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Sustainability of maritime transport plans for deep-sea mining

By

Shanghai Maritime University

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Sustainability of maritime transport plans for deep-sea mining

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Abstract:
With growing demand for metal resources by global economies, deep-sea mining is considered as an alternative for terrestrial mining. Deep-sea mining can boost employment, technical innovation of marine engineering, and offer new opportunities for blue economy development. With the commercialization of deep-sea mining, large quantity of deep sea minerals will need to be shipped from mining sites in oceans to bulk ports. Compared to traditional bulk cargo shipping, maritime transport of deep sea minerals faces new challenges such as uncertain economic viability, significant environmental impact, harsh working conditions for seafarers, as well as safety concerns due to cargo liquefication. Maritime transport requires big investment meanwhile the payback period of time is long. In addition, maritime transport is associated with greenhouse gas (GHG), water pollution and waste generation. From professional health aspect, deep sea minerals are found with significantly higher levels of Alpha radiation compared to naturally occurring radioactive materials. Special attention has to be paid to health protection of seafarers on ships loaded with deep sea minerals. Furthermore, for fully saturated bulk cargo like deep sea minerals, liquefaction during maritime transport may occur and cause serious loss.
In this context, the need to develop and promote sustainable maritime transport plans for deep-sea mining becomes priority. This study is a step towards the establishment of such sustainable maritime transport plans by developing a concept of sustainable maritime transport. In addition, a Maritime Transport Sustainability Framework is built based on the concept. The Framework consists of decomposed activities of maritime transport, a preliminary set of sustainability criteria and indicators, as well as sustainability assessment methods. The Maritime Transport Sustainability Framework can be used as a tool to assess a maritime transport plan for deep-sea mining.

Keyword:
deep-sea mining; maritime transport; sustainability; marine minerals; safety

Executive Summary

Global economies are in demand of metal resources more than ever. Territory mining faces significant challenge to meet this demand especially for some critical metals like Lithium, Nickle, Cobalt. On the other hand, deep sea surveys find that there are significant amount of deep sea minerals reserves on deep seabed of oceans, which could be an important supplement to critical metal supply.

The deep sea minerals resources are considered as the "common heritage of mankind" under the United Nations Convention on the Law of the Sea. The International Seabed Authority regulates deep-sea mining activities whose mission are capacity development of marine minerals mining and protection of marine environment in due time. Both United Nations and International Seabed Authority have developed missions to use the marine resources sustainably. For example, The United Nation's Sustainable Development Goal 14 is to "conserve and sustainably use the oceans, seas and marine resources for sustainable development".

Though currently deep-sea mining still faces major challenge in exploration and exploitation technologies, maritime transport plans have to be studied in order to ship the mined deep sea minerals to shore in a sustainable way. This study provides some preliminary efforts for the sustainability assessment of maritime transport plans.

Firstly, a concept of sustainable maritime transport is promoted. The concept provides the scope and foundation for sustainability assessment. Secondly, a Maritime Transport Sustainability Framework is developed as guidelines for the sustainability assessment of maritime transport for deep-sea mining. The Framework investigates sustainability in 5 dimensions: environment, economic, social, safety and technology. In addition, the Framework consists of decomposed activities of maritime transport, a preliminary set of sustainability criteria and indicators, as well as sustainability assessment methods. Thirdly, case studies of maritime sustainability are conducted. Lastly, practical recommendations for sustainability assessment of maritime transport plans for deep-sea mining are provided.

In order to identify and group activities in maritime transport, the value chain analysis of maritime transport is carried out. Maritime transport activities are categorized into four groups: ship-to-ship mooring, ship-to-ship minerals transfer, shipping, and port unloading. Based on the characteristics of different activity groups, different sustainability dimensions are assigned. For each sustainability dimension, a set of criteria and indicators are developed by the study team, reviewed by selected experts and then further improved as outputs of the study.

Several popular sustainability assessment methods are reviewed by expert team and Analytic Hierarchy Process method is proposed to be applied to conduct sustainability assessment. Case studies of sustainability assessment about ship-to-ship mooring, ship-to-ship minerals transfer, and shipping are presented as examples to use the Maritime Transport Sustainability Framework as a tool for sustainability assessment of maritime transport plans.

In the environment dimension of sustainable maritime transport, criteria and indicators at the micro level are constructed. In addition, the study focuses on quantitative indicators rather than qualitative indicators so that quantitative assessment of environmental sustainability can be achieved.

For the economic dimension of sustainable maritime transport, an economic model of shipping deep sea minerals from mining sites in oceans to bulk ports has been developed. The proposed economic model takes the number of production support vessels, vessel voyage speed, fuel type, vessel transport capacity and other parameters into account. Both high-sulphur fuel oil and very low sulphur fuel oil are considered as fuel options. With the proposed economic model, it is possible to find the most cost-saving configuration of voyage speed, fuel type, and the number of minerals transport vessels. Case studies of shipping deep sea minerals from CCZ mining sites in Pacific Ocean to Ningbo Zhoushan Port, Kashima Port and Rotterdam Port are carried out.

For the social dimension of sustainable maritime transport, equal opportunities, social stability and inclusive growth are discussed. Especially, health risks of seafarers on board of minerals transport vessels are studied. Studies show that Alpha radiation from polymetallic nodules can exceed exemption levels of naturally occurring radioactive materials by several hundred times. Seafarers who inhale such nodules particles can damage lungs and lead to serious body damage.

In this study, safety is considered as an important dimension of sustainable maritime transport. Without safety, sustainable maritime transport cannot be achieved. For the safety analysis of maritime transport, historical ship accidents is analyzed. A total of 6368 bulk accident records from 1995 to 2022 were analyzed, from which temporal and spatial distributions of bulk vessel accidents are presented and analyzed. It is found that machinery damage/failure is the most common reason for bulk vessel accidents, accounting for 39.5% of the total accidents. In addition, bulk cargo liquefaction mechanism is studied. The concern of liquefaction of deep sea minerals is also investigated to improve the safety of maritime transport of deep sea minerals.

Technology is considered as a sustainability dimension in this study because sustainability assessment is conducted at the operational level and technology plays an essential role for maritime transport.

For future research, fine-tuning of the Maritime Transport Sustainability Framework with inputs from stakeholders is essential.

1. Introduction

1.1. Background

With worldwide growing population and economy, the need for metal resources is growing rapidly. Currently almost all metal resources are mined from terrestrial deposits. Given the growing societal, economic and technical challenges with terrestrial mining, attention has turned to the deep sea minerals resources in oceans.

The Earth's oceans cover more than 70 percent of the planet. But most areas of the oceans' floor are unmapped and unexplored until recently. With the exploration of deep sea, large amount of deep sea minerals have been discovered. There are mainly three types of deep sea minerals, polymetallic nodules, polymetallic sulphides, and cobalt-rich crusts. The distribution of these marine minerals in oceans can be seen from Fig 1.1. The main marine minerals distribution in worldwide oceans [1]. For polymetallic nodules deposit, it is estimated that only the Clarion-Clipperton Zone in the Pacific Ocean already hosts 21,100 million dry tons of nodules, which consists of around 6,000 million tons of manganese, about 270 million tons of nickel, and around 44 million tons of cobalt [1]. For polymetallic sulphides, the known global deposits is around 600 million tons covering an area of 3.2 million km2 surface. The average grade of polymetallic sulphides is 3.6 wt.-% copper, 7.9 wt.-% zinc, 1.7 g/t gold, and 115 g/t silver. Halbach et al. estimated that the total cobalt-rich crusts in oceans is about 35,100 million dry tons [2]. Therefore, deep-sea mining is considered to be an alternative for terrestrial mining to meet the growing need of metal resources in future.

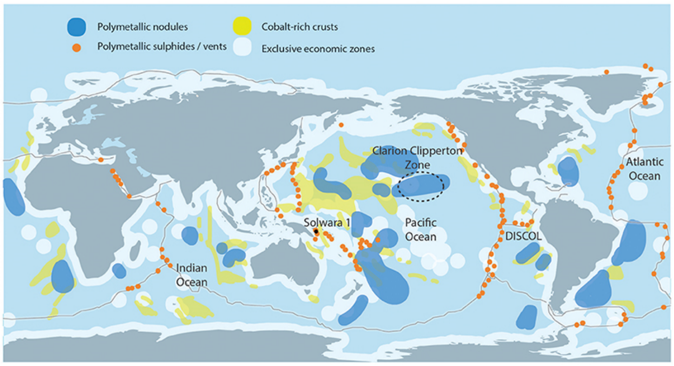

Fig 1.1. The main marine minerals distribution in worldwide oceans [1]

The currently known marine mineral deposits were first sampled by the scientific expeditions of the HMS Challenger in the 1870s [3]. Interest in the economic exploitation of deep sea minerals was initiated in the 1960s when Mero described the potential resource wealth of oceans in the form of polymetallic nodules [4]. However, deep-sea mining activities entered an on-hold status since 1975 till the beginning of 21st century due to the technical challenge of mining minerals at over 4000m depth and unprofitable management of such mega offshore mining project. With recent growing demand for metal resources, the deep-sea mining (DSM) becomes a hot topic in both academia and industry again since 2010s.

