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Structural Aggregation of Feasibility Factors for the Assessment of the Polymetallic Nodules Deep Sea Mining Value Chain

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ABSTRACT

Article presents the methodology for operational research on the polymetallic nodules mining value chain and the assessment of crucial factors influencing its feasibility. Value chain has been analyzed and boundary assumptions having a substantial influence on the decision making process were identified. Geological, technical, economic, environmental and legislative components are related within the unambiguous framework of their functional interactions. Several decision-making tools are presented and the system of SWOT analysis was applied to identify positive and negative aspects. It should be understood, that project conditions are unique for particular evaluated mineral deposit and evaluation is linked to a particular time period.

KEY WORDS: polymetallic nodule, deep seabed mining, operational research, value chain, SWOT analysis

INTRODUCTION

The deep seabed became one of the most potentially rewarding frontiers challenging mankind in minerals exploration. Mineral resources found in deep seabed area represent potential for enormous contribution to the world resource base and their exploitation can affect world metal markets. In 2013, International Seabed Authority (ISA) commenced the development of regulations to govern the future exploitation of seabed minerals, starting with polymetallic nodules (PN).

Deep sea mining (DSM) activities represent value chain similar to the structure of activities performed in land-based mining. However, there are no deep seabed mining activities yet on commercial scale (excluding oil and gas mining, where today's technology allows to extract gas and oil from water depths of almost 3000 meters). Existing offshore mining operations are performed in shallow waters up to 500 meters depth (tin, diamonds, phosphate rocks).

VALUE CHAIN

Before DSM commencement it is necessary to investigate the potential sequence of steps for the purpose of developing legal frameworks for future exploitation and business models creation. Value chain analysis can be applied to study how work selection, planning, scheduling and execution can drive different business approaches to close-to-optimal solutions, when considered as elements of a chain. Those solutions can be related to the available options in scope of technical means, legal frameworks, taxation schemes, CSR policies and building of an overall enterprise model. This approach could also offer an important alternative for the evaluation of enterprises in the absence of real-life data from operations involving direct competition, as is the case of deep seabed mining (Abramowski, 2016).

A deep sea mining cycle is comparable to the that described for conventional mining. The difference is in the nature of environment and extreme conditions where the particular value chain activities takes place. The sequence of activities in any mining project can be divided into four main activities: Exploration, Evaluation, Construction and Operation, subdivided into detailed stages (Verichev et al., 2014). Similar approach (Abramowski, 2016) provides seven main stages:

- prospecting and application
- exploration
- resource assessment, evaluation and mine planning
- extraction, lifting and surface operations
- offshore and onshore logistics, transport operations
- metallurgical processing stage
- distribution and sales.

Stages and related activities of DSM project for polymetallic nodules are presented in Table 1. As can be seen, the complex value chain may contain not only primary technical or managing activities providing support for the chain but is rather a heuristic combination (learning process by investigation and experiments) of technology, legislation, economic, social and information management.

Stages can be arranged individually for the particular deep-sea mining project or contractor. Value chain can be differentiated using the criteria of the type of activities where the value is actually added. Whereas within prospecting, exploration and resource assessment phases the value is added generally to intangible assets of a project, for the extraction, processing and distribution phases the value increases with relation to product processing (Abramowski, 2016).

Exploration phase involves such operations as locating, sampling (deposit and environmental) and/or drilling, using technologies such as echo-sounders, sonars, deep-towed photography, ROVs, laboratory analyses and other techniques.

Evaluation phase incorporates resources/reserves estimation and valuation, examination of deposit data in the context of potential exploitation, mining and processing technology development and tests, environmental assessment, stakeholder survey and others.

Production phase involves equipment procurement (mining, transport, processing), mine and processing plant construction, operation, closure and rehabilitation, and environmental monitoring. Logistics of deep seabed mining project involves technologies analogous to those widely applied in land-based mining, having regard to some specifications of mining technology and transport.

