Volkmann and Lehnen 2017). The ideal state implies constant extraction costs and an extraction ratio of 100%—that is, all SMnN are recovered from the areas (pixels) classified as (potentially) mineable. Mining losses are not considered. Field characteristics or other factors that have (under production conditions) an impact on costs are also not considered. Grades are assumed to be constant. The percentage utilization is plotted against the average nodule abundance. In general, the higher the cutoff (threshold) value, the more areas (pixels) that are excluded from the case study area and the higher the average value, and vice versa.

5.3.2 Development of a Spatial Planning Tool

The spatial planning tool proposed here for SMnN mining is called nomogram (Section 5.2.1). A nomogram is created for each of the four GAP scenarios. Assumptions and estimates (Table 5.1) apply as default parameters. The nomogram is divided into four quadrants and visualizes the mathematical relationships between project economics (quadrant I), mine production (quadrant II), deposit characteristics (quadrant III), and market economics (quadrant IV). A formulaic approach to creating a spatial planning tool for SMnN is presented, which is tied to certain objectives and constraints.

In contrast to the nomogram, different units are used in the formulas to avoid the use of conversion factors. All figures refer to annual or annual average values.

Objectives and Constraints

The break-even cash value ($\hat{R}_A{}''$) and the break-even price ($\hat{p}_{Ni}$) are sought. The break-even cash value is used to identify the areas of potential commercial interest (Section 5.3.1) and to investigate the theoretical resource utilization (RU_{Max}). The break-even price is required to assess the profitability and the techno-economic requirements of a SMnN mining project.

From a socio-economic perspective, the case study area's resource should be utilized in the best possible manner, leaving more equivalent areas unmined for future generations (Volkmann 2014). A theoretical resource utilization of 100% is assumed (i.e., all SMnN is recovered from the entire case study area). However, environmental aspects still need to be effectively integrated. From a financial standpoint (Volkmann 2014), profitability is an absolute prerequisite for a commercial operation, here indicated by the net profit per unit of output (NP').

The "net profit per nickel-equivalent unit" (NP') is defined as the nickel price (p_{Ni}) minus the break-even price ($\hat{p}_{Ni}$). A mining project can only be accepted for positive values ($NP' > 0$; Formula 5.3).

$$\boldsymbol{NP' = p_{Ni} - \hat{p}_{Ni}} \qquad 5.3$$

Where:

NP'	= Net profit per ton nickel-equivalent [$/t, metal content]
p_{Ni}	= Selling price of nickel price [$/t, metal content]
$\hat{p}_{Ni}$	= Break-even nickel (equivalent) price [$/t, metal content]

In addition, techno-operational constraints and assumptions of the Blue Mining case study apply (Volkmann and Lehnen 2017). It is assumed that the maximum production would be limited to 2 Mt per annum. With current mining technology, a maximum mining capacity (MR_{Max}) of 9 m²/s is expected by using one or two seafloor mining tools (SMTs). Furthermore, an operating time of 5,000 hours per year (T_A) and a collecting efficiency of 80% (η_C) are assumed and defined as constants (note that this is a simplification).

Quadrant I: Mine Project Economics

The first quadrant shows break-even revenue (i.e., cost isolines for production capacities) in the range of 0.5 to 2.5 Mt/a. The calculation is based on break-even sales values (i.e., the costs per dmt; Table 5.1). Economies of scale (i.e., cost advantages that would arise with increased output), apply. The annual break-even revenue ($\hat{R}_A$) is plotted against the average mining rate (MR_A) and the seafloor's average break-even cash value ($\hat{R}_A$). The latter needs to be determined to identify the areas of potential commercial interest (Section 5.3.1).

The **"seafloor's break-even cash value"** ($\hat{R}_A{}''$) is the minimum economic value that the mineable (and mined) area must exhibit on average to ensure profitability. The main objective is to ensure sufficient annual revenues to cover all costs incurred in the project. The break-even cash value depends on the break-even revenue ($\hat{R}_A$), the annual operating time (T_A), and the average mining rate (MR_A) (Formula 5.4). The average mining rate indicates the operational performance (Volkmann and Lehnen 2017).

$$\boldsymbol{\hat{R}_A{}''} = \frac{\boldsymbol{\hat{R}_A}}{\boldsymbol{MR_A \times T_A}} \qquad 5.4$$

Where:

$\hat{R}_A{}''$	= The seafloor's break-even cash value (annual average) [\$/m²]
$\hat{R}_A$	= Annual break-even revenue [\$/a]
MR_A	= Annual average mining rate [m²/h]
T_A	= Annual (scheduled) operating time [h/a]

Quadrant II: Mine Production

The second quadrant shows production isolines for rates in the range of 0.5 to 2.5 Mt/a. The annual production rate (P_A) is plotted against MR_A and the average nodule abundance (NA_F). Full capacity utilization is assumed—that is, production and break-even isolines match ($P_A = P_{A\,Max}$). The isolines indicate the dimension (scale) of a SMnN mining system, i.e., the designed capacity.

The **"annual production rate"** (P_A) is defined as the dry mass of SMnN that would be recovered each year (Volkmann and Lehnen 2017). The annual production rate (Formula 5.5) is the product of the average nodule abundance in the mining fields (NA_F), the annual operating time (T_A), the average mining rate (MR_A), and the collecting efficiency (η_C). The collecting efficiency is the percentage of SMnN picked up from the seafloor. Further losses (of metals) are expected to occur in subsequent processes of the mine value chain (Melcher 1989) but are neglected in the calculations because the overall efficiency still needs to be assessed.

$$\boldsymbol{P_A = NA_F \times T_A \times MR_A \times \eta_C} \qquad 5.5$$

Where:

P_A	= Annual production rate [t/a, dry]
NA_F	= Average nodule abundance in the fields [t/m²]
T_A	= Annual (scheduled) operating time [h/a]
MR_A	= Average mining rate (annual average) [m²/h]
η_C	= Constant collecting efficiency [%]

Quadrant II: Deposit Characteristics

The third quadrant shows nickel-equivalent grade isolines in the range of 1% to 7%. Although the nickel-equivalent grade (g_{NiE}) depends on the market conditions, it is rather unlikely that values are outside of this range with respect to historical metal prices and grades of the case study area. The nickel equivalent grade is plotted against NA_F and the recoverable metal content (M''). The relationship is shown for metal content, which is used in the cash value formula (Formula 5.1).

The **"seafloor's recoverable metal content"** (M'') is defined as the metal content that would be recovered from the seafloor. To calculate M'', nodule abundance, the nickel-equivalent grade and the collecting efficiency (η_C) must be determined (Formula 5.6).

$$\boldsymbol{M'' = NA_F \times g_{NiE} \times \eta_C} \qquad 5.6$$

Where:

M''	= The seafloor's recoverable metal content (nickel-equivalent) [t/m²]
NA_F	= Average nodule abundance in the fields [t/m², dry]
g_{NiE}	= Average nickel-equivalent grade [%]
η_C	= Constant collecting efficiency [%]

The nickel-equivalent grade and nodule abundance are results of the economic deposit assessment (Section 5.3.1) and apply as annual averages. The nodule abundance depends on RU_{Max} or vice versa.

Quadrant II: Market Economics

The fourth quadrant shows price isolines in the range of $6,000 to $30,000 per metric ton (metal content). In the light of historical metal prices and break-even cash values, it is rather unlikely that values are outside this range for the case study area. The nickel price (p_{Ni}) is plotted against M'' and the break-even cash value ($\hat{R}_A{}''$). The break-even price ($\hat{p}_{Ni}$) is sought, i.e. required to appraise the project.

The **"break-even nickel-equivalent price"** ($\hat{p}_{Ni}$) is the ratio of $\hat{R}_A{}''$ to the metal content, which would be recovered from the seafloor area (M''; Formula 5.7). It represents the economic minimum price required to cover all costs incurred in the project to result in a positive investment decision.

$$\hat{\boldsymbol{p}}_{\boldsymbol{Ni}} = \frac{\hat{\boldsymbol{R}}_{\boldsymbol{A}}{}''}{\boldsymbol{M}''} \qquad 5.7$$

Where:

$\hat{p}_{Ni}$	= Break-even nickel-equivalent price [$/t]
$\hat{R}_A{}''$	= The seafloor's break-even cash value [$/m²]
M''	= The seafloor's recoverable nickel-equivalent content [t/m²]

Guidance on Using the Nomogram

The nomogram is a specific tool for SMP to assess the techno-economic requirements of a mining project. Using the nomogram requires that a comprehensive assessment is conducted to determine break-even revenues (costs) and constraints, among other model parameters. In combination with the deposit valuation method, the areas of commercial interest can be identified, and the theoretical resource utilization and potential land use can be studied with the generated maps.

To identify the areas of potential commercial interest with the maps generated for the case study area (Section 5.4.1), the break-even cash value ($\hat{R}_A{''}$) needs to be graphically determined. The different quadrants in a nomogram are connected by joint x-axes (to connect the upper with the lower diagrams) and joint y-axes (to connect the right diagrams with those on the left). The vertical line in quadrant I can be extended into the lower left diagram (quadrant III). A horizontal line can be drawn from the intersection of the production isolines (quadrant I) with the vertical line derived from the 100% utilization (14.8 kg/m²,) resulting in a distinct mining rate (Figure 5.5-I). This horizontal line intersects with different break-even revenues and from this intersection the break-even cash value can be read off from the diagrams by drawing a vertical line downward (to quadrant IV). With this information, the areas of potential commercial interest can be identified on the maps (Figure 5.4). Accordingly, the theoretical resource utilization and land use can be estimated (Section 5.5.1).

In order to assess the profitability and/or the techno-economic requirements of the project scenario, the break-even price ($\hat{p}_{Ni}$) must be determined. Firstly, the grade isoline (quadrant III) needs to be determined (Formula 5.2). In the next step, a horizontal line is drawn, intersecting with the vertical line within quadrant IV and the respective grade isoline (quadrant III). The break-even nickel price in question is the isoline where the horizontal and vertical lines intersect. Ultimately, the net profit (NP') reads off as the difference between the nickel price (of the respective scenario) and the break-even nickel price (graphically determined). In conformity with the objectives and constraints, the techno-economic requirements can be determined by variation of the model parameters. The theoretical resource utilization curve may be plotted into quadrant I (Figure 5.5-I, dashed blue line).

5.4 Results

In the following sections, the results of the assessment of the three- and four-metal GAP scenarios (Table 5.1) are presented, using both seafloor maps and nomograms.

5.4.1 Deposit Potential of the Study Area

Maps of the cash value are shown for the different GAP scenarios (Figure 5.4). In these areas, slopes do not exceed 7°. Grades were shown to be constant in the study area. Comparing the four-metal good case (Figure 5.4a) and four-metal average-case scenario (Figure 5.4b), the area divides into two contiguous areas. At higher prices in the good case, more areas fall into the class of cash values > \$9/m². These areas exhibit the highest nodule abundance (15–20 kg/m²; Figure 5.2d) and are situated in the eastern part of the case study area. For the four-metal poor-case scenario (Figure 5.4c), the same can be observed, but cash values fall into the next lower classes. In the case of the three-metal average-case scenario (Figure 5.4d), the study area is more or less one large area with cash values between \$3 and \$6/m².