Deep sea minerals resources are considered as the "common heritage of mankind" under the United Nations Convention on the Law of the Sea. The exploration and exploitation activities of deep sea minerals in oceans are regulated by International Seabed Authority (ISA). Till 2023, ISA has issued 31 exploration licenses of deep sea minerals to different countries [5]. Countries like Japan, Germany, Belgium, China and India have applied exploration licenses in certain regions in the oceans, several countries have conducted *in-situ* experiments of exploration and exploitation of deep sea minerals in the licensed areas. It is expected that large-scale commercial DSM activities will come into reality in next 15 to 30 years.

A brief introduction of DSM production process is described as follows. Firstly, target sea floor areas will be explored for deep sea minerals deposits. Once the resource revaluation concludes that the deposits are rich enough for a commercial project, DSM can be initialized. It has to be noted that DSM can only be initialized after the Contractor obtains an exploitation license from ISA. DSM will utilize miners to collect/mine minerals on seafloors (see Fig 1.2). The collected minerals will be transported to a production support vessel (PSV) through a vertical lifting system. The PSV can provide preliminary mineral processing (i.e. dewatering, screening) and temporary minerals storage. A minerals transport vessel (MTV) will then be employed to transport the deep sea minerals from the PSV to a port for metal extraction processing [6]. The ship-to-ship transfer can be done either via belt conveyor systems or through pipelines [7].

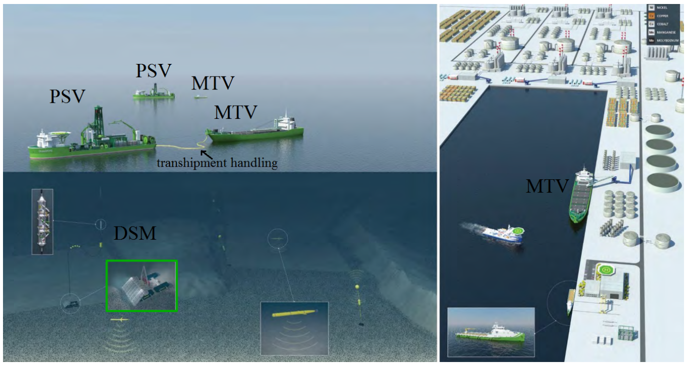

Fig 1.2. Conceptual illustration of a deep-sea mining project including maritime transport of minerals to bulk ports (modified from [8]). PSV represents Production Surface Vessel, and MTV represents Minerals Transport Vessel.

1.2. Motivation

For DSM, it requires complex and coordinated exploration, mining and maritime transport plans. So far DSM research focuses on the development of exploration and mining technologies. Exploration methods such as multibeam bathymetry, multibeam backscatter, video surveys, box core sampling, and geochemical analyses have been widely applied in exploration of deep sea minerals [9]. Regarding mining and vertical lifting technologies, many solutions have been developed. For instance, Nautilus Minerals INC. has developed advanced miners to collect minerals on the seafloor [10]. The Metals Company and Allseas have succeeded in lifting more than 1300 tons of deep sea minerals by using an air lifting system [11]. More cases of mining and vertical lifting systems can be found in reference [12].

However, rare attention has been paid to maritime transport plans for DSM. The content of a maritime transport plan includes storage of minerals on PSVs, ship-to-ship minerals transfer between a PSV and a MTV, and shipping minerals by MTVs to shore. Firstly, DSM requires large-scale storage facilities at PSVs. The storage capacity needs to be coordinated along with DSM production capacity (around 10,000 t/day), as well as MTVs' visiting period of time.

Secondly, the ship-to-ship transfer facility should be able to handle deep sea minerals from a PSV to a MTV safely and sustainably. For ship-to-ship transfer process, the challenge of MTVs mooring to PSVs in oceans (ocean wave effects, PSV and MTV movements etc.) should be taken into consideration. The handling equipment also needs to have the capability to transfer minerals from a PSV to a MTV efficiently and reliably. Furthermore, environmental impacts like dust and sound emission should be considered.

Thirdly, DSM usually comes with multi PSVs at multi mining sites. Therefore, it requires multiple MTVs to have optimum routine planning if they visit multi PSVs in one trip with considerations of inventory, location, and routine. Besides that, different mining sites may have different deep sea minerals. It is challenging for a MTV to collect and store different minerals on board while maximizing its transport capacity.

In order to support DSM development meanwhile protecting marine environment, sustainable maritime transport plans should be made before commercial DSM activities occur. The research on sustainability of transport plans for DSM is a complex and interdisciplinary research topic, which is majorly related to several aspects including technical feasibility, economic profitability and environmental impacts.

Firstly, feasible technical solutions are required for the storage, ship-to-ship transfer, and maritime transport of deep sea minerals. Such technical solutions should take offshore environment, minerals material properties and flowability into consideration. From an economic perspective, a sound transport plan should minimize investment capital and operation cost to improve profitability. Regarding environmental impacts, waste, dust, sound, and CO2 emission by PSVs, ship-to-ship transfer equipment, and MTVs should be considered. The environmental impacts should be minimized to protect marine ecology system in the oceans.

So far, limited research on assessment methods for the sustainability of maritime transport plans for DSM have been done. Criteria of sustainable maritime transport plans for DSM are still absent. In view of this, design of such an assessment approach is critical to develop scientific guidelines for maritime transport plans, as well as international regulations of DSM activities by authorized regulators such as International Seabed Authority and International Maritime Organization (IMO). Recently the ISA and the International Maritime Law Institute (IMLI) have agreed to work together to develop and implement specific initiatives aimed at addressing the capacity development needs of ISA Member States. Studies on sustainable maritime transport of deep sea minerals will enhance cooperation between the ISA and the IMO and provides cross-discipline knowledge and regulation basis for related authorities.

1.3. Objectives

The aim of this study is to develop a Maritime Transport Sustainability Framework for deep-sea mining. To achieve this goal, several sub-objectives should be reached:

- The value chain analysis of DSM will be conducted. Technologies for exploration, resource assessment, extraction, lifting and surface operations, maritime transport and onshore logistics, as well as processing will be analyzed. Particularly, the value chain analysis of maritime transport should be done in depth and correlated sustainability issues need to be discussed.

- Definition of sustainable maritime transport for deep-sea mining needs to be formulated. The definition should provide a scope of maritime transport that takes the special location and environmental characteristics of deep-sea mining into account. In addition, the meaning of sustainability should be customized to the characteristics of maritime transport.
- Maritime Transport Sustainability Framework needs to be developed. The framework should act as a guideline and foundation for sustainability assessment of maritime transport plans for deep-sea mining. Sustainability dimensions, criteria and indicators need to be investigated and a suite of dimensions, criteria and indicators should be provided for the proposed framework.
- Operational sustainability assessment for maritime transport will be investigated. Mainstream sustainability assessment methods will be reviewed and suitable methods will be recommended for sustainability assessment of maritime transport for deep-sea mining. Rules for surveys and score mechanisms of indicators will also need to be studied and practical guidelines can be made.

1.4. Research design

In order to assess the sustainability of maritime transport plans for deep-sea mining, firstly the definition of sustainable maritime transport must be provided. The study team investigates existing maritime sustainability research and find that a research gap exists between sustainability assessment between the macro and micro levels. To fill in this knowledge gap, the team tries to develop a Maritime Transport Sustainability Framework. The Framework is considered as a guideline for sustainability assessment, as well as a supporting structure to measure the sustainability level of activities with criteria and/or indicators. Several case studies are provided to help readers to understand the Maritime Transport Sustainability Framework, and to conduct sustainability assessment step by step. The research design of this project is illustrated in Fig 1.3. Research design flowchart. ·

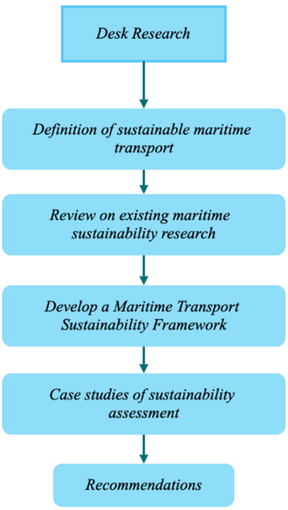

Fig 1.3. Research design flowchart

1.5. Report outline

Chapter 2 will investigate the literature related to deep-sea mining and sustainability assessment methods. Based on the literature review, definition of sustainable maritime transport is formulated and Maritime Transport Sustainability Framework is proposed. In the framework, four links of maritime transport are identified and sustainability of each link will be discussed in following chapter.

Chapter 3 will study the sustainability of the mooring process of a minerals transport vessel to a production surface vessel. The focus is on the safety of the mooring process.

Chapter 4 will investigate the sustainability of ship-to-ship transfer of deep sea minerals from production surface vessels to minerals transport vessels.

Chapter 5 will study the sustainability of shipping deep sea minerals with a focus on development of an economic model of maritime transport of deep sea minerals.

Chapter 6 will look into the sustainability of unloading deep sea minerals at bulk ports.

Chapter 7 will provide some conclusions and recommendations obtained from this project.

2. Defining sustainable maritime transport

Interest in deep sea minerals is growing. However, deep-sea mining technologies are not fully developed yet. Without reliable and sustainable technologies, deep-sea mining may lead to irreversible environmental impacts to marine ecosystems. In this chapter, deep-sea mining activities are first reviewed in a form of value chain. Several popular sustainability assessment methods are reviewed. Afterwards, definition of sustainable maritime transport is formulated. Based on the definition, the Maritime Transport Sustainability Framework is proposed.