Table 1. Stages and related activities of DSM project for polymetallic nodules

Stage	**Exploration**	**Evaluation**	**Production**
Activities	- deposit identification (mapping, sampling, measurements, analyses) - resources/reserves estimation - baseline environmental studies	- resources/reserves classification - mining technology development and tests (pilot mining test) - processing technology development and tests - environmental assessment - stakeholder survey, CSR - economic viability assessment	- equipment procurement (mining, transport, processing) - mine / processing plant construction - mine / processing plant operation - closure and rehabilitation - environmental monitoring
Technology and methods	- research vessel - sampling devices (box corer, gravity corer, trawler) - scanning devices (multi-beam and side scan sonar, ROV, AUV) - laboratories (chemical, geotechnical, biological)	- applications and software for resource estimation (GIS based) - research vessel and test mining equipment for pilot mining test - laboratory processing technology tests and large-scale processing tests in existing plants - environmental research devices (disturbers, scanners, sensors)	- mining ships - mining devices (collectors, vertical risers) - transportation and PSV vessels - processing plant - environmental monitoring instruments
Legislation	- regulations on prospecting and exploration for polymetallic nodules in the area	- regulations on prospecting and exploration for polymetallic nodules in the area	- mining code - payment regime (royalties, taxes, including revenue to contribute to CHM)
Deliverables	- exploration license (contract) - reports to administering body (ISA)	- feasibility studies (PEA, PFS, FS) - environmental impact assessment - reports to administering body (ISA)	- mining license - reports to administering body (ISA)

ISA – International Seabed Authority, CSR – corporate social responsibility, CHM – common heritage of mankind, GIS – geographic information system, PEA – preliminary economic assessment, PFS – preliminary feasibility study, FS – feasibility study (bankable), PSV – platform supply vessel, ROV – remotely operated (underwater) vehicle, AUV – autonomous underwater vehicle, PN – polymetallic nodules