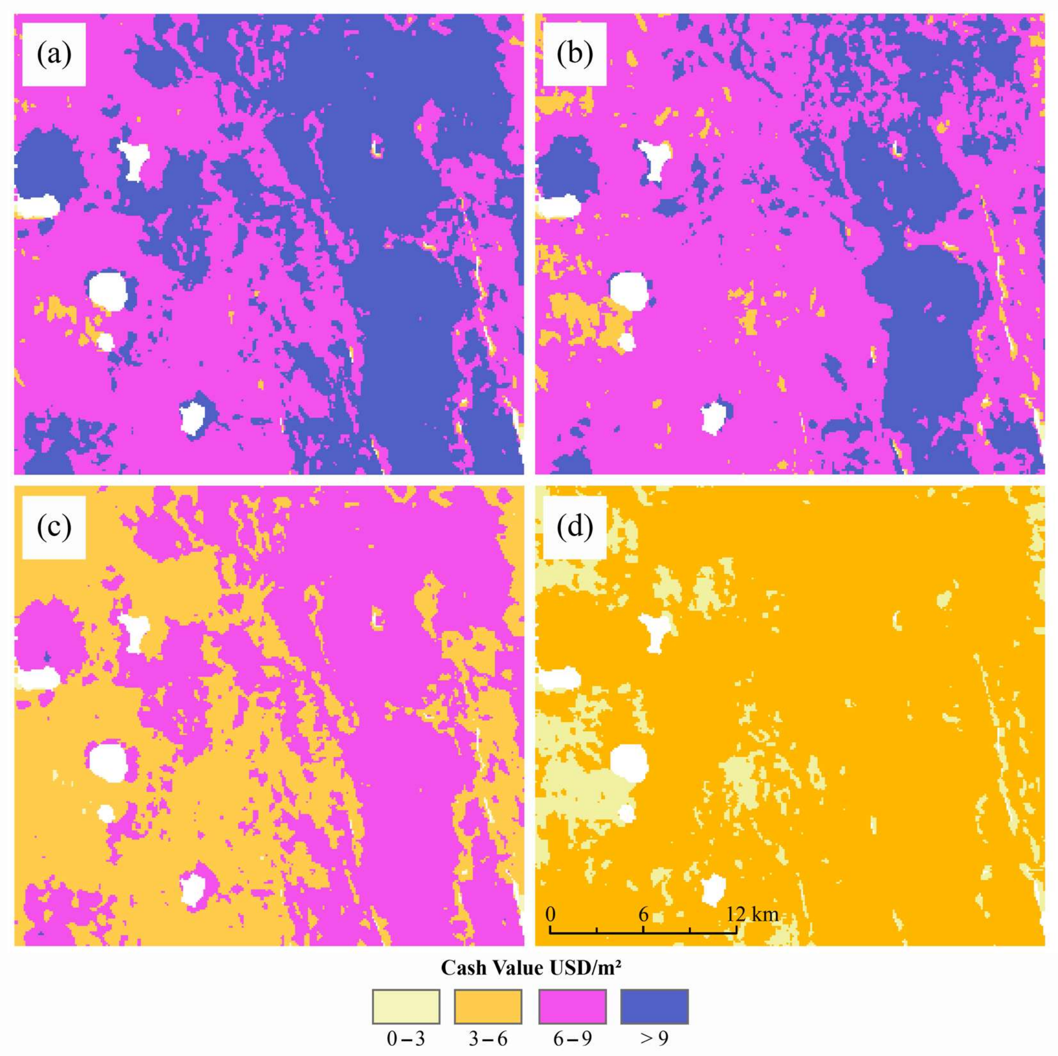


Figure 5.4. Maps of estimated cash values in the case study area in the eastern German exploration area. A) Four-metal good-case scenario. B) Four-metal average-case scenario. C) Four-metal poor-case scenario. D) Three-metal average scenario.

According to the metal prices and recovery rates of the GAP scenarios (Table 5.1), the average nickel-equivalent grade would be about 4.5 wt% in the case of four-metal and around 2 wt% in the case of three-metal recovery. For the good-case scenario (Figure 5.4a), and planning with an average mining rate of ~7 m²/s or higher (Table 5.2), the entire model area could be mined from an economic perspective (referring to violet and blue image pixels). The potentially mineable area (the areas of commercial interest) would be significantly smaller when cherry-picking only the violet areas (> $9/m²), which, however, would be mandatory at mining rates less than ~5 m²/s. The techno-economic requirements are particularly high for the three-metal average and the four-metal poor-case scenario, aiming to achieve a positive net profit (NP'; cf. results of Section 5.4.2) and the overall ambition to best utilize the given resource of the model area.

Table 5.2. Minimum average seafloor's cash values required to break even depending on the mining rate; estimated for the Blue Mining case study.

	Economic Minimum Average Cash Values [$/m²]			
	Good-Case scenario	**Moderate (Average)-Case scenario**		**Poor-Case scenario**
MR_A [1] **[m²/s]**	Four-metal Ni, Co, Cu, Mn 2 Mt/a	Four-metal Ni, Co, Cu, Mn 1.5 Mt/a	Three-metal Ni, Co, Cu 1.5 Mt/a	Four-metal Ni, Co, Cu, Mn 1 Mt/a
10	4.4	4.6	3.6	4.5
9	4.9	5.1	4.0	5.0
8	5.5	5.7	4.5	5.7
7	6.3	6.5	5.2	6.5
6	7.4	7.6	6.0	7.5
5	8.8	9.1	7.2	9.0
4	11.1	11.4	9.0	11.3
3	14.7	15.2	12.0	15.1
2	22.1	22.8	18.0	22.6
1	44.2	45.5	36.1	45.2

[1]Average mining rate (MR_A) based on 5,000 operating hours per year (T_A).

5.4.2 Comprehensive Evaluation of the Case Study

The nomograms relate to the case study area (Figure 5.2) and to the assumptions defined for the four different GAP-scenarios (Table 5.1). Objectives and constraints apply (Section 5.3.2).

Four-Metal Good-Case Scenario

In the case of the four-metal good-case scenario (Figure 5.5), an average mining rate of about 9.8 m²/s would be required to result in a production of 2 Mt/a, while aiming to best utilize the resource of the case study area. The break-even price would amount to about $8,000/t, in contrast to a selling nickel price of about $16,000/t assumed for the scenario. The average seafloor's cash value should not be less than ~$4.5/m². In this case, the net profit (NP') is positive and the mining project would be economically viable. However, mining rates exceeding 9 m²/s are not expected to be achievable on average at present.

At a lower mining rate of 8 m²/s, a production of only ~1.7 Mt/a can be reached, based on an average nodule abundance of 14.8 kg/m². However, at a break-even cash value of ~$5.7/m², still a positive but lower net profit (NP') could be achieved (Figure 5.5-IV). In Figure 4a, the cash values per square meter have been mapped, and it becomes apparent that a value of $5.7/m² is reached in almost the complete case study area. If the mining rate would only be 4 m²/s, ~0.8 Mt/a could be mined in the model area at 100% resource utilization. The break-even nickel price would amount to about $12,000/t, with a break-even cash value of ~$6.5/m². However, almost all areas (i.e., pixels) of the case study area are higher than the average minimum cash value (Figure 5.4a).

Based on the assumption to mine the entire case study area, the smaller the project's scale (capacity), the more pixels (Figure 5.4a) are below the economic minimum average value (Figure 5.5-I). In the light of constant metal prices and grades, profitability is improved by upscaling the system's capacity (economies of scale). Higher production rates require higher mining rates. As expected to be unrealizable for the good-case scenario (~9.8 m²/s), uneconomic pixels would have to be excluded from mining to result in a higher average nodule abundance (Figure 5.4-III). Planning with 2 Mt/a, a (lower) mining rate of 7.5 m²/s would result in the same net profit (NP′; Figure 5.4-IV) but would lead to a RU_{Max} of only ~5%, relating to an average abundance of ~19 kg/m² (Figure 5.4-II).

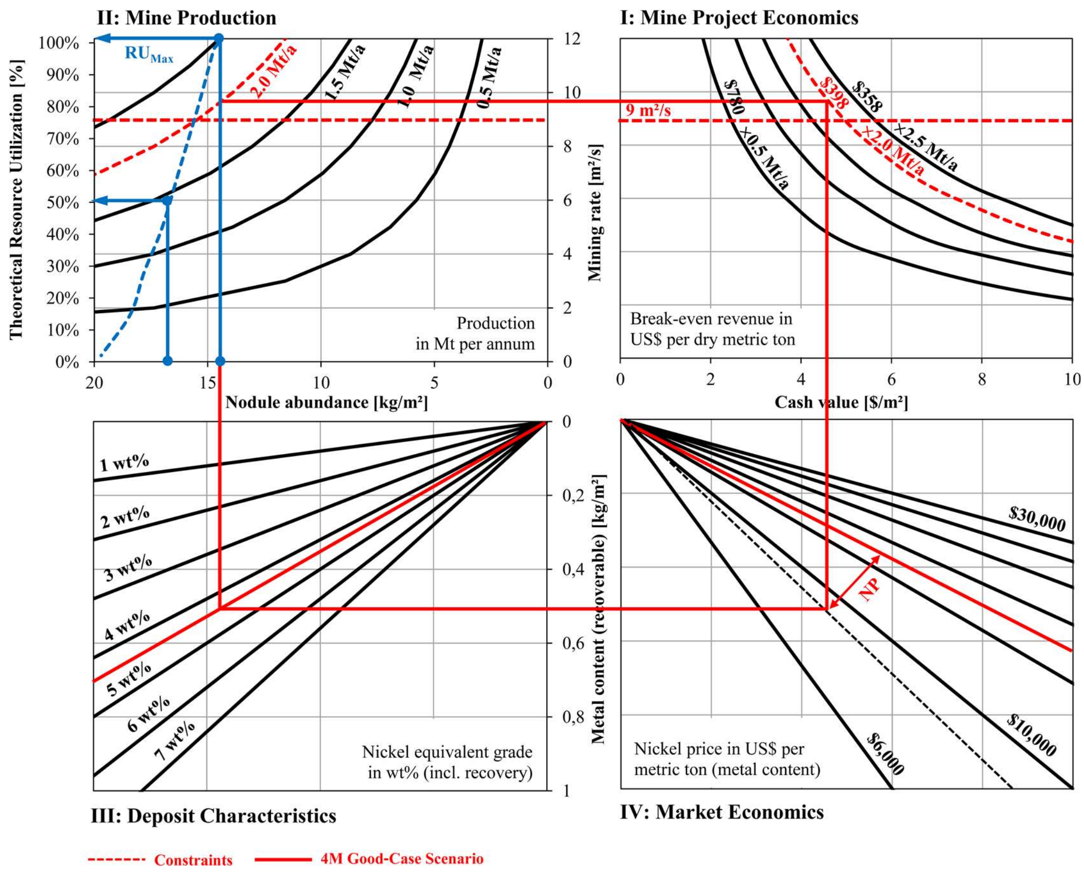


Figure 5.5. Nomogram of the good-case scenario (red rectangle) implying four-metal recovery (Ni, Co, Cu and Mn). The dashed blue line in quadrant I relates to the RU_{Max} curve and not to the production isolines.