2.1. Overview of deep-sea mining activities

The feasibility of deep-sea mining in the near future will depend heavily on the regulations of ISA, as well as contractors to provide such systems which can operate efficiently and environment friendly in deep ocean. To date, no exploitation license has been granted for commercial deep-sea mining. In terms of economics, the mining value chain of deep-sea mining systems can be divided into six units, which are: Exploration; Resource assessment, evaluation and planning; Extraction, lifting and surface operations; Offshore and onshore logistics; Processing; Distributions and Sales. (see Fig 2.1)

Fig 2.1. Schematic overview of deep-sea mining value chain [13]

2.1.1. Exploration

Over the years, there have been significant advances in the detection and sampling techniques for these resources. Several technical solutions have been developed in the exploration of deep sea minerals deposits. Cable-operated grabs and cameras provide more reliable information, although at a slower rate [14]. Recent improvements in sonar technology should facilitate the development of new devices to more accurately measure the density of nodule distribution [15]. Since the 1930s, echo-sounding (sonar) technology has been used to survey the topography of the ocean floor [16]. Conventional echo-sounder emit a wide beam (40 degree) of acoustic waves vertically from the bottom of the vessel. The water depth can be calculated based on the time interval between the emission of the sound pulse and the reception of the echoes according to the speed of sound propagation in the water (about 1500 meters per second) based on the time interval between the emission of the sound pulse and the reception of the echoes. The continuous bathymetric data obtained during the vessel's travel provides a topographic profile below the vessel's track [17]. To accurately map the topography of a block of the seafloor, it is necessary to walk an equidistant parallel track.

In the late 1970s, the multi-beam echo-sounder emerged [18]. The device emits a series of narrow beam (2 degrees) acoustic signals, which are fan-shaped and orthogonally aligned with the ship's hull axis [19]. Each emission yields a series of bathymetric data corresponding to the points below and beside the ship's track. The modern multibeam echo-sounder (side-scan sonar) carries more than 150 measurements per scan (one data every 130 meters on average), covering a range of up to 20 kilometers wide and up to 4,000 meters deep, allowing the identification of many previously invisible terrains. Surface surveys are supplemented by deep-towed sonar surveys above the seafloor [20].

Most prospectors also use free-fall devices such as grabs to plunge into the seafloor for sampling and photography. Several kilograms of nodules can be collected at a time and photographs can be taken for an area of 2 to 4 square meters. From all this information, it is possible to estimate the abundance of nodules on the seafloor (kg/m^2). This will enable the abundance of nodules over a large area to be surveyed in a shorter time. Fig 2.2 shows a model of the topography of the explored deep sea.

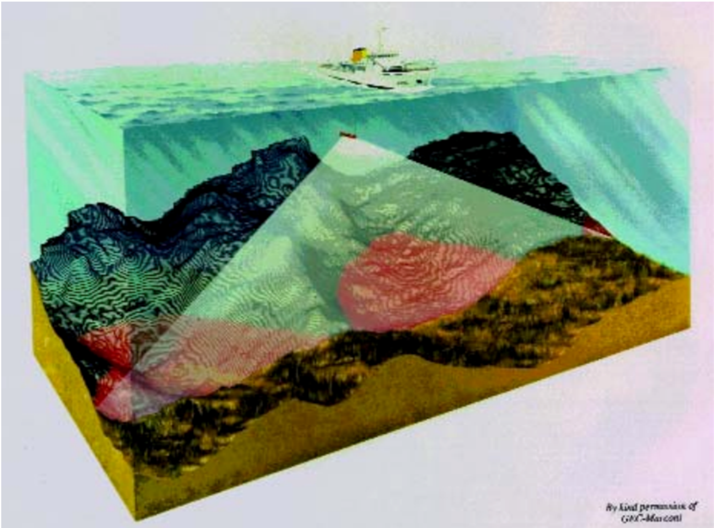

Fig 2.2. The model of seabed topography [20]

2.1.2. Resource assessment, evaluation and planning

There is growing recognition of the distribution and potential of deep sea minerals [21]. The growing awareness has kept the world interested in these deposits and even facilitated the preparation of a geological model of deep sea minerals in the Clarion-Clipperton Fracture Zone in the Pacific Ocean [22]. However, metal prices are highly volatile due to factors such as recovery, new land-based deposits and technology. Deep sea minerals deposits are considered important in the overall metal supply of the planet and constitute a substantial resource to meet the 21st century demand for manganese, iron, nickel, cobalt, copper, molybdenum and many other metals, including rare earth elements. Therefore, in addition to the technology required to actually mine the seabed deposits, it is important to have a reliable resource estimate before starting a commercial scale operation [23].

As each "exploitation contract" is allocated an average area of tens of thousands of square kilometers in international waters, the recoverable resources are expected to be in the millions of tons. For example, with the resource potential of an exploitation contract (i.e. 75,000 km^2) in the Central India Basin area and the cut-off value for abundance (5 kg/m2), the total resource for this area would be 375 million tons (wet) or 206.25 million tons (dry) with a metal equivalent of 54.12 million tons with the known metal concentrations in the area (Mn=24%, Ni=1.1%, Cu=1.04% , Co=0.1%)[21]. Of the 206.25 million tons, only 14.5-29% (i.e. 30-60 million tons) of the resource will be exploited in a 20-year period at the proposed extraction rate of 1.5 million tons/year or 3 million tons/year, while a significant balance (71-85.5%) will be mined in the future [24].

2.1.3. Extraction, lifting and surface operation

This phase is the core part of deep-sea mining and includes the excavation of deep sea minerals, their vertical transport to the surface, and dewatering processing and handling operations offshore. For seafloor excavation and lifting, cutters (for seafloor massive sulphides and crusts) or collectors (for nodules) and vertical transport systems are identified [25]. It may also be possible to perform pretreatment at the seafloor. The vertical transport system is also a key component [26]. The production support vessel (PSV) is an important platform for the surface operation. The vessel may serve as a dispatch system, a storage facility, should have a dewatering system on board [27], and even may provide a processing facility on board. Depending on the extraction technique used, the distance to shore and the volume, the sediment can be dewatered on board and the fines recovered by cyclones. The extracted water can be returned to the water body, which requires appropriate filtration/cleaning facilities and monitoring devices. When the mining site is far from shore, adequate storage capability on the PSV is required to manage the logistics process [20].

In 1970, the first test of a prototype nodule mining system was carried out in the Atlantic Black Hills off the Florida coast at a water depth of 1000 meters. "Deep Ocean Expeditions installed a 25-meter-high boom and a 6-meter by 9-meter central pool on the 6,750-ton freighter Deep Sea Miner (from which the mining unit was deployed). The nodules were lifted by an air-lift system which had been tested in a 250-meter mine [20].

In 1972, a group of 30 companies tested a system invented by Yoshio Masuda, a Japanese shipping official [20]. Continuous chain bucket system in an eight-kilometer-long swing chain every certain distance hanging a court bucket. The low-built bucket was dropped from the bow of the former whaling ship "Shirakamine Maru" and recovered at the stern of the ship. Some nodules were collected, but the chains were entangled, and the experiment was terminated. In 1975, a new experiment was planned, using two ships instead of one, but it was finally cancelled due to lack of funds [20].

In the late 1970s, three major U.S. consortia conducted mining tests in the Pacific Ocean using a hydraulic mining system [20]. The seafloor nodules were collected by a dredging device and transferred to the bottom of a lift pipe suspended below the surface vessel. Ocean Management Incorporated (OMI) used a power-positioned drill ship, the SEDCO 445 [28]. The vessel was equipped with a boom supported by a standing frame to reduce the impact of the vessel motion on the lift pipe. The two lifting systems tested were: suction by a centrifugal axial pump installed in the lift pipe at a water depth of 1000 m and lift by compressed air between 1500 and 2500 m (air lift). Two collecting devices were towed behind the lift pipe: a hydraulic suction dredging device with water jets and a mechanical collector equipped with a reverse conveyor belt. The first collecting device was unfortunately lost due to an operational error. However, three experiments conducted 1,250 km south of Hawaii yielded a total of about 600 metric tons of nodules [29].

In 1978, the Ocean Minerals Company (OMCO) chartered the Glomar Explorer from the United States Navy [30]. This powered locator vessel, with a displacement of 33,000 metric tons and a length of 180 meters, deploys pillars and cables using a sophisticated system. The ship's large moon pool (61 x 22 meters) facilitates large collector operations. The company built electric collectors equipped with Archimedes spirals to crawl over loose sediments. In February 1979, the operation was finally carried out successfully. In addition, the ship's advanced computer system collected a lot of data. These operations succeeded in demonstrating that the basic approach of dredging and lifting is the right one [20].

On October 12th, 2022, The Metals Company announced that it has successfully collected the first subsea polymetallic nodules and transported them to the surface along a 4-kilometer riser system [31], the first since the 1970s in the Clarion-Clipperton Zone of the Pacific Ocean. Following the successful completion of the offshore construction of the riser system and its integration with the flexible jumper hoses and the pilot nodule collector vehicle, a dedicated team of 130 crew members and engineers began initial nodule collection runs on board the Hidden Gem, traveling the pilot collector 147 meters on a predetermined path and collected 14 tons of nodules in one hour. The nodules were transported from the collector to a jumper hose and into a riser where they were lifted by compressed air from the seafloor to the Hidden Gem, where the return water was discharged into the mid-water column. So far, in the current campaign, the collector has been successfully test-run for about 18.1 km within NORID. Fig 2.3shows the air lifting system of The Metals Company [31].