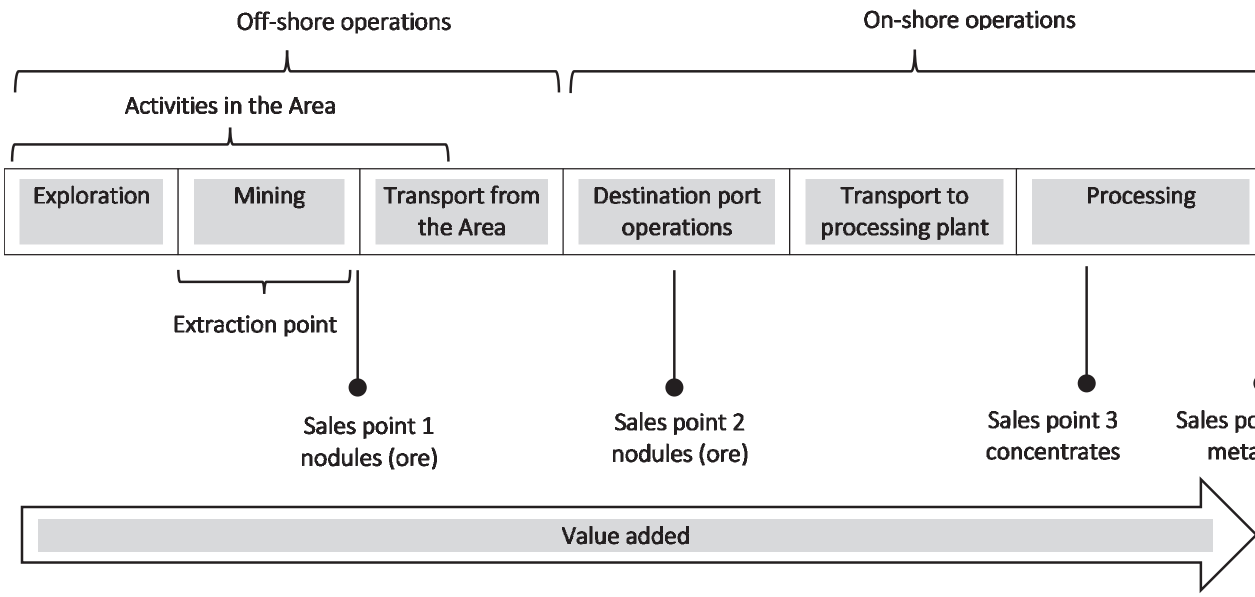

Fig. 1. Options for valuation (sale) points in the DSM value chain

Important advantage of the value chain analysis is the possibility to study the influence of the position of the point of valuation. Point of valuation is the point where a tax is calculated if it is based on a value of the extracted deposit or final product. This possibility allows to investigate various payment mechanisms and to execute a full review of all possible scenarios of its application (Brown, 2014). It is sometimes acknowledged that the valuation point needs to be at, or as close to, the extraction point of a resource. This point in land-based mining is referred to as the "ex-mine" or "mine head" value (Brown, 2014). It is the point at which compensation is due to be paid to the owner of the non-renewable resource.

A standard valuation point provides consistency across all mining projects and may have some impact on the mechanical design of machinery. The point of valuation can only be analyzed in the case of value chain based on product processing (Fig. 1). The chain of activities presented here comprises activities in the Area (exploration, mining and initial processing, transportation) and onshore operations (port operations, transport, processing and sales).

The extraction point in case of DSM is the point where deposit is collected and subsequently transferred to the riser subsystem. Material (ore) is stored onboard the mining ship then. This is the first possibility in the chain to establish valuation point and execute value calculation for the mined ore. Although in the presence of commercial activity the valuation of ore without its actual processing seems to be feasible, the weighing of material at sea can be difficult to achieve with sufficient accuracy (Abramowski, 2016). Mined and initially processed material (dewatered/dried) is then transported to the port. Port operations include unloading, weighing, sorting and preparation for further transport or delivery to customer - this is the second possibility for valuation and sale. At this point, activities can be performed under much favorable conditions (relevant port equipment and logistics), then sales on extraction point. Final products as a result of ore processing (concentrates, alloys, pure metals) represent highest value added in DSM project value chain.

Valuing of ore (or products) is related to location and it will be crucial for calculation of royalties and other payments (CHM, Enterprise, ISA). Once ore leaves the Area, ISA jurisdiction is limited. DSM payment regime will be clarified in Mining Code (under preparation at this time by the ISA).

ECONOMIC MODEL

The proposal for the planning of the overall structure of economic model is given in Fig. 2. At first, the key assumptions should be identified and adopted. Subsequently, at least an initial design of the mining, transport and processing systems configuration should be developed during engineering works. On that basis, economic evaluation can be carried out with further cash flow analysis, accounting for the duration of the project and cash discount ratios. After the assessment an adjustment can be introduced to the initial assumptions, and this loop is repeated until satisfactory results are found (Abramowski, 2016).

It is necessary to assess any DSM project viability by feasibility study including determination of standard economic indicators: net present value (NPV), internal rate of return (IRR), payback period and others. Financing cost for the feasibility study can represent important item of overall cost structure and should be taken into account in financial modelling. In early phases of project (assessed by pre-feasibility study) risk is higher due to lack of verified information and potential investors require higher rates of return. Internal rate of return on the level of about 30 % is required by the mining industry. Risk and sensitivity analyses should cover volatility of metal markets (metal prices, supply and demand).

Important question is obtaining financing for DSM. For investors it is necessary to obtain reliable information on project viability, based on information on reserves, mining and processing technology, economic indicators and clear legislative background (including Mining Code and environmental regulations). Start of real DSM project is subject to the above assumptions.