Four-Metal Average-Case Scenario

In the case of the four-metal average scenario (Figure 5.6), a mining rate of ~7.5 m²/s would be required on average to result in a production of 1.5 Mt/a ($RU_{Max} = 100\%$). The break-even price would then amount to about $11,000/t, in contrast to a nickel price of $14,000/t assumed for this scenario. The average seafloor's cash value should not be less than ~$6.1/m². This prerequisite is met since most pixels are higher than this average value (Figure 5.4b). Planning to recover 1 Mt per annum would result in a break-even cash value of ~$7.8/m², and the net profit (NP') would be just sufficient to accept the project. A significant share of areas (pixels) of the case study area are now below the minimum average of $7.8/m² (Figure 5.4b). As in the case of the good-case scenario, the mining rate can be reduced by targeting high-abundance areas (pixels). At a production of 1.5 Mt/a and a RU_{Max} of ~5% (~19 kg/m²), a mining rate of about 5.8 m²/s would be sufficient without compromising profitability (by downsizing the system to a lower capacity).

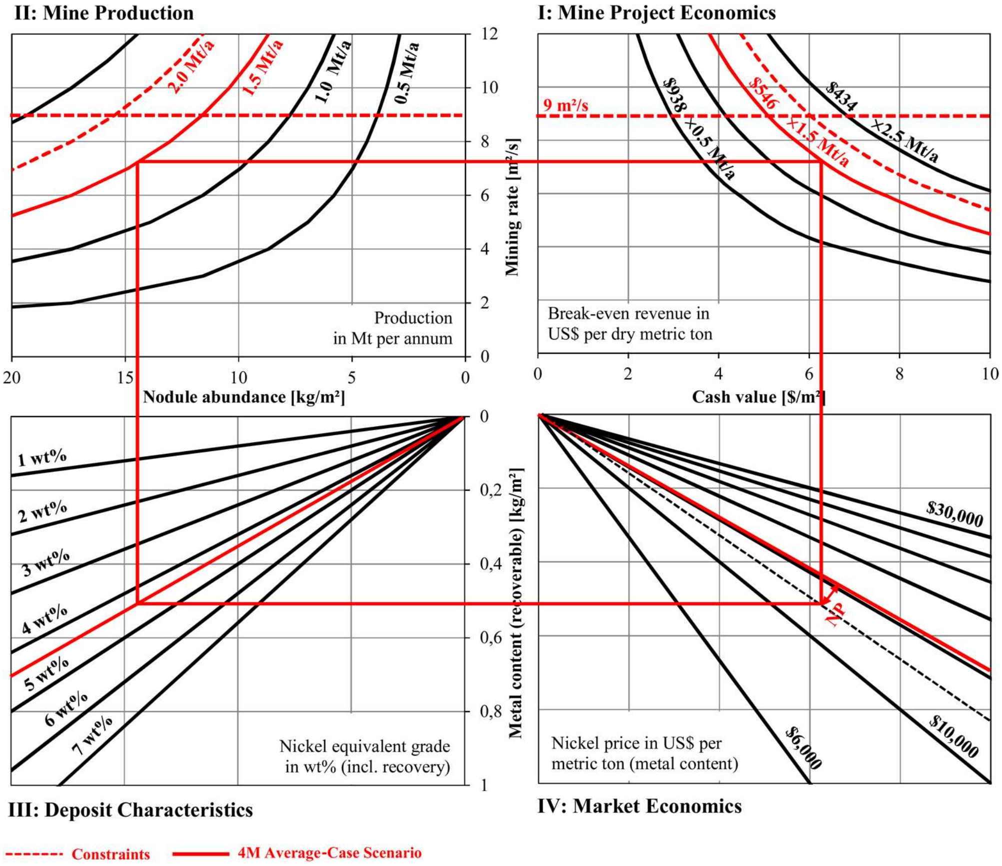


Figure 5.6. Nomogram of the average (moderate)-case scenario (red rectangle) implying four-metal recovery (Ni, Co, Cu, and Mn).

Three-Metal Good-Case Scenario

In the case of the three-metal average scenario (Figure 5.7), the average mining rate would also be 7.5 m²/s aiming for an optimal utilization. Compared to the four-metal case scenario, the specific break-even value of ore is lower (due to lower costs of the three-metal processing route), while the break-even nickel price is significantly higher and amounts to about $20,000/t. This is due to the lower value of ore (Table 5.1). The nickel-equivalent grade amounts to approximately 2% compared to about 4.5% when recovering four metals. The average break-even cash value would be ~$5/m². However, a project with these parameters would not be profitable (negative net profit; NP'). Even when taking larger capacities (larger-scale systems) into account to reach higher production (e.g., 2.0 Mt/a), this would not result in positive net profit (NP').

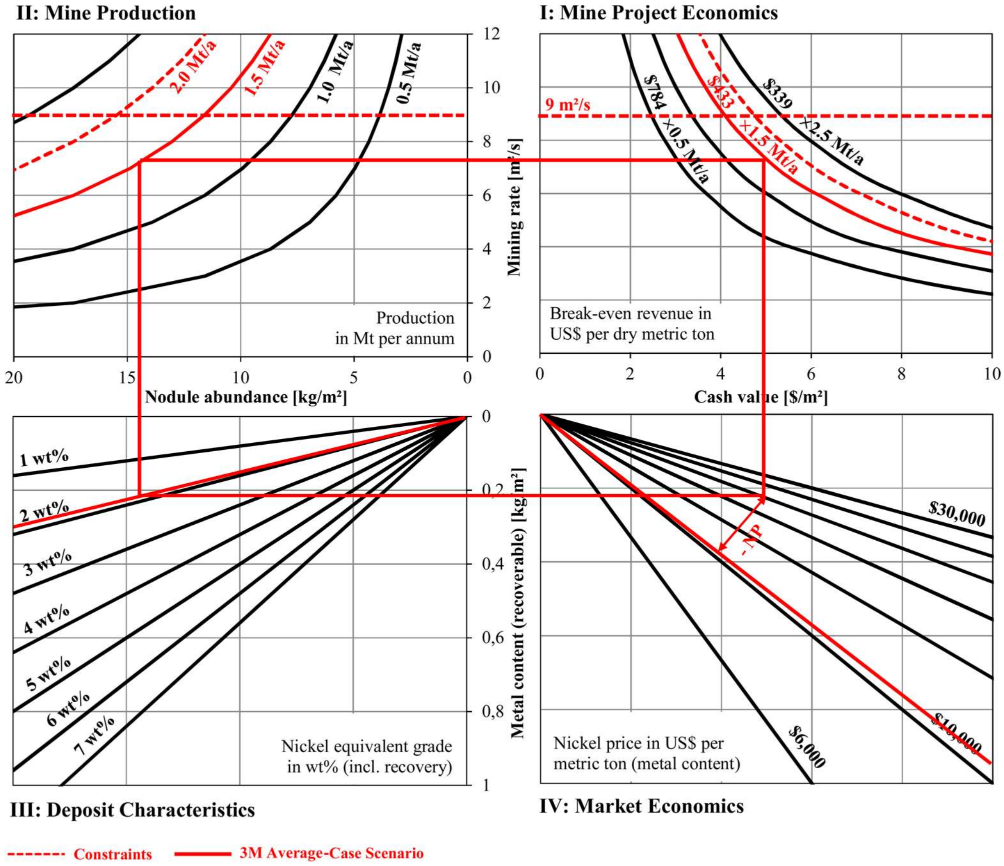


Figure 5.7. Nomogram of the average (moderate)-case scenario (red rectangle) implying three-metal recovery (Ni, Co, and Cu). A negative net profit (NP') can be observed.

Four-Metal Poor-Case Scenario

The same result can be observed for the four-metal poor scenario (Figure 5.8). The break-even price is about \$16,000/t, while a price of \$11,000/t would be required to break even at low prices. The average seafloor's cash value should not be less than ~\$9/m² at a mining rate of about 5 m²/s. There is no seafloor region in the case study area, which has a cash value of \$9/m² or more (Figure 5.4d). Therefore, and due to the negative net profit (NP'; Figure 5.8), this mining scenario should not be pursued. Moreover, investing in a 2 Mt/a capacity system, cost savings due to economies of scale do not render the project attractive.

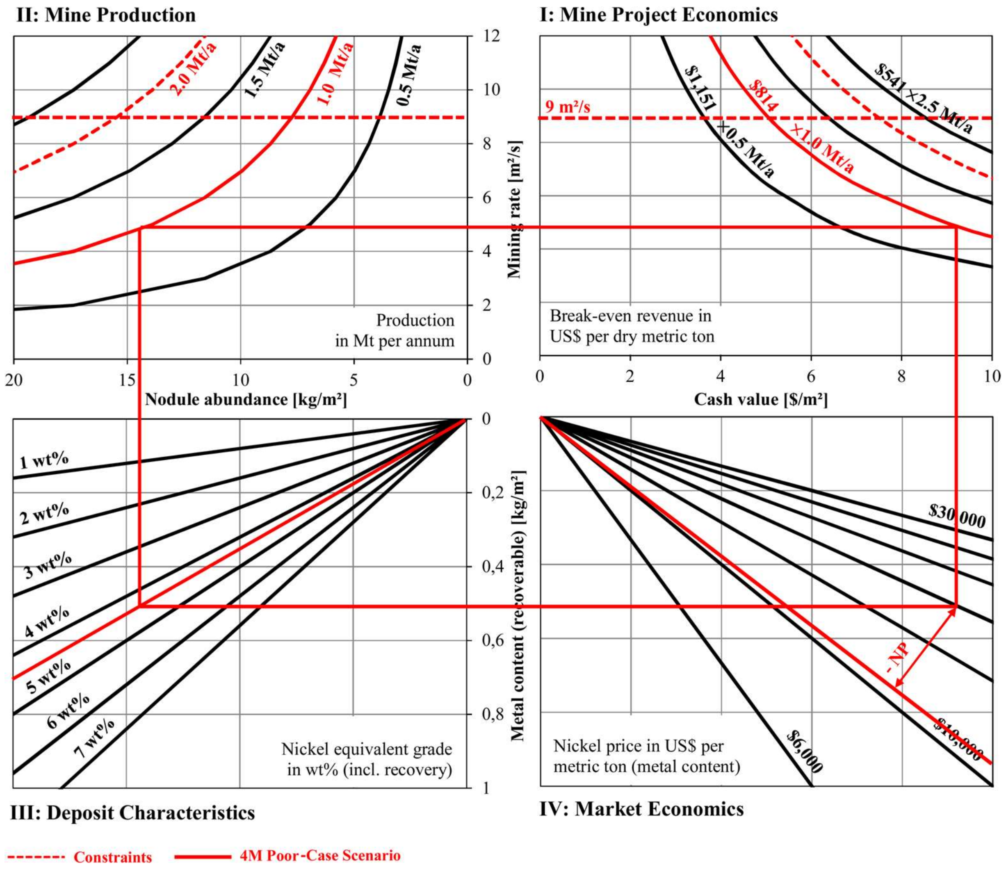


Figure 5.8. Nomogram of the poor-case scenario (red rectangle) implying four-metal recovery (Ni, Co, Cu, and Mn).