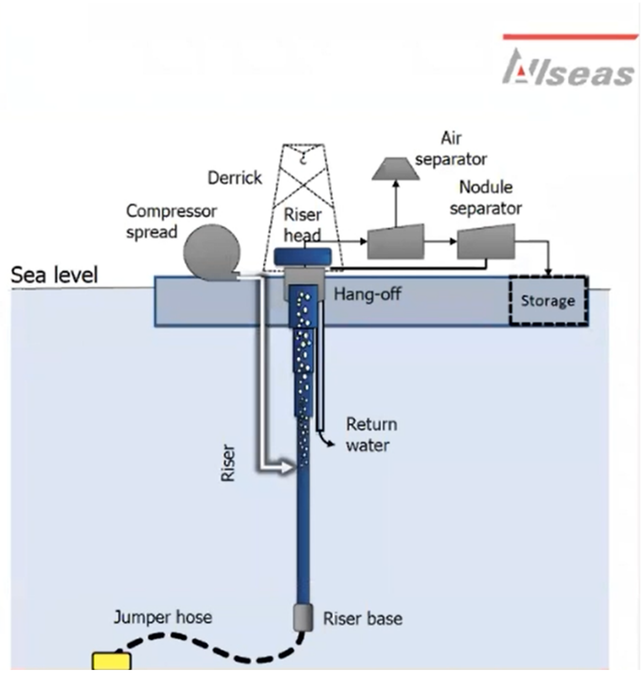

Fig 2.3. Air lifting system for deep sea minerals (figure courtesy of The Metals Company & Allseas)

2.1.4. Offshore and onshore logistics

For offshore logistics or maritime transport, minerals transport vessels (MTVs) will be utilized to transport mined deep sea minerals from PSVs to bulk ports. On the other hand, onshore logistics mainly deals with the transport process of minerals from ports to processing plants by trucks or trains.

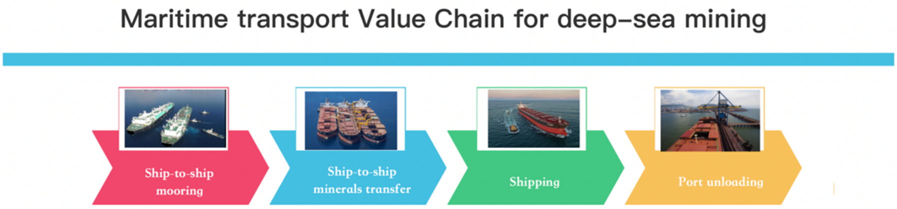

Fig 2.4. Value chain of marine transport in this study

In addition, by applying the value chain analysis approach, maritime transport can be divided into four essential links: ship-to-ship mooring, ship-to-ship minerals transfer, shipping, and port unloading (Fig 2.4). Each of these links plays a crucial role in maritime transport of deep sea minerals,

The ship-to-ship mooring phase is the first step of maritime transport of deep sea minerals. It involves precise positioning and anchoring of specialized vessels in open oceans. Accurate mooring ensures stability, minimizing the risk of ship damage. Without a secure connection between vessels, subsequent stages such as minerals transfer and shipping could be jeopardized, highlighting the paramount importance of this initial step.

Minerals transfer represents the phase of handling minerals from the PSVs to designated MTVs. This step demands meticulous coordination to prevent loss and contamination of valuable resources. Advanced technology and equipment are vital to ensure that the minerals are transferred without degradation, maintaining their quality and economic value. A seamless minerals transfer process maintains the integrity of the cargo, setting the stage for smooth shipping operations.

The shipping phase is the most important part of maritime transport. The efficiency of shipping operations determines the overall timeline and cost-effectiveness of the deep-sea mining venture. Weather conditions, vessel maintenance, and adherence to maritime regulations all play pivotal roles in this phase. Moreover, effective communication between vessels, ports, and logistics teams is paramount to adjust to potential disruptions and maintain the integrity of the minerals during transit.

Upon arrival at the designated port, the unloading process will be initialized. Port facilities must be equipped to handle the unique requirements of deep-sea mineral cargo, which may differ significantly from conventional port operations. For instance, polymetallic nodules are bulk cargo of high value meanwhile with extraordinary Alpha radiation. Specialized handling equipment and storage facilities are need for port unloading. Specialized infrastructure, skilled personnel, and efficient unloading procedures are imperative to prevent bottlenecks and ensure the swift offloading of minerals. A well-organized port unloading process facilitates the subsequent stages of processing, refinement, and distribution of the extracted minerals.

2.1.5. Processing

A number of processes have been developed and studied for the processing of deep sea minerals. Initially, only three metals, nickel, copper and cobalt, were considered for extraction. After 1978, manganese was also considered for extraction to increase total revenue and to reduce waste. The technology is divided into two categories: hydrometallurgy - leaching the metal from the nodules with acidic (hydrochloric or sulfuric acid) or alkaline (ammonia) reagents;

and smelting - reducing the hydroxide (de-oxygenation) to separate the molten metal by gravity. An example is given below [20].

First, the Cuprion Process method - this method was developed by Kennecott is described here as an example of deep sea minerals processing [20]. Nodules are grounded into slurry and reduced at low temperature with carbon monoxide and ammonia in a stirred drum. After counter-current decantation through a series of thickeners, the copper, nickel and drill are in a soluble state. Nickel and copper are then removed by electrolytic metallurgy (separation by electrolysis) through a liquid ion exchanger; the auger is removed by sulfide precipitation. However, it is difficult to recover manganese from ferromanganese slag. Fig 2.5 shows the flow chart of Cuprion Process [20].

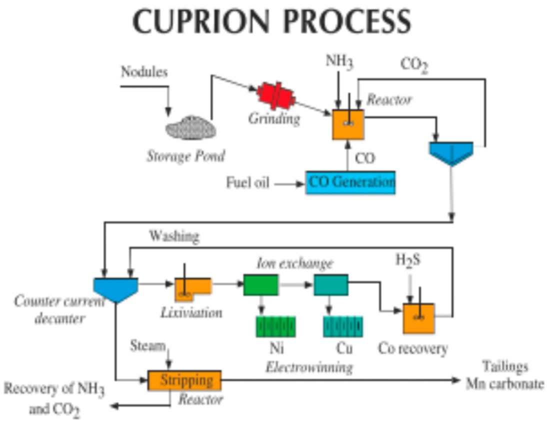

Fig 2.5. The flow chart of Cuprion Process [20]

2.2. Analysis of bulk vessels accidents

Bulk carriers play a crucial role in the maritime transportation of unpackaged goods such as mineral, coal, and grains [32]. However, accidents involving bulk carriers have had significant impacts on maritime safety and the environment, including loss of lives, economic losses, and ecological damage. In recent years, the use of larger capacity bulk carriers in maritime transport has increased the risk of accidents [33]. Therefore, the occurrence of bulk carrier accidents should not be overlooked due to their negative effects on the global supply chain and the safety of lives and property.

Many scholars have conducted research on various aspects of maritime accidents to enhance maritime safety. Currently, there is a significant amount of research on global maritime accidents. Yang Zhang et al utilized geospatial techniques such as Kernel Density Estimation (KDE) and K-means clustering to study the spatial patterns of global maritime accidents and provide an overview in space [34]. Huanxin Wang et al employed the Zero-Inflated Ordered Probit (ZIOP) model and severity data extracted from accident investigation reports from 2000 to 2019 to explore the factors influencing two potential severity states [35]. Huanhuan Li et al incorporated maritime accident data into a Bayesian Network (BN) model to study the major factors affecting vessel safety [36]. Luo conducted a literature review of maritime accidents from 1965 to 2014, indicating a shift in research focus from naval architecture to human errors and the potential expansion into socio-Economic Factors [37]. Sidum Adumen et al considered the complex interaction between factors influencing human dynamic cognitive behavior and core risk factors, proposing an adaptive model for analyzing and classifying human factors in maritime accidents [38]. Additionally, some studies focused on individual accident types. Tian Chai et al evaluated human life losses and oil pollution resulting from ship collisions [39]. Shanshan Fu et al quantitatively analyzed Arctic ship grounding accidents to identify potential risk factors [40]. Currently, there is limited research on bulk carrier accidents. Beatriz Navas et al used the MALFCM method to explore the causes of bulk carrier accidents, concluding that situational awareness and inadequate communication were key factors in collision accidents [41]. Ahmet Lutfi Tunçel et al conducted a risk and safety analysis of bulk carrier fire and explosion accidents using the Fuzzy Fault Tree Analysis method to understand the potential root causes of such incidents [33]. Ahmet Lutfi Tunçel et al also performed a comprehensive risk analysis of collision and grounding accidents involving bulk carriers and general cargo ships using various probability-based methods [32].

The existing literature on bulk carrier accidents is relatively limited, highlighting the need to expand research in this specific field. This study aims to bridge this research gap by providing a comprehensive description of global bulk carrier accidents, revealing the characteristics and development trend of bulk carrier accidents in recent years.