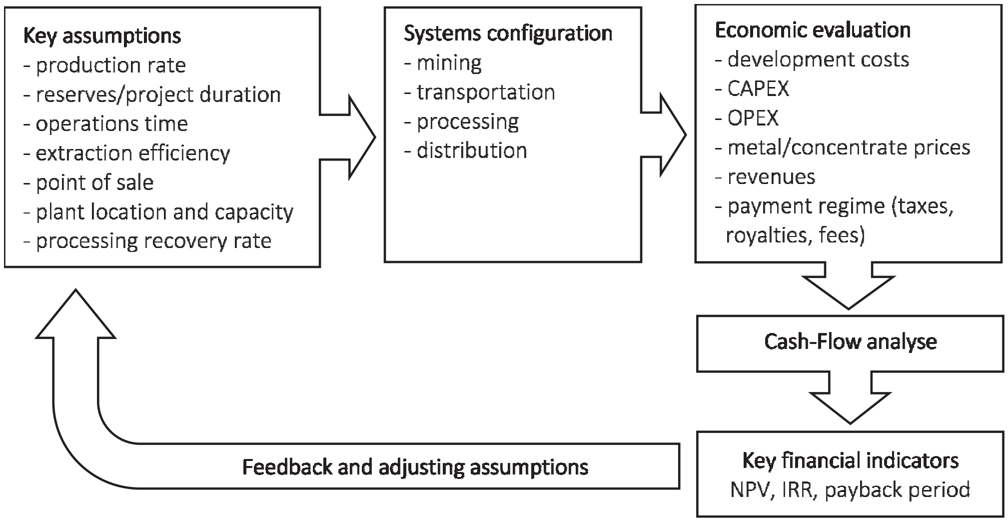

Fig. 2. DSM project economic model structure loop

SWOT ANALYSIS

SWOT analysis is a tool of strategic management, which aims to identify strengths/weaknesses and the opportunities/threats of specific project. It is used mainly in the economic sphere for fast overview of the strategic situation of assessed entity. Strengths and weaknesses are internal factors (internal analysis), opportunities and threats are external factors (external analysis). The basic element of the SWOT analysis is to identify and evaluate these factors. Selection of factors has been adapted for the evaluation of PN deposit.

Identification of factors for the assessment of mineral deposit

Selection of factors was carried out in order to maximize embracing issues, affecting real use of nodule resources. Internal factors (strengths and weaknesses) characterize the internal (geological and technological) aspects of nodule deposit, based on the results of exploration and reserves estimation (amount of reserves, reserves classification, quality and technological properties of nodules, deposit geological setting), mining and processing technology (viable way of deposit accessing, technical mining and processing conditions). External factors (opportunities and threats) characterize the exterior aspects that have a direct impact on the exploitation possibilities: legislation (regulations, conflicts of interest), economy (economic feasibility, demand, market) and environmental impact assessment.

Model

Evaluation of each factor determines for its strength or weakness (internal factors, Table 2), respectively opportunity or threat (external factors, Table 3). The parameters can be dynamically changed in time, although most of internal parameters (reserves, mineral/ore quality, technical conditions) are relatively stable input items. Any SWOT analysis is thus valid in a particular time period. SWOT analysis matrix is presented in Fig. 3..

The model can also be used in case we do not have information on all parameters. In this case, a factor to which we do not have adequate information is considered as weakness or threat respectively. The proposed selection of factors for evaluation of PN resources do not represent a definitive model. It is an open system that can be adjusted as appropriate and adapted to the needs of the evaluator. The allocation of different weights to individual parameters can contribute to a more realistic assessment. By this way, it is possible to initially evaluate individual nodule deposits or groups of deposits and depending on the objective of evaluation select potentially suitable objects.

SWOT strategies

SWOT analysis can be used to evaluate the situation and suggest the appropriate strategy by modeling of changes in input factors. It is noted that in case of mineral deposits, internal parameters are set by the geological situation and technology development level, which is relatively constant for some time (level of knowledge may be changed and thus categorization of certain parameters). External parameters are, compared to internal, changing relatively quickly.

Table 2. Internal factors of SWOT analysis matrix of polymetallic nodules model deposit

Internal factors	
S (strengths)	**W (weaknesses)**
Resources	
- simple geological settings - resources/ reserves sufficient to provide 3 million tpy of dry nodules for 20 years - vast areas with cut-off abundance over 10 kg per m^2 - wide range of metals included - polymetallic nodules adopted by CRIRSCO system	- relatively expensive exploration - vast area of typical PN deposit complicating detailed exploration for determining mineable areas - most of published data refer to inferred and indicated resources only
Technology	
- simple way to collect nodules (no destruction method needed) - chartered ship transportation available - tests confirming technological properties suitable for processing and use - cost and energy reducing technological development	- deep seabed mining conditions (depth 5,000 meters, pressure 500 bars, temperature 1-2 °C, total darkness, cross cutting currents) - technology of mining, rising and processing known only on the test level, dynamics of the mining system - limited possibility of use of existing processing plants

There are four strategic options (quadrants) in the SWOT matrix – SO (prevailing strengths and opportunities), ST (prevailing strengths and threats), WO (prevailing weaknesses and opportunities) and WT (prevailing weaknesses and threats). These determine the appropriate strategy applicable to a particular situation (Fig. 3).