5.5 Discussion

This section discusses the validity of the approach developed to identify the areas of (potential) commercial interest and the plausibility of the results of the Blue Mining case study. The discussion aims to clarify the technical and economic requirements for spatial mining planning. The discussion does not focus on the background of the research (i.e., the assumptions and estimates related to the characterization of deposits and financial analysis).

5.5.1 Critical Review of the Methodology

Deposit Valuation Method

Using the method presented here (Section 5.3.1), it is not yet possible to identify the (potentially) mineable area. Although technical and economic criteria have been considered (Figure 5.2), additional criteria might need to be considered, such as the size of SMnN, seafloor trafficability, and areas of environmental interest that require protection, among others. Nevertheless, sound criteria to differentiate between nonmineable and mineable areas need to be investigated, and these methods should be further fine-tuned and validated for other areas within the CCZ (ISA 2010). Moreover, none of the known SMnN resources has reached the status of a “reserve” yet. This is due to the lack of geological confidence, economic technological readiness, and a missing legal framework for the exploitation of SMnN (Volkmann and Lehnen 2017).

The approach to identify the areas of potential commercial interest provides only a rough representation of the reality. The break-even cash value (Formula 5.4) and the slope angle are used as criteria—that is, pixels are excluded from mining which are below the economic minimum value and are not accessible for the SMTs (> 7°). Filters to identify contiguous areas have been developed, which have been inspired by traffic patterns of farming machines (Volkmann and Lehnen 2017). These filters were not applied to the case study area in order to not further increase the complexity of the analysis. However, maps of the seafloor’s cash value (Figure 5.4) can be used to visually identify potentially mineable fields—seeking for coherent, large-scale areas, with a simple geometry and only a few geological disturbances (obstacles). Surrounding areas and areas within should be included if accessible and as long the (annual) average value is not less than the minimum cash value.

The break-even cash value depends on the mining rate achieved in the particular area (Formula 5.4). The mining rate may depend, among other factors, on the slope angle, seafloor condition, number of obstacles, and field shape. Furthermore, field and (mine) site conditions may influence costs (e.g., the steeper the slope, the higher the energy consumption and costs). In contrast, the collecting efficiency, a factor of the cash value formula (Formula 5.1), may depend on the burial depth and size of SMnN, among other factors. Therefore, these influencing factors should be analyzed for different area- and field-specific “patterns” by conducting pilot-mining tests, experiments, or simulations. In the next step, a “preliminary reserve” could be estimated, not considering field design and route planning at this stage. The preliminary reserve (i.e., the mineable area) could serve as a basis for further route planning to determine the “in-field reserve” (Volkmann and Lehnen 2017).

Spatial Planning Tool

The nomogram (Section 5.3.2) has several limitations. Because the break-even calculation (Section 5.2.3) is based on a discounted cash flow (DCF) method, the nomogram is to be seen as a supporting tool for the strategic planning of a commercial mining project. Assuming that the cash flows of the financial model are constant over time is a simplification: from experience, metal prices, costs and production rates, among other model parameters, change during the life time of a mine. This is, however, counterbalanced by considering multiple scenarios with different parameter values (Table 5.1). Moreover, other methods may apply to determine the economic break-even value (Wellmer et al. 2008). A further limitation is that the size and location of the case study area is fixed, whereas seafloor consumption is variable. It chiefly depends on the production (target) and average nodule abundance in the mining area (Volkmann and Lehnen 2017). Because equivalent areas have been identified for E1 (BGR unpublished data), it is assumed that the model area would be extensible—that is, the characteristics of the model area apply to (smaller) subareas or fields.

Because the creation and use of the nomogram is relatively time-consuming, especially for larger data sets, computer-aided SMP should be sought. Using computer software, data handling, analysis, and visualization would be easier, faster, and dynamic. The tool could be integrated into GIS software (e.g., ArcGIS), which is designed to store, manipulate, analyze, and visualize spatial data. Moreover, the presented tool may also apply for other spatially distributed marine minerals (e.g., phosphate nodules). In precision farming, for instance, soil properties are obtained via close sensing, while remote sensing is commonly used to obtain information on the field (e.g., the yield). The collected data are used to generate application maps providing the user and the agricultural tools with information (e.g., fertilizer suggestions and traffic routes; Mulla 2013). For SMnN mining software, respective tools and methods still need to be developed, which will allow determination of the mineable area, the engineering of mining fields, and route planning. Then, it may be possible to benchmark the economic performance of a mining system while assessing the environmental and societal implications of SMnN mining.

5.5.2 Validity of the Results

The model case study and scenarios are hypothetical and based on assumptions and estimates of the Blue Mining case study. To assess the general techno-economic requirements in view of resource utilization, results of other projects need to be evaluated and compared.

Techno-Economic Requirements

A prerequisite of any mining project is economic feasibility. Based on the results of the Blue Mining case study (cf. nomograms), at least moderate conditions (Table 5.1) are necessary to realize economic SMnN mining, while focusing on the metals nickel, cobalt, copper, and manganese. This fits with the general consensus on the profitability of SMnN mining (Johnson and Otto 1986; Martino and Parson 2013; SPC 2016). Especially the high expectations on the internal rate of return (IRR), which are reflected in the break-even revenue (costs; Table 5.1), make SMnN mining technologically difficult—although the techno-economic feasibility of SMnN mining has not yet been demonstrated. Currently, an IRR (discount rate) of around 30% is anticipated to be commensurate with the level of risk associated with SMnN projects (Martino and Parson 2013; BMWi 2016). However, it should be noted that commercial ventures must make a profit, while governments and their agencies may not (Gertsch and Gertsch 2005).

In the past, low profitability forced companies to focus on large-scale (> 1 Mt/a) rather than on small-scale projects (≤ 1 Mt/a), with a median of 1.5 Mt/a of dry SMnN (SPC 2016). Also, the lifting system developed by Blue Mining partners is designed for production rates of up to 2 Mt/a. SPC (2016) states "that three-metal plants only become attractive as long as the plants receive 2-3 million dry tons of nodule per year as inputs. […] Four metal plants can sustain a much smaller operation at 1.5 million dry tons of nodules per year, as long as there is a high manganese recovery rate to make the operation competitive with respect to the additional capital and operating expenditures." However, boosting profitability by harnessing economies of scale is restricted because the production from one vessel or platform has shown to be limited to about 1.5 to 2 Mt/a dry SMnN, due mainly to technical, operational and geological reasons (Volkmann and Lehnen 2017).

In the recent past, recommendations suggest (Martino and Parson 2013) that small-scale projects (Søreide et al. 2001; Handschuh et al. 2003) may be advisable under the dominance of the conventional (land-based) mining industry and low profitability of SMnN mining. Although cost savings due to economies of scale are tempting, an oversupply of metals due to an emerging number of SMnN projects could abruptly stop the rapid spread (Martino and Parson 2013). The conventional mining industry could recognize a reduction of metal prices as an effective barrier or even measure to drive SMnN mines out of the market (Marvasti 1998, 2000). Based on the results (cf. nomograms), small-scale mining would be most profitable under good conditions, while it would be just profitable under conditions assumed for the average-case scenario (Table 5.1). Thus, the development of cost-efficient and high-performance mining concepts as well as adequate prices will be decisive to ensure economic viability.

The nomograms and the generated maps on the areas of potential commercial interest show that mining must be selective to be economically viable. Even in the good-case scenario (Figure 5.5-II), the miner would have to cherry-pick the most economic parts from the model area (> \$9/m²; Figure 5.4a) due to the capacity restriction of the SMT. To achieve average mining rates of 4 to 10 m²/s, mining capacities of 7.5 to 20 m²/s would have to be provided by one or several SMTs, depending on the time efficiency and the operating time (Volkmann and Lehnen 2017). Improving operating and time efficiency by adopting a most simple mining pattern and navigating the SMT(s) through the most nodule-rich areas with favorable field conditions (mostly flat and with only few obstacles) may be reasonable to increase productivity or if technically and/or economically unavoidable. However, an excessive practice would lead to a lower mining efficiency and reserve recovery (extraction ratio) within a mine site, thus making a poor utilization of resources and land (Volkmann and Lehnen 2017).

Environmental Considerations

Besides profitability and land and resource utilization, the affected seafloor area has been advocated to be an important aspect of sustainability (Volkmann 2014). Using the nomograms and maps of the areas of potential commercial interest, it may be possible to ecologically investigate the affected seafloor area (Thiel and Schriever 1993; Sharma 2013; MIDAS 2016b). Mining nodule-rich mine sites in the best possible manner may reduce the areal extent of the impacted area. Thus, cherry-picking by targeting the most economic (and abundant) mine sites within a license area seems to be favorable on a large scale, while "equivalent areas" must be protected. Also, it is yet uncertain if cherry-picking would be reasonable to preserve the abyssal ecosystem or to foster its recovery on a smaller scale (Vanreusel et al. 2016)—that is, within a mine site or mining field (Volkmann and Lehnen 2017). At the present time, the "impacts and effects of mining surrounding the directly mined area are poorly understood" (MIDAS 2016a). Although it is known that fine particles whirled up by SMTs and released from the MSV can be transported over large distances of several hundreds of kilometers, forming a thin sediment layer on the seafloor that may overlap and suppress the benthic ecosystem (Sharma et al. 2001; SPC 2013), it is not yet possible to define absolute threshold values or to predict the severity of the impact (MIDAS 2016a). Sound criteria still need to be defined.

5.6 Conclusions

The presented tool and deposit valuation method contributes to an early understanding of the relationships between geological, technical, operational, economic, and financial aspects of SMnN mining, and the implications of SMnN mining in terms of resource and land utilization are considered. However, the comprehensive approach needs to be fine-tuned and validated with larger data sets, and possible environmental impacts still need to be considered. To work toward sustainable development, the development of a spatial planning and management strategy needs to be tackled. This requires that sound objectives, indicators, and regulations are formulated. In addition to a mining code, a computer code (i.e., a software for spatial mine planning; SMP) is required. In this context, interdisciplinary research, mining tests and simulations, accompanied by comprehensive environmental studies, need to be conducted to determine the mineable area and to predefine proper mining concepts.