2.2.1. Data collection and processing

Based on the statistics of global bulk carrier accident data from Lloyd's List Intelligence, the accident characteristics were analyzed from the time and space dimensions respectively, and the safety analysis of bulk carrier accident was carried out from the aspects of accident date, flag state, vessel type, accident ship age, accident type, accident sea area and accident severity. Processing of the 12,542 accidents of bulk carrier accidents recorded in the Lloyd's List Intelligence [42] database was carried out. The relevant information includes vessel name, the ship's International Maritime Organization (IMO) code, dead weight tonnage, flag, vessel type, accident ship age, accident type, accident date, accident severity, accident latitude and longitude, etc. The processing steps are as follows: (1) Removal of partially incomplete data, resulting in 8,398 remaining entries; (2) Selection of bulk carrier accident data from 1995 to 2022, resulting in 8,101 remaining entries; (3) Removal of abnormal data, such as total tonnage greater than or equal to deadweight tonnage, non-severe accidents involving pollution or total loss, resulting in 7,968 remaining entries; (4) Exclusion of accidents categorized as war, piracy, arrest, port detention, disappearance, and uncertainty in accident type, resulting in a final count of 6,368 accidents of bulk carrier accidents.

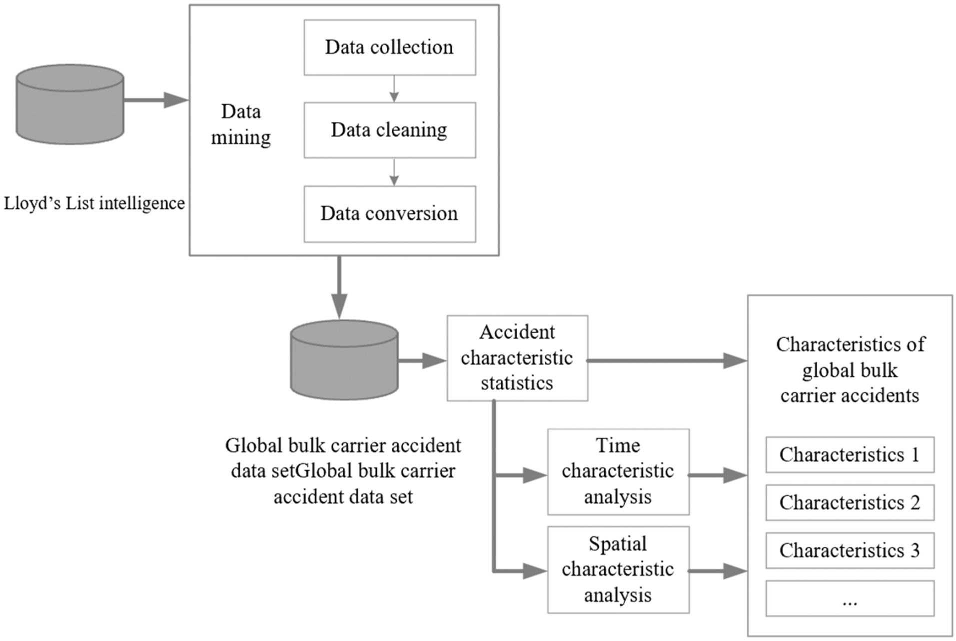

Fig 2.6. Framework for analyzing the characteristics of global bulk carrier accidents

The data extraction process focused on the period of the past 28 years (1995-2022), resulting in a collection of 12,542 accidents of bulk carrier accidents. For each accident entry, vessel information (vessel name, flag, deadweight tonnage, accident ship age, vessel type) and accident details (accident date, location, accident type, severity) were extracted, while incomplete accident information was excluded. A total of 6,368 accident entries were obtained. The descriptive statistics and frequency distribution of the accident variables are presented in Table 2.1.

Table 2.1. Accident database information description and frequency statistics

Attribute	Variable	Variable classification and description	Number of accident	Percentage(%)
Accident bulk carrier information	Flag	Flag of convenience	3612	56.7
		Non-flag of convenience	2756	43.3
	Vessel Type and Size	Small, -10'dwt	340	5.3
		Handysize, 10'-35'dwt	2327	36.5
		Handymax, 35'-50'dwt	1353	21.3
		Supramax, 50'-60'dwt	650	10.2
		Panamax, 60'-100'dwt	1255	19.7
		Capesize, 100'-200' dwt	368	5.8
		VLBC, 200'+ dwt	75	1.2
	Age	[0,5)	1136	17.8
		[5,10)	1172	18.4
		[10,15)	956	15.0
		[15,20)	749	11.8

		[20,25)	731	11.5
		[25,30)	620	9.7
		[30,∞)	1004	15.8
Accident information	Cause of Casualty	Machinery damage/failure	2512	39.5
		Collision	1263	19.8
		Wrecked/Stranded	1278	20.1
		Contact	599	9.4
		Fire/Explosion	369	5.8
		Others	347	5.4
	Serious Indicator	Loss Type	164	2.6
		Serious non-loss	2510	39.4
		General accident	3694	58.0

In order to analyze the characteristics of global bulk carrier accidents, this report categorizes ship flags into convenience flags and non-convenience flags. Ship types are divided into seven categories: Small Handysize, Handymax, Supramax, Panamax, Capesize, and Very Large Bulk Carriers (VLBC), enabling a comprehensive understanding of the accident patterns across different vessel sizes.

Ship age is classified into five-year intervals. According to the "Regulations on the Management of Old Transport Ships" issued in 2021, there are specific regulations governing ship purchase, bare charter, and reconstruction. The mandatory scrapping age for bulk carriers is set at 33 years. Therefore, ships older than 30 years are grouped into a separate interval.

IMO classifies maritime accidents into ten categories: collision, grounding, contact, fire or explosion, sinking, hull damage, mechanical failure, ship or equipment damage, natural disasters, and others. This study focuses on five highest frequent accident types: machinery damage/failure, wrecked/stranded, collision, contact, and fire/explosion. Other categories include 54 accidents of foundered, 276 accidents of hull damage, and 17 accidents related to labor disputes.

The outcomes of accidents are classified into three categories: total loss accidents, serious non-total loss accident and general accidents. This classification provides a comprehensive understanding of the severity and impact of bulk carrier accidents.

The statistical results of the number of bulk carrier accidents from 1995 to 2022 in Table 2.1 reveal the following characteristics:

- Bulk carrier accidents primarily occur on convenience flag vessels, accounting for 56.7% of the total accidents;
- Medium-sized vessels dominate bulk carrier accidents, with the Supramax type accounting for 23.27%, followed by the Handymax and Panamax types at 21.3% and 19.7%, respectively;
- Bulk carrier accidents primarily involve newer vessels, with ships aged 0-9 years accounting for 36.2% of the total.

In addition from Table 2.1 it can be seen that:

- In terms of accident type, mechanical failure is the most common type of accident, accounting for 39.5% of the total accidents. Grounding and collision accidents follow, accounting for 20.1% and 19.8% of the total accidents, respectively.

- In terms of accident severity, the proportion of total loss accidents is relatively low at 2.6%, but there are a significant number of severe accidents, accounting for 42% of the total accidents.

Since the storage capacity of deep-sea mining production support vessels (PSVs) is around 39,000 ton, small and Handysize vessels are not considered in the selection of minerals transport vessels (MTVs). Some ports cannot serve VLBC vessels. Therefore, only four vessel types, Handymax, Supramax, Panamax and Capesize, were statistically analyzed. The proportions of each accident type in the four bulk carrier types are shown in Fig 2.7 :

Handymax, Supramax, Panamax, and Capesize are all classifications of bulk carrier vessels, and they differ primarily in size, capacity, and the ports they can access.

Handymax ships typically have a capacity ranging from 40,000 to 50,000 Deadweight tonnage (DWT) and are versatile in the types of cargo they can carry, from bulk commodities to more substantial items. They are also more flexible in the ports they can access due to their smaller size.

Supramax vessels are a slight upgrade from Handymax, with a capacity usually between 50,000 to 60,000 DWT. They often come equipped with onboard cranes, allowing for self-loading and unloading, which can be advantageous in ports lacking infrastructure.

Panamax ships are specifically designed to navigate the Panama Canal, which has certain size restrictions. The standard dimensions for a Panamax vessel are 294.13m in length, 32.31m in width, and 12.04m in depth, and they can carry up to approximately 65,000 to 80,000 DWT.

Capesize vessels are the largest among these classes, with capacities exceeding 100,000 DWT. These ships are so large that they cannot navigate through the Panama Canal (hence the name, as they must navigate around the Cape of Good Hope or Cape Horn). They are typically used for very large bulk cargo, such as mineral and coal.

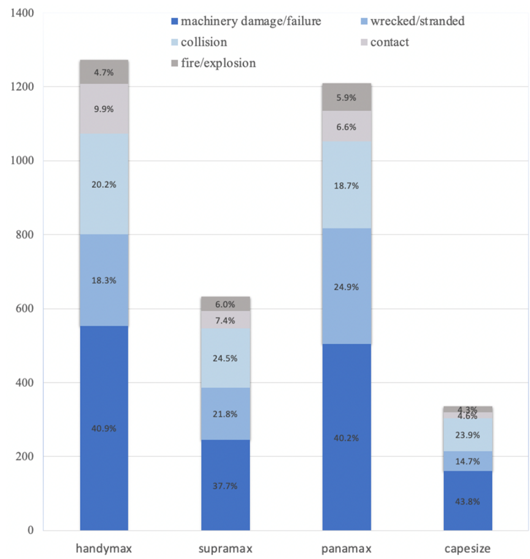

Fig 2.7. The proportion of each accident type in the four bulk carrier types

According to the statistical results of ship type and accident type, mechanical damage/failure, wrecked/stranded and collision are the most common accident types for each vessel type. Comparison of different accident types for different vessel types reveals that as the ship size increases, the probability of collision decreases. Compared with other vessel types, Supramax has the lowest probability of mechanical damage/failure and the highest probability of collision, fire/explosion. Panamax has the highest probability of wrecked/stranded accidents compared with other vessel types. Capesize ships are the most prone to mechanical damage/failure but have the lowest incidence of wrecked/stranded accidents compared to other vessel types.