Table 3. External factors of SWOT analysis matrix of polymetallic nodules model deposit

External factors	
O (opportunities)	**T (threats)**
Legislation	
- limited range of expected conflicts of interests (international waters) - seabed mining patents expiring	- absence of relevant legislation (Mining Code and environmental regulations for DSM)
Economy	
- promising preliminary economic model results (suitable economic conditions varies in real and accessible value ranges) - depletion of onshore resources - demand in the market (new metal consuming technologies, world population rise, industrialization) - declared importance for securing economic growth of developed and developing countries (critical minerals – Co, REE and others) - rapidly increasing interest in deep seabed minerals during last years (a number of new contracts for exploration signed with the ISA)	- not enough relevant technological information for preparation of detailed feasibility study for complex mining project (increased investment risk) - oversupplying of metal market after start of DSM, affecting the metal prices - discovery of new onshore deposits - recycling becoming more commonplace, introduction of material saving technologies and substitution materials - economic (and metal price) growth fluctuations
Environment	
- probability of less environmental impact of nodules collecting than that of land based mining operations	- uncertain result of impact assessment of real mining project (limits for pollution, sediment plume, sewage)

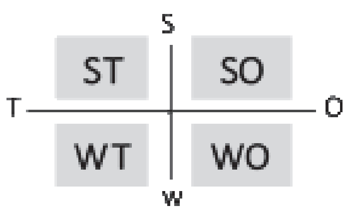

Fig. 3. SWOT strategies matrix

PILOT MINING

The linking operation between exploration, evaluation and production is a pilot mining test. The main steps of deep-sea mining value chain can be differentiated using the criteria where the value is actually added. Whereas within prospecting, exploration and evaluation phases the value is added generally to intangible assets of the project, for the production phase the value increases with relation to product processing.

The pilot mining test could be considered an inevitable step in the shift from "resources" to "reserves" classification, where the actual value starts. This objective is achievable only when the pilot mining test will be planned carefully and executed to provide sufficient information on all critical factors influencing production.

Ultimate planning will allow organizing the process of gradual transfer of the equipment used from tests to full-scale production. It remains open to decide whether to include metallurgical processing phase in the pilot mining test, but the proper examination of the value chain would require at least consideration of such commitment.

In any case, organization of the pilot mining test is a smaller scale equivalent of the production phase thus, it should consider the basic assumptions for the following:

– Production factors: cumulative and annual mass recovery and the duration,
– Site factors: mineable proportion and average nodule abundance and variability of nodules distribution,
– Technical factors: dredge efficiency and sweep efficiency.

All the above factors entail an iterative procedure to be executed, e.g. for the design of mining equipment an operator/designer has to assume cumulative recovery, but in the case of unsatisfied economic numbers, it has to be re-adjusted. The role of the pilot mining test is to provide first approximation based on real experiment and provide the data for the design process of mining equipment and as well for geological estimation of minable reserves.

The characteristics of a designed test site for pilot mining should be selected to reflect the above factors. Minable proportion of a site can be defined as the measure of an area where mining is actually executed to the total area of an exploration block. Nodule abundance corresponds to the area of mineable proportion. Dredge efficiency is the measure of the quantity of nodules recovered by the collecting device to the quantity of nodules in the dredge paths. Sweep efficiency is the ratio of the area swept by the collector to the minable area. Whereas dredge efficiency if connected to the operational principle of a collecting head (usually hydraulic or mechanical), the sweep efficiency corresponds to the collector's seafloor maneuvering abilities.

Factors affected the outcome of the pilot mining test are summarized in Table 4. The summary ensures proper planning and results analysis of the test. Obviously, the final group of factors, i.e. economic assessment is expected to deliver information on feasibility of the project in terms of indications allowing to scaling-up procedure and operational research procedure for full-scale production.