6 General Discussion, Conclusions, and Recommendations

In this chapter, the key findings of the thesis are discussed in the broader context of sustainability/sustainable development (S/SD; Section 1.2). There is then a summary of the most important results and contributions of this work and its limitations and directions for future research, showing how the mining of SMnN can be planned. The chapter concludes with recommendations for spatial management.

6.1 General Discussion

As discussed in previous chapters, a prerequisite for a conventional, land-based mining project is techno-economic feasibility. Techno-economic feasibility appears in the economic dimension of S/SD and implies that a deposit has proven to be economically and technically mineable (Section 1.2). Besides techno-economic feasibility, legal and other (e.g., environmental) aspects must be considered in mine planning to obtain, for example, mining permits, financial (state) support, and the social license to operate.

6.1.1 Economic-Environmental Aspects

Although achieving techno-economic feasibility will be a key objective in SMP, the maximization of profitability "without consideration of environmental issues during planning is not really an optimum design" (Rashidinejad et al. 2008). As the utilization of SMnN will impact the environment and its deep-sea ecosystem, the affected seafloor area must be appropriately considered in SMP, even if this is not yet possible because it remains uncertain how much damage SMnN mining would cause and how much damage the deep-sea ecosystem could sustain; furthermore, the requirements (and costs) to preserve a "healthy ecosystem" and to return a mine site to an acceptable state for a pre-arranged use of the seafloor remain uncertain (Chapter 2).

Due to the extensive seafloor utilization, SMnN mining may be perceived as unsustainable. Compared to the world's largest open-pit mine (the Bingham Canyon Mine, Utah, USA), the directly affected area is assumed to be significantly higher, covering an area of about 7.7 km² and producing about 25% of the copper used in the USA (Lanier et al. 1978; Pankow et al. 2014). Compared to SMS mining, which may also take place in the deep sea in the future, the seafloor consumption is also expected to be significantly higher. An SMS[15] mine is estimated to require a manageable number of soccer fields to be profitable, compared to a SMnN mine with an annual production rate of 1.5 to 2 Mt (Volkmann and Osterholt 2017). In contrast, about 60 to 100 soccer fields would need to be mined per day in case of SMnN mining (Volkmann and Lehnen 2017).

Although it was possible to spot the areas of potential commercial interest (Volkmann et al. 2018a), it was not possible to determine their ecological value and to compare monetized values (Groot et al. 2012) with commercial values of the seafloor areas. Moreover, ecologic values are not necessarily solely cost-driven, assuming that stakeholders have a different opinion of the value of the seafloor, especially when put in contrast to other ecosystems on land or to the possible social and economic costs and benefits of SMnN mining (SPC 2016). However, a comparison with the "land use" in agriculture (Foley et al. 2005) is distorted as SMnN are nonrenewable resources. Nevertheless, the achievements in research are a step toward identifying the affected seafloor area.

Once the areas of commercial interest are identified, the affected seafloor areas could be investigated through plume simulations (MIDAS 2016a). With high-resolution exploration data, detailed route planning could be carried out. Computer-aided software would be needed to determine mining routes and field layouts considering legal and other (e.g., environmental) aspects that are relevant for SMP as well as project-specific planning aspects such as seafloor geology or technical specifications (Chapter 2). Mine plans and reserve estimates could be created via mining simulations (Volkmann et al. 2018a).

6.1.2 Socio-Economic Aspects

In addition to techno-economic feasibility and environmental sustainability, showing that SMnN mining is beneficial to society is a prerequisite to receiving state support and the social license to operate (Prno and Slocombe 2012). A recent example is the hydraulic fracturing of shale gas deposits in Germany. Despite the advantage of domestic production, the resistance of the population to this method, which is applied to oil or gas wells to stimulate or restore production, has led to a ban on fracking activities due to environmental concerns (The Guardian 2016). Although this method does not have much in common with SMnN mining, the example shows that social (societal) aspects must be carefully considered (in SMP) to receive the social license to operate.

[15] Seafloor Massive Sulfides (SMS); see Footnote 1.

Under the assumption that tax and royalty rates would be adequate to land-based mining (Otto 2006), tax revenues of up to \$5 billion and royalty revenues of up to \$0.8 billion could possibly be generated over 20 years (Volkmann et al. 2018b). Since tax revenues are directly linked to the profitability of a project, higher tax revenues could be generated through the expansion of mining activities (e.g., by increasing the number of mining projects and by considering selective mining, or cherry-picking, in SMP). Although the figures are consistent with estimates reported by SPC (2016), the socio-economic benefits remain uncertain, along with the economic viability, the tax regime, and the purpose of the taxes and the taxes' beneficiaries.

Besides possible tax revenues and profits for companies, SMnN deposits have proven to be an interesting option for import-dependent countries such as Germany to reduce supply risks (Volkmann et al. 2018b). Although SMnN contain a considerable number of metals (Hein et al. 2013), Co is currently the only metal classified as critical to the European economy for which extraction has proven potentially profitable (Volkmann et al. 2018b). However, the socio-economic benefits for current and future generations remain uncertain as the reserve life estimated for E1[16] is rather more speculative than scientifically proven (Volkmann and Lehnen 2017). Nevertheless, to maximize the benefits for future generations, resource utilization should be considered in SMP, and poor planning and mining practices should be avoided (Appendix; Figure A.7.1).

Resource utilization can in several cases be increased without rendering mining unprofitable (Yasrebi et al. 2017; Menabde et al. 2018). As in land-based mining or agriculture, poor practices may hamper or delay the potential for economic reuse of areas and their remaining resources for future generations (Foley et al. 2005; Dubiński 2013; Motavalli et al. 2013; Carvalho 2017). Thus, it may be a poor practice not to mine those areas and their resources in the "best technically possible manner" that, while not leading to maximum profits, nevertheless has an "acceptable profitability" and applies to areas "seriously affected" by mining anyway (Volkmann 2014). This may not contribute to a "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission 1987).

[16] From today's perspective, the German license area E1 may sustain 84 to 186 years of mining, assuming that only one third of the known resources could be mined and the annual production per operation would be limited to 1.5 to 2 Mt according to Volkmann and Lehnen (2017).

6.1.3 Legal and Regulatory Aspects

Typically, a feasibility study prepared by the mining company to obtain a mining permit must meet certain requirements and cover the content defined by the authorities. As described in Chapter 2, rules, regulations, and procedures for the exploitation of SMnN have yet to be adopted by the ISA into “the Mining Code.” Therefore, the definitions (and formulas), methodologies, models and tools presented in the thesis need to be approved by authorities such as the ISA or an authorized organization such as the JORC[17] to be used in official feasibility studies. Moreover, the definitions for, for example, *mine plan*, *mine site*, and *mining field* are project-specific. Recommendations are made as to how this thesis could contribute to the development of the Mining Code (Section 6.2.2).

Although S/SD has become an integral part of the activities of most mining companies (Hilson 2000; Mudd 2010; Giurco and Cooper 2012), the integration into SMP has not been achieved due to uncertain legal and other (e.g., environmental) requirements. The interpretation of the research findings in the context of S/SD (Figure 1.4) is therefore limited. Nevertheless, this thesis presented several aspects that could be integrated into SMP, namely resource and seafloor utilization, profitability, and the affected seafloor area. Some consensus may be reached on how S/SD could be implemented—along with the findings of this thesis—once the “scale of mining”[18] and the role of “the Authority” (ISA) and “the Contractor” are considered as follows.

Assuming the Contractor would have been encouraged—or forced—to maximize resource utilization at the scale of the license area, a larger area would need to be mined with as-yet-untested mining technology to result in the same metal output (Reydellet and Volkmann 2017). The erection of mine sites in the areas of current commercial interest would reduce the size of such a mine site and the techno-economic requirements to operate profitable (Volkmann and Lehnen 2017; Volkmann et al. 2018a). A cherry-picking practice might however be reasonable at a larger scale for economic and ecologic reasons (Sharma 2011) if equivalent areas to those to be mined are protected, even if criteria have yet to be defined for these areas (e.g., PRZs; Volkmann et al. 2018a).

[17] The Australasian Joint Ore Reserves Committee (JORC) has defined a widely accepted code of practice that “sets out minimum standards, recommendations and guidelines for Public Reporting in Australasia of Exploration Results, Mineral Resources and Ore Reserves ” (JORC 2012).

[18] It is proposed that SMP-related activities are classified based on the “scale of mining”; a mine design (Figure 3.3) and a classification concept for SMP-related activities were proposed (Figure 2.6).

However, scientific research is still needed to determine whether the erection of protected areas within a mine site would be ecologically sensible (Chapter 2). In view of the research finding that not all seafloor areas would be eligible for mining (Volkmann und Lehnen 2017), the erection of protected areas could be omitted at the pioneer stage. Instead, the emphasis may be placed on adaptive management. Adaptive management is a practical way to balance demands for development with ecological (environmental), economic, and social (societal) goals in an open and planned way (SPC 2013), which attempts to reduce uncertainties over time in a structured and regulated process of “learning by doing” (Walters and Hilborn 1978; Johnson 1999; Williams 2011).

Adaptive management may be reasonable for three main reasons: (1) The first pioneers may experience first-mover disadvantages (Shankar et al. 1998; Cleff and Rennings 2012). They will have to develop the full mining technology chain and may experience technical and operational difficulties with no precedents to learn from (Reydellet and Volkmann 2017). Furthermore (2), subsequent operations could be more cost-effective, while a growing number of new operations could increase competitive pressure between land-based mining and SMnN mining and between pioneers and successors (Reydellet and Volkmann 2017; Volkmann et al. 2018b). Finally (3), based on experiences in land-based mining (National Research Council 2002), the development of technologies, depleting reserves, fiscal incentives, and competition may promote S/SD.

6.2 Conclusions and Recommendations

The answer to the main research question on how the mining of SMnN can be planned arose from the working process of this PhD thesis. Therefore, this section summarizes the thesis and draws conclusions after each planning step.

6.2.1 Conclusions on Spatial Mine Planning

Spatial mine planning (SMP) is a process of analyzing and allocating the spatial and temporal distribution of human activities on the seafloor associated with a mining project. Similar to conventional, land-based mine planning, SMP covers the entire value chain—from exploration and extraction to the sale of refined metals. It is multidisciplinary research that includes geological, technical, economic, financial, environmental, and legal aspects. Unlike conventional mine planning, the evaluation of SMnN projects and deposits requires that these aspects be spatially linked.