The severity of accidents of the four types of bulk carrier is shown in Table 2.2. Handymax ships have the highest probability of total loss accidents and serious accidents; the severity of accidents does not differ significantly between Panamax and Supramax vessels; Capesize ships have the lowest probability of total loss accidents and serious accidents. Therefore, we can conclude that larger ship types are associated with lower accident severity.

Table 2.2. Statistics of accident severity of four types of bulk carrier

Vessel Type	Accident frequency	General accident		Serious non-total loss accident		Total loss accident	
Handymax	1353	816	60.31%	516	40.22%	21	1.64%
Supramax	650	344	52.92%	297	13.08%	9	0.40%
Panamax	1255	650	51.79%	584	13.91%	21	0.50%
Capesize	368	197	53.53%	159	2.05%	12	0.15%

The severity of accidents occurring in each age range of bulk carriers is presented in Table 2.3.The average age of global bulk carrier accidents is 17.15 years. Newer vessels have a lower probability of total loss accidents, accounting for less than 2% of the total accidents. Among them, ships with an age of 10-14 years have the lowest probability of total loss accidents. As the age of the vessels increases, the probability of total loss accidents also increases. For vessels with an age of 0-4 years, although the probability of accidents is relatively higher, they are mostly general accidents, indicating a lower severity of accident consequence.

Table 2.3. Statistics of accident age and accident severity of bulk carriers

Vessel	Number of accidents	General accident	Serious non-total loss accident	Total loss accident
[0,5)	1136	676	59.51%	451
[5,10)	1172	628	53.58%	530
[10,15)	956	523	54.71%	430
[15,20)	749	440	58.74%	292
[20,25)	731	385	52.67%	303
[25,30)	620	349	56.29%	228
[30,∞)	—	—	—	—

2.2.2. Temporal analysis of maritime accidents

If we look at the yearly distribution of bulk carrier accidents (Fig 2.8), the number of bulk carrier accidents showed an increasing trend from 1995 to 2022, increasing from 88 in 1995 to 337 in 2022, with an average annual number of 227. The number of serious accidents is also on the rise, increasing from 13 in 1995 to 257 in 2022, with an annual average of 95.5 serious accidents. The second-order polynomial is used to fit the accident number. The results show that the accident number and the serious accident number can be expressed by the second-order polynomial respectively:

$$y_1 = -0.4124x2 + 28.071x \quad , \quad R^2 = 0.9095$$

$$y_2 = 0.0445x2 + 6.2766x \quad , \quad R^2 = 0.7564$$

The closer the R^2 value to 1, the better the fitting degree is. Hence, the second-order polynomial fitting degree of accident number is more reliable than that of serious accident number.

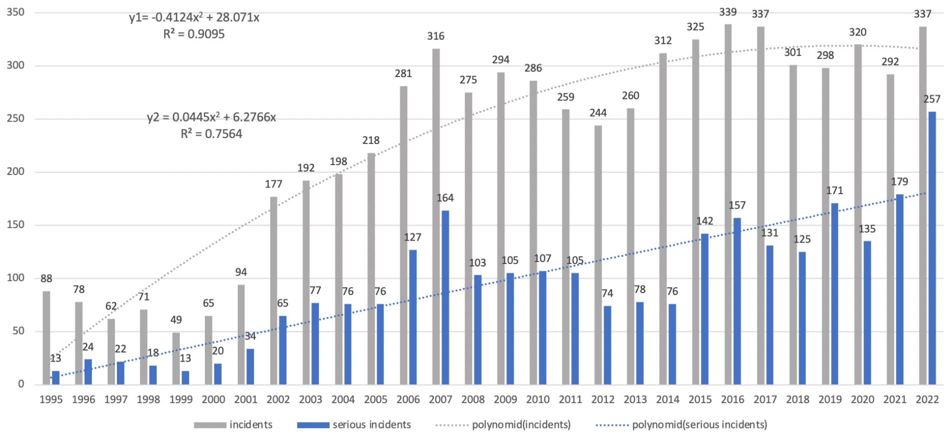

Fig 2.8. Trend of occurrence of bulk carrier accidents from 1995 to 2022

Based on the statistical results of accident types and years shown in Fig 2.9,the number of mechanical damage/failure accidents sharply increased from 2013 to 220 accidents in 2022. The number of wrecked/stranded and collision accidents showed a decreasing trend after 2016. The number of collision and fire/explosion accidents has been stable in recent years, with no more than 50 accidents per year.

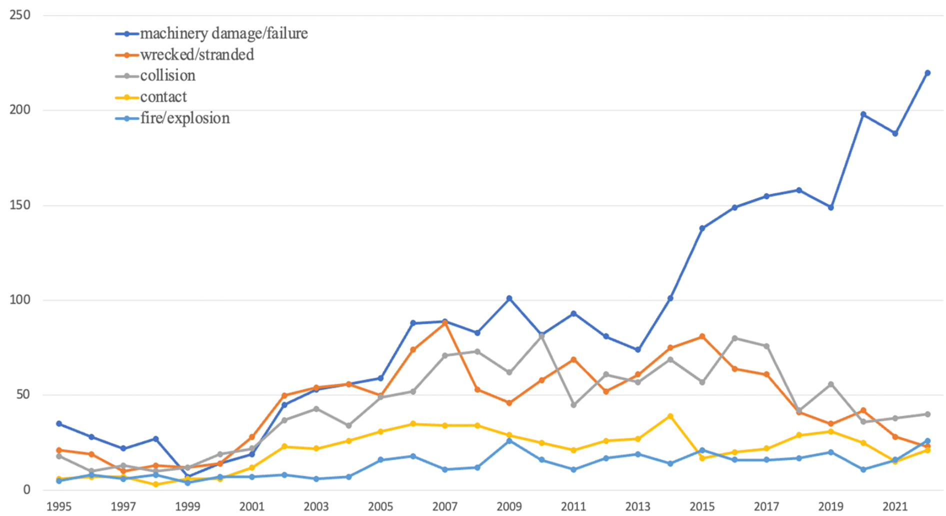

Fig 2.9. Trend of accident types of bulk carriers from 1995 to 2022

2.2.3. Spatial analysis of maritime accidents

According to the longitude and latitude information of bulk carrier accidents recorded in the Lloyd's database, the spatial characteristics of global bulk carrier accidents during 1995-2022 are analyzed. There are a total of 32 sea areas world widely, and this research lists the top 10 sea areas with the highest number of accidents. The accident ratios of the four types of bulk carriers in each sea area are shown in Fig 2.10.

From the frequency ratios of the four ship types in the accident areas shown in Fig 2.10, it can be observed that the Great Lakes, the East Mediterranean & Black Sea, and the British Isles are high-risk regions for bulk carrier accidents, accounting for 22.46%, 11.06%, and 10.21% of global bulk carrier accidents, respectively. In the Great Lakes, the incidence of accidents is highest for Small Handysize vessels, accounting for 28.53% of total accidents, with mechanical damage/failure being the main accident type, representing 56.48% of accidents. There is no significant difference in the proportion of accidents involving Supramax ships across different sea areas. Among them, the East Mediterranean & Black Sea is seen the highest proportion at 12.92%, followed by the South China, where collision accidents are predominant, accounting for 41.67% of accidents. The major accidents of Panamax and Capesize were in the British Isles, accounting for 13.31% and 14.67% respectively. The major accidents were mechanical damage/failures, accounting for 51.5% and 61.1% respectively.

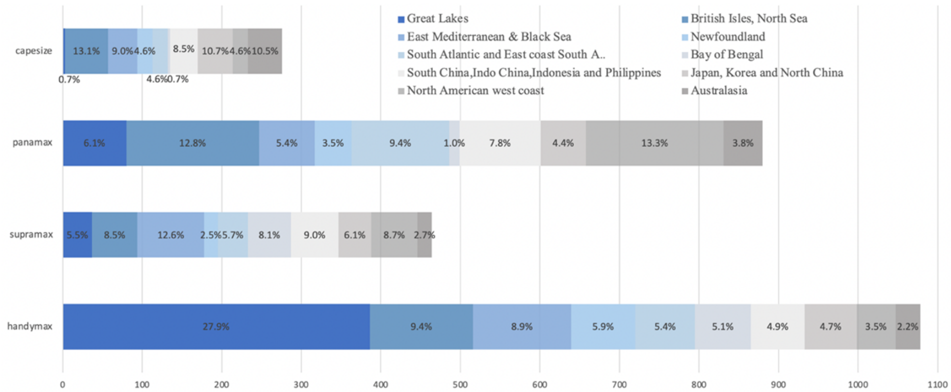

Fig 2.10. Relationship between four types of bulk carrier and accident area

The longitude and latitude of bulk carrier accidents were imported into Arcgis for visualization processing, shown in Fig 2.11. It can be observed that bulk carrier accidents are concentrated in the near shore area, while the distribution of accidents in the open sea area is relatively scattered.