Prediction of commercial performance from pilot or pre-commercial/demonstration plant data requires scaling up procedure. The answer to a question whether a process can implemented directly from pre-commercial applications like pilot tests, requires the proper prediction of process characteristics in unit operations. A model of unit operations is a necessary condition for ensuring the proper sizing and output determination of larger-scale implementations. Thus, an essential goal of scaling-up procedure is the accurate prediction of commercial performance of a process, allowing to commercial technical design and the determination of economic viability.

Mining site determination procedure requires the delineation of seabed portion(s) containing sufficient reserves to meet economic production expectations. Given an entire exploration area containing nodules of adequate average grade and abundance, parts of that area will not be mined due to topographic obstructions, adverse bottom conditions and patches below cutoff grades. Considering the part of the mining-site where extraction would actually be carried out, the proportion of the nodules that could be recovered from that part will further be dependent upon efficiencies of the mining system used (dredging and sweeping efficiencies mentioned earlier). Calculating the area requirements for a mine-site must take into consideration these factors as well as the uncertainty associated with their estimation.

Environmental monitoring activities and impact assessment analysis relate to the temporal and spatial discharges of the mining system if they occur, sediment plumes investigation, disturbance to the benthic environment, and the analysis of the regions affected by seafloor machines. This involves an examination of disturbances near the seafloor, as well as disturbances near the surface. Observations include the examination of the discharges at the seafloor level while environmental baseline comparisons are to be carried out for the sake of quantitative assessments.

Table 4. Factors to be considered or confirmed during mining test

Group of factors	Description
Mining technology	– efficiency of mining system (dredge efficiency, sweep efficiency) – deployability – power requirements in various mining conditions – reliability of the system – dynamics of the riser – maneuverability and possibilities of collector movement control on the ocean floor – slurry/ nodules mixture flow velocities – rising efficiency – nodule crushing or/and size separation – underwater navigation operation
Transport, transshipment and storage	– transfers time – transport losses – transshipment output – risks associated with transshipment operations – storage capacity and influence on ship seakeeping – stowage factors
Environmental factors	– sediment penetration in operating conditions – sediment dispersal and plume characteristics – fauna communities impact in collector tracks – potential water column and near surface effects – technical considerations for environmental monitoring system
Metallurgical processing	– metals/concentrates recovery characteristics – energy consumption – waste disposal options – by-products/rare earths elements distribution in processing stages
Economic assessment, scaling-up procedure, mining site determination and production factors	– unit cost as a function of recovery output – units cost as a function of mass – unit cost as a function of energy requirements – minable portion – mining system working days – structure of OPEX/CAPEX or possible revenues if applicable for mining test

Monitoring system during pilot mining test requires application of different carriers for measuring devices. During the test, direct and instant measurements can be executed with the aim of ROVs or AUVs. It is anticipated however that a certain time of observation is required for post-test monitoring and environmental recovery of the area. It is questionable if the time for such activities from mining tests to production commencement could be sufficient to satisfy all possible expectations. Nevertheless, the fixed sensors should be installed and can be further used for production. Such fixed devices have the structure of near bottom moorings or columns. Besides the information on the mining impact itself, the outcome of environmental monitoring is supposed to provide a set of deep sea mining industry management practices and should assist in developing of protocols and standards.

CONCLUSIONS

Proper value chain analysis requires the coordination of knowledge and information flow regarding the marine mining operations (extraction, pumping, storing), as well as the processes like all the way to product transport and shipping (transport logistics), processing, final production and even the marketing for the products.

Rising demand for metals (new technologies, industrialization of developing countries) and depletion of mineral deposits on land (lowering metal grades and increasing mining depth) can enhance the possibility of deep seabed mining. On the other hand, recycling, new exploration as well as other technological developments offset the same (Sharma, 2011).

Commercialization of polymetallic nodule mining is influenced by wide range of geological (resources), technological (mining, processing), economic (feasibility evaluation), legislation (mining and environmental regulations) and environmental factors. They can be assessed by SWOT analyze (evaluation of strengths, weaknesses, opportunities and threats).

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