Definition of Objectives

The investigation of the mineable area and the estimation of SMnN reserves by means of a multicriteria analysis are strategic goals of SMP. Achieving these goals may allow mining engineers to proceed with the definition of mine sites, mining fields, and routes and further activities that have not been investigated in this thesis. A requirement of strategic planning is the implementation of techno-economic feasibility. Techno-economic feasibility implies that a deposit has proven to be economically and technically mineable and that a project has proven economically viable under reasonable assumptions and estimates. As discussed, legal and other (e.g., environmental) aspects must also be considered to obtain, for example, mining permits, financial (state) support, and the social license to operate.

Data Collection

The first step in investigating the mineable area is to research information on the current state of the art in research and technology and on data required for SMP. At this planning stage, mining engineers are confronted with uncertainties from various scientific fields and are forced to make assumptions. There is a lack of geological certainty and high-resolution maps, and mining technologies and methods have not been fully developed and tested. Moreover, there is as yet no mining code for the exploitation of SMnN in international waters and legal and other (e.g., environmental) requirements for mining, and the implications for SMP are uncertain.

In summary, the literature research conducted in Chapter 2 contributed to the selection and development of suitable models, methodologies, and tools for the techno-economic evaluation of SMnN projects and deposits. The knowledge from the Blue Mining project, which is the background of the research work, made it possible to test these.

Evaluation of SMnN Projects and Deposits

The evaluation of SMnN projects and deposits is a further step. To assess them against the background of techno-economic feasibility, the definition of key figures is a basic requirement. In turn, their calculation requires that appropriate equations (or formulas), models, methodologies, and tools be used. Deposit models are required to create spatial maps that provide mining engineers with information on the seafloor geology (e.g., bathymetry, metal grades, and nodule abundance). As described in Chapter 2, the technical specifications of a mining system are required in order to calculate production key figures and to conceive of mining methods. Furthermore, economic/financial models are needed to calculate economic key figures, such as the NPV, IRR, and NP.

A research highlight was the development of the graphical mine-planning tool (nomogram) and the deposit evaluation technique described in Study 3. Each of the individual studies helped to identify areas of potential commercial interest. Study 3 used the background and foreground of Studies 1 and 2 (i.e., the formulas for calculating key figures, the background data, and the estimates derived from the economic/financial model). Finally, it was possible to convert the geological deposit model into economic maps of the seafloor and to investigate the implications of SMnN mining for resource and seafloor utilization. This achievement may in the future form the basis for the development or the techno-economic evaluation of mining systems and mine plans. This can also be a further step in determining the environmental footprint on the seafloor.

Despite this milestone in research, it was not possible to complete the identification of the mineable area due to uncertain legal and other (e.g., environmental) requirements and their effects on SMP. Furthermore, the definitions (formulas), models, methodologies, and tools as well as the procedures described in this work must be accepted by their potential users (e.g., industry, authorities and scientists). Also, the developed mining and knowledge-based solutions are limited in their applicability since they were designed for strategic mine planning and not for long-, medium-, or short-term or production planning. To increase the accuracy of the calculations, further investigations must be carried out. Further research perspectives for SMP are summarized below:

- Research into further SMP-related activities to define the requirements for long-term, medium-term, short-term, and production planning.
- Research and development of indicators for sustainability/sustainable development and integration into SMP.
- Research and development of models for the 2-D/3-D simulation of DSM and the investigation of “optimal” mining routes and field designs.
- This includes the integration of environmental impact/risk models into SMP.
- This includes studying the interference between the mining operation, the environment, and processes at sea and below the sea surface and studying the implications of mining on the affected seafloor area, profitability, and resource and seafloor utilization.

Interpretation and Validation of Results

The interpretation and validation of results is the next step in planning. In accordance with the objectives of the individual studies, the results were interpreted against the background of technical (Study 1), economic (Study 2), and finally technical-economic feasibility (Study 3). The most important findings of the studies are summarized and grouped below:

– **Study 1:** The spatial analysis showed that the geological conditions of the study area would favor a striplike mining pattern in designated fields (Figure 3.7). It was shown that the annual production rate would be limited to around 1.5 to 2 Mt (dry SMnN). About 60 to 100 soccer fields would be harvested per day at maximum production. However, not all areas would (currently) be eligible for mining, and about 4% to 6% of E1, which encompasses about 58,000 km², would be utilized over 20 years. From today's perspective, E1 may sustain about 84 to 186 years of mining if one third of the explored resources can be utilized.
– **Study 2:** The economic analysis demonstrated economic potential (before-tax NPVs between about −\$1 and \$4 BN) for the Blue Mining case study. The comparison of sales values (based on price trends) with estimated break-even values (4M good case: \$400/dmt, 4M moderate: \$550/dmt, 3M moderate: \$430/dmt, 4M poor \$815/dmt) pointed out that a project would be profitable under moderate and good conditions if selling Ni, Co, Cu, and FeMn (Table 4.2). The 4M poor-case scenario or a recovery of three metals would only be possible with the high metal prices of 2008. Prices of Ni and FeMn, the TC/RC, and the production rate would be the driving factors of profitability. Under the assumption that tax and royalty rates would be adequate to land-based mining, tax revenues of up to \$5 billion and royalty revenues of up to \$0.8 billion could be generated over 20 years.
– **Study 3:** Mining would have to be selective to be technically and economically feasible, as not all seafloor areas of the model area (less than 50%) would be eligible for mining. Even in the 4M good-case scenario (Figure 5.5-II), the miner would have to cherry-pick the most economic parts from the potential mine site (> \$9/m²; Figure 5.4). Mining these areas would reduce seafloor utilization significantly. To achieve average mining rates of 4 to 10 m²/s, mining capacities of 7.5 to 20 m²/s would have to be provided by one or several SMTs, depending on the (unknown) time efficiency and operating time.

In summary, the findings of these studies have proved to be largely consistent with the results of other studies and thus demonstrate the applicability of the formulas, models, methodologies, and tools. Furthermore, assumptions such as the mining concept could be validated. However, economic feasibility/viability is project-specific and depends on the type of deposit, the level of study that has been carried out, and the financial criteria of the individual company. Also, the seafloor geology will be site- and field-specific; thus, the mining concepts may be different for the individual project. For this reason, the results of the Blue Mining case study may not be representative for other projects. At this stage of mine planning, a statement on techno-economic feasibility is not reliable, primarily due to geological, technical, legal, and environmental uncertainties.

As discussed, the studies do not include all contents of a typically land-based feasibility study since they focus on economic viability and do not include the entire DSM mine value chain. In addition, the contents of a feasibility study and standards have yet to be defined for SMnN. This is another reason why techno-economic feasibility cannot be confirmed. Apart from potential commercial benefits, SMnN mining has potential socio-economic benefits, but "land use" would be more extensive than compared to land-based mining. Nevertheless, it is as yet not possible to interpret the results in the context of S/SD and to conclude the implications or requirements for SMP—for example, defining good/poor planning practices. Although there are indications that selective mining (cherry-picking) would be ecologically reasonable, studies still have to be carried out.

Final Thoughts

Despite these limitations, this PhD thesis contributes to the development of mining engineering and knowledge-based solutions to assess SMnN deposits and mining projects, the definition of the techno-economic requirements, and the validation of assumptions. Parallels to conventional, land-based mining and agricultural engineering in terms of machine, seafloor (land), and resource management became evident and support the research hypothesis. Moreover, the thesis also contributes to the establishment of a common technical language. However, the way in which SMnN mining is planned will depend on advances in various areas of technology and science—and may therefore be different to what is assumed in the current work. Further exploration, research, and development activities must be carried out, accompanied by comprehensive environmental studies and the formulation of a spatial planning policy to ensure S/SD.

6.2.2 Recommendations for the Mining Code

Finally, this thesis calls for the development of a spatial management policy to implement S/SD. It is proposed to apply adaptive management that attempts to reduce uncertainties over time in a structured and regulated process of learning by doing. The recommendations and comments are as follows:

Licensing

I. In accordance with the Technical Study No. 11 (ISA 2013), it is recommended that the Contractor be granted a tenured (staged/phased) mining license if the precommercial production phase has proven a project's compliance with the environmental, technical and fiscal demands of the Authority (Figure 6.1).

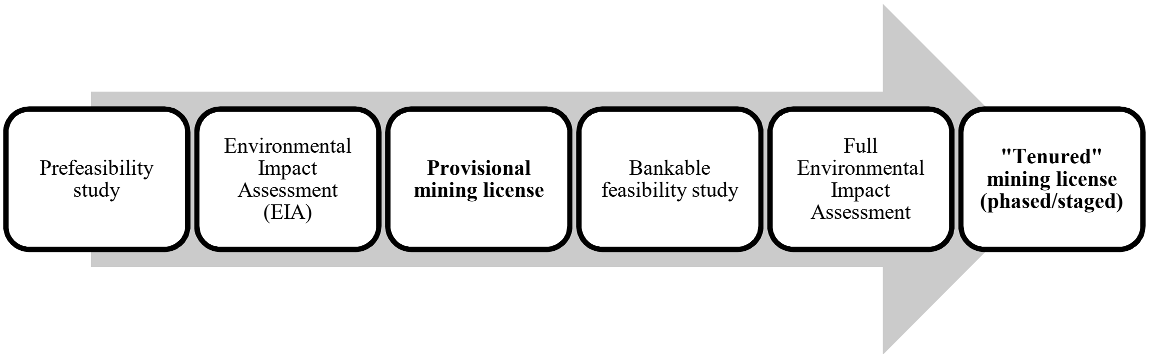


Figure 6.1. Licensing process published in ISA (2013).

II. In accordance with the Technical Study No. 11 (ISA 2013), it is recommended that the whole of the deposit mine plan include (1) a comprehensive resource and reserve assessment, (2) the adoption of a sequential mining plan, (3) provision for periodic review and updating of the mine plan, and (4) performance guarantees and "failure to perform" penalties.

III. A mine site should provide enough reserves to carry out mining for a defined period of time under reasonable techno-economic assumptions. An official resource and reserve reporting code is appreciated. "Moving forward" in the mine plan should only be permitted if the contractual obligations concerning the specified mining area (see IV) are met by the Contractor.

IV. Relating to III, a mine plan should contain information on, among other things, the location, the size, and outline of the mine site; the mineable area and fields;

the (potentially) affected area (e.g., indicating the risk and severity of impacts; and basic fundamental geological factors relevant for mining (e.g., grade, slope, nodule abundance, etc.). Moreover, the cash value may also be a useful indicator of the areas of commercial interest. Although mining may not develop from one field to another (as being project-specific), the mineable area and field outlines should be included in the official mine plans to allow the Authority to investigate if the Contractor meets the contractual obligations (see VII–IX).

V. Relating to III and IV, it is suggested to divide a license area and mine site into rectangular cells. The size of a mine site could be based on the expected (minimum) duration of a typical large-scale mining project (e.g., 20 years) or could be based on the duration of the licensing tenure. A mine site could be further subdivided into smaller cells, depending on the duration of each phase/stage. A tenure of 3 to 5 years may be appropriate to not restrict the Contractor too much. A mine site may be further subdivided according to obligatory reporting intervals (see IX). The boundaries of a mine site and mining field defined by the Contractor during the design/engineering process are additional features of the mine plan (Figure 3.3).