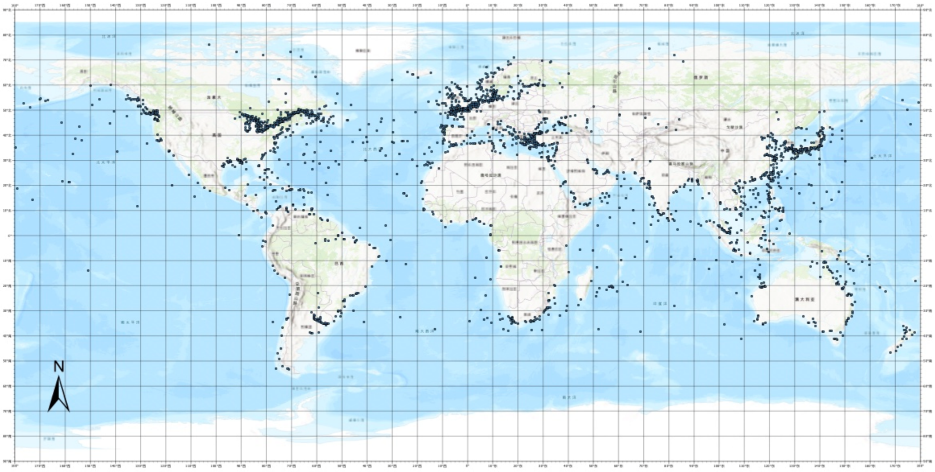

Fig 2.11. Global distribution of bulk carrier accidents

Fig 2.12 displays the spatial visualization results of global bulk carrier total loss accidents. It can be observed that total loss accidents mainly occurred in the Northeast Asia sea area (North China, Japan, South Korea) and the East Indies. Selecting 43 total loss accidents of bulk carriers that occurred in parts of the Northeast Asia sea area, further analysis was conducted on the accident characteristics in the areas traversed by deep-sea mining routes. The statistical results of accident types are shown in Fig 2.13.

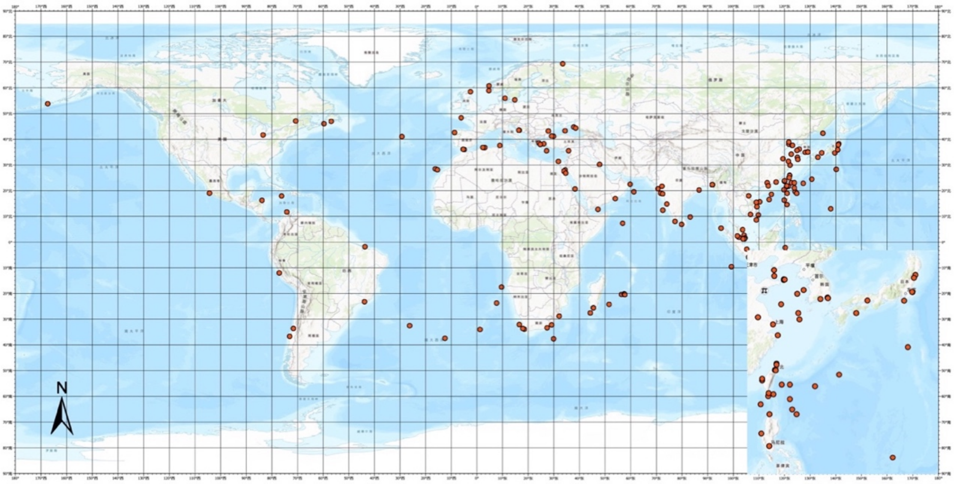

Fig 2.12. Total loss accident distribution of bulk carriers

The types of total loss accidents in the deep-sea mining route area share similarities with the overall bulk carrier accidents. Foundered and wrecked/stranded accidents are the main causes of total loss accidents for bulk carriers, followed by collision accidents. However, the total loss rate due to fire/explosion in the deep-sea mining route area (4.65%) is lower compared to the overall bulk carrier accidents (8.54%).

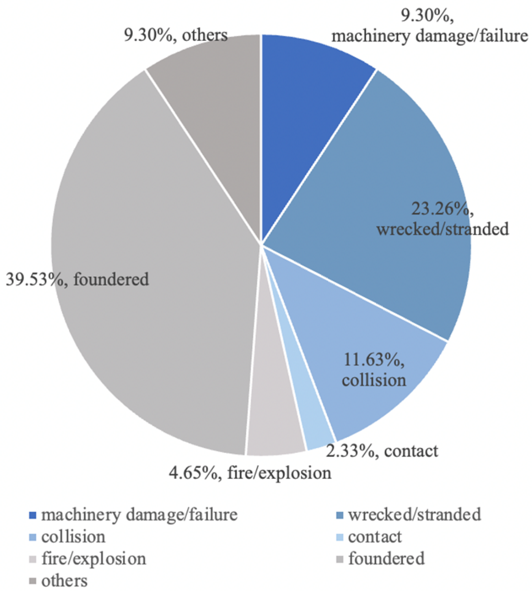

Fig 2.13. The proportion of each accident type in total loss accident in deep-sea mining route area

2.3. Definition of sustainable maritime transport

Sustainability is an essential prerequisite for the future development of various industries, and the maritime transport sector is no exception. To develop a working definition of sustainable maritime transport, the study team reviewed existing literature related to "maritime sustainability" and analyzed these literatures against different dimensions like economic, social, environmental aspects. The primary research directions of maritime sustainability encompass topics including green ports, shipping, carbon emissions, and climate change. Another aspect of maritime sustainability involves optimizing shipping routes/voyage speed to reduce greenhouse gas emissions and thus lowering logistics costs. Both Xiaofang Wu and Sung-Ho Shin have provided comprehensive overviews of existing literature on maritime sustainability [43, 44]. Wu supplements research gaps in strategic planning within the industry, while Shin conducts a bibliometric analysis, highlighting that most sustainable development issues related to ports, shipping, and maritime logistics are intertwined with economic and environmental dimensions of sustainability. However, in terms of societal aspects such as labor laws and standards, working conditions, maritime employment, regional development, and community livability, the academic research attracted to the maritime domain remains relatively limited.

For the purpose of this study, a working definition of sustainable maritime transport is proposed as follows:

A sustainable maritime transport promotes economic benefit, embrace advanced technologies, guarantees shipping safety, improves livelihood, meanwhile minimizes impacts to environment.

2.4. Maritime Transport Sustainability Framework

The proposed definition of sustainable maritime transport provides a basis for the structure of Maritime Transport Sustainability Framework (see Fig. 2-6). In this study, five sustainability dimensions, namely environment, economic, social, safety, and technology are proposed. The sustainability dimensions are more than conventional Triple Bottom Line (environment, economic and social) is because sustainability assessment in this study is at micro operational level, safety and technology are taken into considerations.

Furthermore, four phases of maritime transport are recognized from the value chain analysis in Section 2.1.4, ship-to-ship mooring, ship-to-ship minerals transfer, shipping and port unloading. Sustainability assessment will be conducted for each phase of maritime transport, in which different sustainability dimensions may be applied. For instance, sustainability assessment of ship-to-ship mooring is involved with three environment dimensions: economic, safety, and technology. For sustainability assessment of ship-to-ship minerals transfer, four dimensions of environment, economic, social and technology are included in the sustainability assessment. For sustainability assessment of shipping and port unloading, five dimensions are involved.

Maritime transport				
	Ship-to-ship Mooring	Ship-to-ship Minerals Transfer	Shipping	Port Unloading
Environment	–	✓	✓	✓
Economy	✓	✓	✓	✓
Society	–	✓	✓	✓
Safe	✓	–	✓	✓
Technology	✓	✓	✓	✓

Fig 2.14 Maritime Transport Sustainability Framework

2.5. Review on sustainability assessment methods

Increasing environmental awareness creates new challenges for the development of deep-sea mining. In addition, the limited knowledge about deep sea species and ecosystem calls for adaptation measures that aim at minimizing environmental impacts (i.e. plumes, sediment, waste water, air pollution) when deep-sea mining projects are initialized. International and national legislation for deep-sea mining are incorporating these issues and are increasingly based on strict regulations aiming at forming sustainable deep-sea mining roadmaps for contractors to follow. To achieve such roadmaps, sustainability assessment methods can be powerful tools to study the societal, environmental, and economic aspects of deep-sea mining in qualitative and quantitative manners. Several popular sustainability assessment methods are described briefly as follows.

2.5.1. AHP method

Analytic Hierarchy Process (AHP) is a quantitative analysis method for multi-criteria decision-making(MCDM), which was proposed by American operations researcher Thomas Saaty in the

1970s [45]. The AHP method is designed to help decision makers to determine the best decision-making scheme through comparison and evaluation between criterion and options.

The AHP method is based on the thought of a hierarchical structure, which decomposes the decision-making problem into different levels of criterion and choices. Hierarchies consist of the relationships between the levels and the comparison of elements within each level. Usually, the top layer of a decision problem is the target layer, the next layer is the criterion layer, and the third layer is the selection layer [46].