VI. Concerning environmental management, seafloor areas should be withheld, protected, and gradually released, while "equivalent" areas to those being mined (at the scale of a mine site) should be permanently conserved to preserve and restore ecosystems as widely applied by authorities regulating mining and agricultural activities on land. Furthermore, areas that cannot be mined for technical or economic reasons should be protected from being degraded. An adoptive spatial management strategy is recommended. Depending on the requirements of the environment, which will become evident by "learning and doing," areas are either conserved or released for mining.

Monitoring and Control System

VII. A monitoring and control system is recommended that allows the Authority to intervene during the preproduction and production phases, if necessary. On one hand, intervention may be necessary if a Contractor fails to perform or as a preventive measure to protect the environment from "serious damage." On the other hand, fiscal incentives may apply (1) to award good practices, (2) to encourage sustainable development, and (3) to stimulate the economy as measure to protect DSM.

VIII. It is recommended that "good and bad" practice and performance be awarded as proposed by Blue Mining (Bertrand and Volkmann 2017). For example, these could be tax breaks (including royalties), preferential treatment, and so on. Performance indicators are required; these could be the affected area (including the severity and risk of impact) or the affected/mined area ratio, the resource utilization, and the extraction efficiency. As "good and bad" practices and performance will need to be assessed during the precommercial phase, priority should be given to reduce the affected/mined area ratio and to increase reserve recovery (extraction efficiency).

IX. A comprehensive assessment of a Contractor's performance should be scheduled before each stage/phase to decide if new mining areas are released; further reporting and smaller assessments may be obligatory during a stage/phase. To prevent fraud, it is recommended that inspections be performed on a regular basis by independent persons, including the required instruments and software used onboard of the MSV.

7 Appendix

Additional Contents of Chapter 2: Route Planning

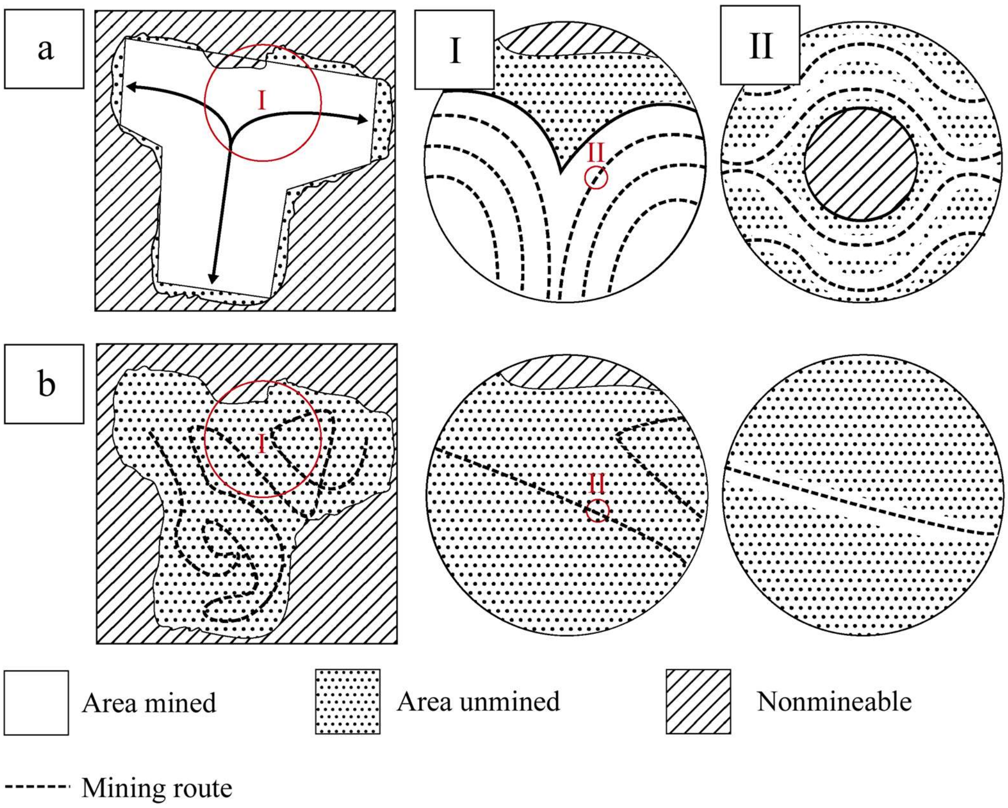


Figure A.7.1. Schematic route planning concept proposed for SMnN mining. Picture a) shows a well-mined field, and b) a badly mined field, which is assumed to be particularly noticeable on smaller scales. The typical size of a potential mining field would be about 25 km². These fields would be 1 to 4 km wide and 5 to 14 km long, north-south orientated (Volkmann and Lehnen 2017).

Additional Contents of Chapter 3: Field Efficiency

This section contains additional information on the field efficiency. In contrast to time efficiency (Formula 3.11), field efficiency (in agricultural engineering) is expressed as the percentage of the mining capacity achieved in the fields under real conditions (Hanna 2016). It accounts for the failure to utilize the full operating width of the machine (i.e., overlapping) and many other time delays. The reasons for unproductive times in SMnN mining are assumed to be partly similar to those in agriculture. List points 1 to 4 and 10 are included in time efficiency, however, not in field efficiency (Formula A.7.1).

$$\boldsymbol{Field\ efficiency} = \frac{\boldsymbol{List\ point\ 5}}{\boldsymbol{List\ point\ 5\ to\ 9}} \qquad \text{A.7.1}$$

Where:

1. Scheduled downtime (for example, due to sea state, major maintenance)
2. Travel to mine site and setting-up time
3. Field-to-field travel time
4. Machine preparation time in field
5. Theoretical field time
6. Turning time and time bypassing obstacles
7. Time delays due to processes at and below sea level
8. Machine adjustment time
9. Maintenance time
10. Repair time
11. Operators' personal time (only if manually controlled)

The factors that may influence field efficiency as in agriculture (Grisso et al. 2000; Hunt and Wilson 2015; Hanna 2016) are described below:

Theoretical field time

As in agriculture, theoretical field time is assumed to be important for SMnN mining if fields would be sequentially mined. It is defined as the working time spent in a field at full-capacity utilization.

Turning time and time to bypass obstacles

As in agriculture, it is expected that the fewer maneuvers performed, the higher the field efficiency (thus, the productivity).

Time delays due to processes at sea and below sea level

Processes at and below sea level are expected to influence productivity (e.g., downtime related to ship-to-ship transfer). In addition to downtimes caused by coupling and uncoupling, the maneuverability of the SMT may be restricted during ship-to-ship transfer.

Machine adjustment time, maintenance time and repair time

As in agriculture, machine adjustment time, maintenance, and repair are expected to have influence on time efficiency. Special AUVs/ROVs could be used to, for instance, eliminate blockages inside the SMT or to disconnect, connect, or lift the SMT.

Speed and slope

As in agriculture, maximum capacity is expected not to be maintained over long periods of time due to slope and nodule size, among other factors. Also, as this is the case for harvesting machines, it is assumed the higher the production the higher the weight on the machine and thus the lower the operational speed.

Overlapping

As in agriculture, the theoretical field capacity takes into account full-capacity utilization, which is unlikely to be achieved in the event of overlaps due to inaccurate navigation or the bypass of obstacles at crossing traffic routes.

Field shape, size, and pattern

As in agriculture, field shape, size, and pattern are assumed to indirectly have influence on field efficiency. In farming, for example, the number of turnings and overlapping depends on the field's shape, size, and traffic pattern.

Additional Contents of Chapter 4: Economic Analysis

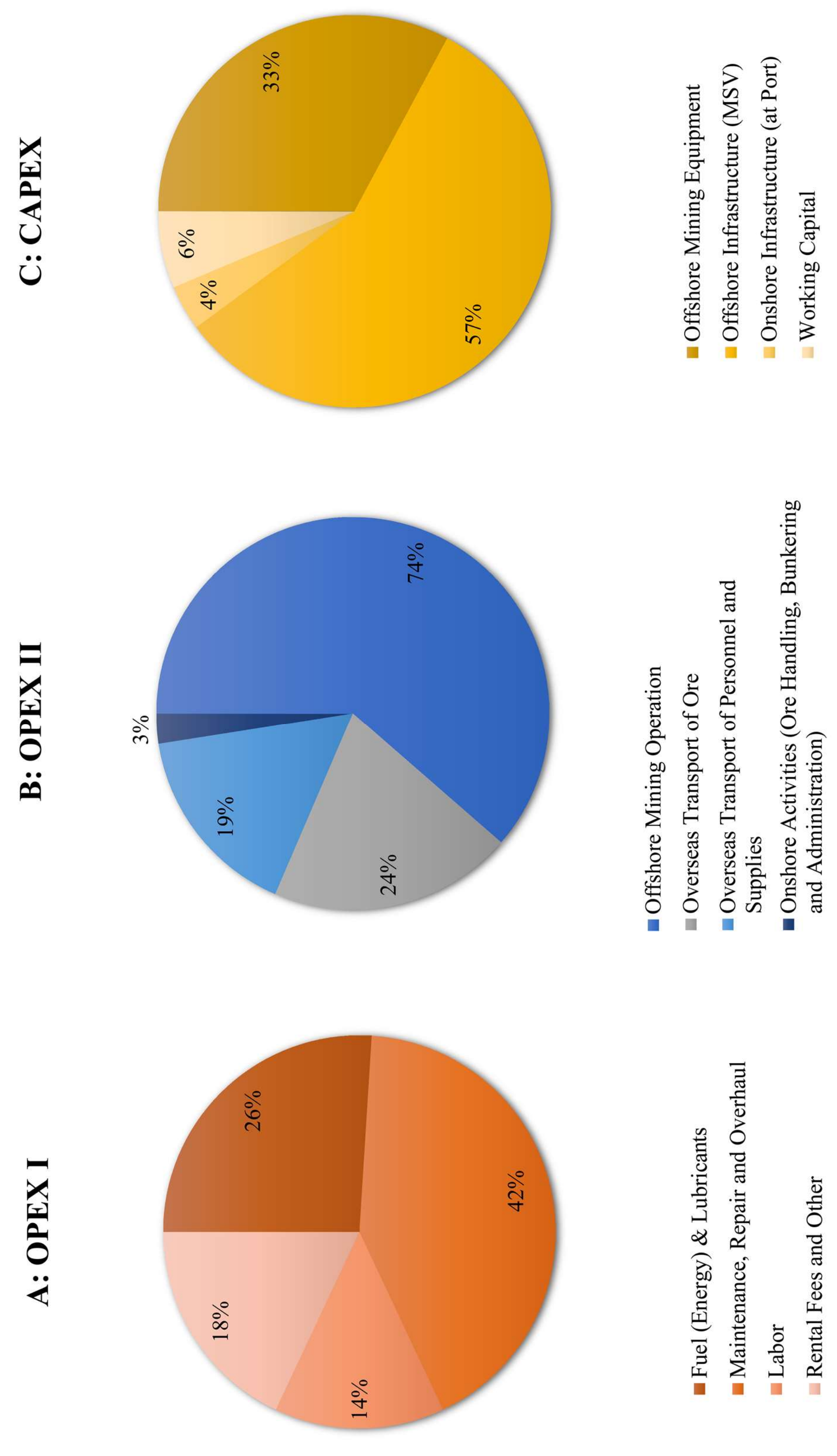


Figure A.7.2. Cost allocation for mining and transport. The costs were determined as part of the Blue Mining project. Diagram A: The OPEX are shown here broken down by cost element; Diagram B: The OPEX are shown here broken down by cost area; Diagram C: The CAPEX are shown here broken down by cost area (including working capital).

Table A.7.1. Determination of the break-even NSR (miner).

No.	Derivation	Item	Value			Unit
			Good	Average	Poor	
1		Annual production	2	1.5	1	Mt, dry
2		(Break-even) NSR	143.3	210.4	330.1	\$/t
3		CAPEX (investment)	595.6	559.4	511.2	\$M
4		OPEX	75.6	95.9	129.2	\$/t
5		Corporate tax rate	30	30	30	%
6		Royalty rate (on NSR)	4	6	8	%
7		Discount rate (*i*)	15	20	25	%
8		LOM (*T*)	20	20	20	a
9	1 × 2	Annual NSR	286.6	315.6	330.1	\$M
10	1 × 3	OPEX	151.1	143.8	129.2	\$M
11	3 / 8	Depreciation	27.9	26.2	23.9	\$M
12	(9 − 10 − 11 − 13) × 5 (0 if negative)	Corporate tax payment	28.8	38.0	45.1	\$M
13	9 × 6	Royalty payment	11.5	18.9	26.4	\$M
14	9 − 10	Cash flow (before tax and royalty)	135.4	171.8	200.8	\$M
15	14 − 12 − 13	Cash flow (after tax and royalty)	95.15	114.88	129.28	\$M
16	$\frac{1-(1+i)^{-T}}{i}$	PVAF(i, T)	6.3	4.9	4.0	
17	(14 × 16) − 3	NPV (before tax and royalty)	252.2	277.4	282.9	\$M
18	(15 × 16) − 3	NPV (after tax and royalty)	0.0	0.0	0.0	\$M

Table A.7.2. Determination of the break-even TC/RC (processor).

No.	Derivation	Item	Value				Unit
			Good	Average		Poor	
			4 M	4 M	3 M	4 M	
1		Annual production	2	1.5	1.5	1	Mt, dry
2		(Break-even) TC/RC	253.4	334.3	221.5	482.5	\$/t
3		CAPEX (investment)	907.4	873.6	661.9	804.8	\$M
4		OPEX	158.7	175.0	101.0	207.8	\$/t
5		Corporate tax rate	30	30	30	30	%
6		Discount rate (i)	15	20	20	25	%
7		LOM (T)	20	20	20	20	a
8	1 × 2	Annual revenue	506.7	501.5	332.3	482.5	\$M
9	1 × 3	OPEX	317.4	262.5	151.5	207.8	\$M
10	3 / 7	Depreciation	41.4	40.4	31.2	37.6	\$M
11	(8 − 9 − 10) × 5 (0 if negative)	Corporate tax payment	44.4	59.6	44.9	71.1	\$M
12	8 − 9	Cash flow (before tax)	189.3	239.0	180.8	274.7	\$M
13	12 − 11	Cash flow (after tax)	144.96	179.40	135.92	203.56	\$M
14	$\frac{1-(1+i)^{-T}}{i}$	PVAF(i, T)	6.3	4.9	4.9	4.0	
15	(12 × 14) − 3	NPV (before tax)	277.8	290.1	218.5	281.1	\$M
16	(13 × 14) − 3	NPV (after tax)	0.0	0.0	0.0	0.0	\$M

Table A.7.3. Constant dollar prices of Co, Cu, Ni, and FeMn for 1970 to 2015, based on nominal prices reported by the USGS used in financial modelling.

Year	Co	Cu	Ni	FeMn[1]	Price deflator[2]
	Constant 2015-\$ per dmt (metal content)				
1970	\$ 26,028.33	\$ 6,870.29	\$ 15,262.06	\$ 931.60	5.37
1971	\$ 25,101.29	\$ 5,943.30	\$ 15,174.87	\$ 1,000.13	5.18
1972	\$ 26,992.34	\$ 5,667.29	\$ 15,424.19	\$ 965.73	5.00
1973	\$ 31,414.83	\$ 6,147.59	\$ 15,810.75	\$ 982.59	4.69
1974	\$ 29,371.80	\$ 6,540.52	\$ 14,728.22	\$ 1,119.24	3.84
1975	\$ 30,190.96	\$ 4,866.97	\$ 15,702.33	\$ 1,532.72	3.44
1976	\$ 31,875.79	\$ 4,962.50	\$ 16,044.86	\$ 1,515.03	3.23
1977	\$ 37,447.47	\$ 4,449.05	\$ 15,125.58	\$ 1,445.34	3.02
1978	\$ 152,409.44	\$ 4,090.57	\$ 12,680.07	\$ 1,274.39	2.82
1979	\$ 180,609.76	\$ 5,071.71	\$ 14,633.63	\$ 1,127.93	2.50
1980	\$ 103,261.47	\$ 4,794.42	\$ 14,007.97	\$ 1,174.17	2.15
1981	\$ 67,000.22	\$ 3,600.57	\$ 11,587.15	\$ 1,073.56	1.94
1982	\$ 35,648.40	\$ 3,031.78	\$ 9,078.68	\$ 965.21	1.89
1983	\$ 23,726.71	\$ 3,152.44	\$ 8,732.75	\$ 832.31	1.87

1984	$ 42,088.79	$ 2,695.05	$ 8,708.02	$ 838.54	1.83
1985	$ 45,902.22	$ 2,689.48	$ 9,076.03	$ 841.27	1.82
1986	$ 31,192.35	$ 2,750.67	$ 7,329.58	$ 816.72	1.89
1987	$ 26,627.03	$ 3,348.67	$ 8,889.21	$ 765.87	1.84
1988	$ 27,776.61	$ 4,721.24	$ 24,485.73	$ 1,018.60	1.78
1989	$ 28,509.88	$ 4,886.61	$ 22,539.22	$ 1,530.18	1.69
1990	$ 36,286.81	$ 4,429.22	$ 14,457.18	$ 2,019.67	1.63
1991	$ 60,484.02	$ 3,908.23	$ 13,226.41	$ 1,975.67	1.62
1992	$ 81,339.63	$ 3,810.51	$ 11,280.42	$ 1,712.82	1.61
1993	$ 48,259.58	$ 3,204.24	$ 8,399.06	$ 1,351.83	1.59
1994	$ 85,084.81	$ 3,831.58	$ 9,936.91	$ 1,230.27	1.57
1995	$ 96,929.07	$ 4,590.28	$ 12,377.45	$ 1,183.22	1.51
1996	$ 83,421.50	$ 3,567.17	$ 11,122.87	$ 1,239.39	1.48
1997	$ 76,116.04	$ 3,486.86	$ 10,240.12	$ 1,182.21	1.48
1998	$ 71,511.16	$ 2,624.19	$ 7,007.63	$ 1,189.85	1.51
1999	$ 56,031.89	$ 2,499.05	$ 8,987.49	$ 1,105.39	1.49
2000	$ 46,835.54	$ 2,723.63	$ 12,110.51	$ 1,097.00	1.40
2001	$ 32,377.17	$ 2,358.47	$ 8,286.10	$ 1,112.52	1.39
2002	$ 21,734.83	$ 2,384.23	$ 9,656.43	$ 1,074.82	1.43
2003	$ 31,735.47	$ 2,545.12	$ 13,083.40	$ 1,071.98	1.36
2004	$ 67,518.46	$ 3,786.45	$ 17,690.80	$ 1,211.46	1.28
2005	$ 41,489.35	$ 4,512.10	$ 17,391.21	$ 1,695.51	1.18
2006	$ 42,484.15	$ 7,765.32	$ 27,138.54	$ 1,180.27	1.12
2007	$ 72,659.31	$ 7,801.07	$ 40,146.95	$ 1,095.40	1.08
2008	$ 84,481.75	$ 6,911.87	$ 20,725.21	$ 3,909.26	0.98
2009	$ 42,550.65	$ 5,750.77	$ 15,819.50	$ 2,813.99	1.08
2010	$ 46,433.42	$ 7,757.61	$ 22,025.25	$ 3,189.57	1.01
2011	$ 37,089.08	$ 8,368.24	$ 21,406.11	$ 2,043.02	0.94
2012	$ 28,993.06	$ 7,568.69	$ 16,388.19	$ 1,521.55	0.93
2013	$ 26,443.75	$ 6,973.03	$ 13,974.77	$ 1,405.08	0.93
2014	$ 29,545.53	$ 6,490.63	$ 15,609.34	$ 1,361.13	0.93
2015	$ 29,762.41	$ 6,106.80	$ 12,634.69	$ 1,241.38	1.00
Mean	$ 51,755.96	$ 4,696.44	$ 14,481.38	$ 1,368.81	
Upper quartile	$ 67,388.90	$ 6,065.93	$ 15,817.32	$ 1,497.61	
Lower quartile	$ 29,599.75	$ 3,240.35	$ 10,012.71	$ 1,072.38	

[1] Metal prices for FeMn (100 wt% Mn) are based on nominal ore prices reported by the USGS. The nominal values were adjusted for inflation and adjusted to the 2015 US dollar price for HC FeMn ($900/t; 70–75 wt.% Mn).

[2] The price deflator is the factor by which a nominal price is multiplied in order to arrive at constant dollar prices. The factor was determined by dividing the PPI index for the respective year by the base year index 2015.

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ABOUT THE THESIS

Seafloor manganese nodules are potatolike mineral concretions that cover large parts of the deep-sea floor. They contain various elements, among them metals, that are used in today's high- and green-tech applications. However, there is currently a lack of knowledge in how to plan and execute deep-sea mining projects in a sustainable manner.

The main objective of this dissertation is to provide mining engineers with the knowledge required for "planning the mining of seafloor manganese nodules." This includes the development of appropriate mining-engineering and knowledge-based solutions to technically and economically assess such projects and deposits, the definition of requirements, and the validation of assumptions for spatial mine planning.

The dissertation comprises three techno-economic studies, which are based on a specific case study of the European research project Blue Mining, with focus on the German license area E1, Clarion-Clipperton Fracture Zone, Pacific Ocean.

"THE BLUE MINING OF MARINE MINERAL RESOURCES FOR THE BENEFIT OF MANKIND WILL BE ONE OF OUR FUTURE CHALLENGES."