At the heart of the AHP method is the use of a one-to-one comparison matrix, in which a decision maker compares two elements to determine their relative importance. The element values in the comparison matrix represent the decision maker's preference for one element over another. Decision makers express this degree of preference using a scale, usually a numerical scale from 1 to 9. These comparison matrices are mathematically normalized and checked for consistency, resulting in weights for individual elements in the hierarchy.

In the AHP method, decision makers also need to conduct consistency checks to ensure that the comparisons made are reasonable and consistent. The consistency test is based on the comparison of the characteristic root and the consistency indicator to judge whether the comparison provided by the decision maker is reasonable. If the comparison matrix passes the consistency check, the weight of each element in the hierarchy can be calculated using the eigenvector method.

In general, the AHP method is a quantitative analysis method for multi-criteria decision-making. It helps decision-makers to determine the relative importance of each criteria and choice through steps such as hierarchical structure, one-to-one comparison matrix, and weight calculation, and finally determines the best decision-making option.

2.5.2. Singular working MCDM methods

Singular working MCDM methods are a class of methods for dealing with multi-criteria decision-making problems, which are different from integrated multi-criteria decision-making methods. The singular working method focuses on dealing with decision-making problems with singular structures, that is, decision-making scenarios involving some special situations or conflicts.

Multi-criteria decision-making methods for singular work are usually used to deal with problems with special properties, such as special constraints of decision-making problems, preference conflicts, uncertainty, risk, etc. Such problems may render traditional integrated multi-criteria decision-making methods inapplicable or unable to provide accurate results. Singular working methods try to solve these special problems through unique algorithms and techniques, and find decision-making solutions applicable to these problems [47].

Multi-criteria decision-making methods for singular work include, but are not limited to: Singular Value Decomposition (SVD), Singular Matrix (Singular Matrix) processing, Singular Point (Singular Point) analysis, etc. These methods use special mathematical models to solve specific problems in order to achieve more accurate and reasonable decision results.

The advantage of singular multi-criteria decision-making method is that it can solve decision-making problems with special properties and provide customized solutions for the special constraints and conflicts of the problem. These methods can overcome some limitations of ensemble multi-criteria decision-making methods and provide more precise and feasible decision results. However, singular working methods also face some challenges, such as the complexity of problem modeling, the computational complexity of algorithms, and the need of domain expertise.

In short, singular working MCDM method is a kind of method which focuses on dealing with special decision-making problems and provides customized solutions through special algorithms and techniques. However, in specific applications, it is necessary to select an appropriate singular working method according to the characteristics and requirements of the problem, and to carry out reasonable problem modeling and algorithm design.

2.5.3. Integrated MCDM methods

Integrated MCDM methods are a class of methods for dealing with multi-criteria decision problems which aim to support the decision-making process by integrating multiple evaluation criterion. These methods assist decision makers in comprehensive evaluation and decision selection by combining different decision criterion and considering the interactions and weights among the criterions.

Integrated multi-criteria decision-making methods can be applied to various decision-making scenarios, such as engineering project selection, investment decision, supply chain management, environmental planning. In the decision-making process, multiple decision criterion are usually involved, which may involve different dimensions, weights and objectives. The integrated multi-criteria decision-making approach provides a systematic framework for quantifying and comparing the importance between different criteria and generating optimal decision alternatives [48].

The advantage of integrated multi-criteria decision-making methods is the ability to integrate the decision-making process into a systematic framework which takes into account the weights and interrelationships of multiple criterion, thus providing more comprehensive, objective and consistent decision results. However, these methods also have some challenges and limitations, such as subjectivity in weight determination, limitations in model assumptions, and increased computational complexity.

In conclusion, integrated multi-criteria decision-making methods provide decision makers with a systematic way to deal with multi-criteria decision-making problems. By combining different criteria and considering their interrelationships and weights, these methods help to support decision makers in making integrated, comprehensive, and effective decision choices. However, the selection of appropriate methods and reasonable model settings for specific decision problems still requires comprehensive consideration on a case-by-case basis.

2.6. Conclusions

In this chapter the value chain of deep-sea mining is discussed in details and several sustainability assessment methods are reviewed. From the analysis of the value chain of deep-sea mining, it is found that rare attention has been put on sustainable maritime transport. A definition of sustainable maritime transport is proposed. Maritime Transport Sustainability Framework is developed as a tool for sustainability assessment of transport plans for deep-sea mining.

3. Sustainability of ship-to-ship mooring

For the maritime transport of deep sea minerals, the first step is the ship-to-ship mooring of minerals transport vessels (MTVs) to production support vessels (PSVs). The ship-to-ship mooring is challenging because it will occur in open ocean waters. The wave and wind may have large influence on the maneuverability of the MTVs while the PSVs may experience roll and pitch though it is capable to stay at consistent position with the favor of Dynamic Positioning systems. In this chapter we will first conduct a global accident analysis of bulk vessels. With this analysis, main reasons which cause serious accidents of bulk vessels are identified and considered as indicators for the safety of ship-to-ship mooring. Afterwards, safety assessment is conducted by applying the AHP method Information Entropy.

3.1. Characteristics of ship-to-ship mooring in oceans

The traditional mooring system is an important facility in the field of marine engineering, which firmly fixes the ship or platform on the seabed or shore through the connection equipment such as anchor chain and cable to ensure its stability and safety in the harsh Labor Costs. The basic components of mooring system include anchor chain, cable, anchor, fender and so on.

In the traditional mooring system, the anchor chain plays the role of connecting the ship or platform and the anchor and is one of the most important parts of the system. The mooring chain is usually composed of multiple steel chains, with the length of each chain generally ranging from 25-27.5 meters, and its diameter and strength are determined according to the required mooring force and Labor Costsal conditions [49]. The cable is used to connect the anchor chain with the platform or ship, generally made of high-strength synthetic material or steel cable, and its length and diameter are determined according to the size of the platform or ship and the required mooring force. Anchor is the equipment used to fix the anchor chain on the seabed, generally made of heavy-duty cast steel or steel plate, and its shape and size are determined according to the topography of the seabed and the Labor Costs and other factors. The fender is the equipment used to protect the platform or ship from the wear and tear of the anchor chain and cable, and is usually made of rubber, polymer and other materials.

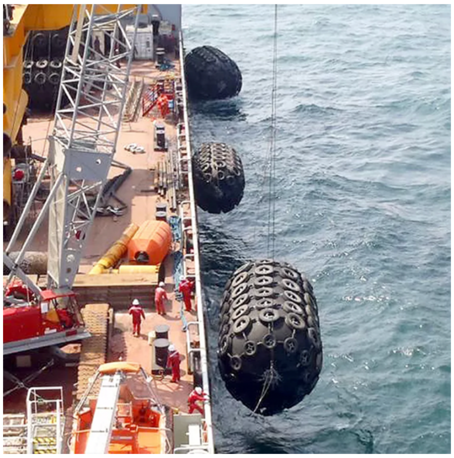

Fig 3.1. Pneumatic Fender [50]

In the process of mooring, safe problem is so important that we cannot ignore. It can be easily found that there will be many collisions among ships, and a fender between two ships is necessary. A Pneumatic Fender / Yokohama Fender as shown in the Fig 3.1 has a huge energy absorption capacity and acts on ships with a low pressure per unit surface. It has become an ideal ship protection medium widely used by LPG vessels, ocean platforms ,harbors and so on. A variant of the pneumatic rubber fender that can be deployed vertically to provide total protection underwater and on the surface. This type of fender utilizes hydraulic ballast and is equipped with counterweights at the bottom of the fender. It is available in various forms and designs and the most suitable type depends on its application and the requirements of the vessel/facility [50].

The design, material selection, construction and maintenance of traditional mooring system are key factors for the proper operation and safety of the system [51]. In terms of design, the specifications and quantity of equipment such as mooring chains, cables and anchors need to be determined according to the size of the platform or ship, the Labor Costs in which it is located and the wind. In terms of material selection, materials with high strength, corrosion resistance and fatigue resistance need to be chosen to ensure the stability and safety of the system. In terms of construction, it is necessary to follow the corresponding standards and specifications to ensure the construction quality and safety of the system. In terms of maintenance, the equipment and components in the system need to be regularly inspected and maintained, and potential safety hazards need to be found and dealt with in a timely manner to ensure the reliability and safety of the system.

Because of the mooring locations of the PSVs where water depth can be more than 4000m, it is not possible to use traditional mooring system. The offshore vessel mooring discussed in this section is an important facility for PSVs and MTVs to maintain the relative position of the vessel in the harsh Labor Costs, where dynamic positioning system (DP) is a key technology.

The DP system in the offshore vessel mooring system regulates the attitude and position of the vessel by collecting the motion parameters of the vessel and adopting corresponding control strategies to ensure the stability and safety of the vessel. The control strategies used in DP system usually include PID control, model predictive control, adaptive control, and so on [52]. DP system is a technology which uses sensors and control system to calculate dynamic parameters such as ship position, direction, speed and attitude in order to precisely control the movement and position of the ship on the water. It adopts advanced computer algorithm and control system to ensure that the ship keeps stable position under severe environment such as strong wind and big waves by collecting data and calculating with dynamic control theory. DP system mainly includes three parts: position sensing system, control system and actuator.

The position sensing system senses the position, speed and attitude of the ship in real time through GPS, inertial navigation, sonar and other sensors. The control system uses advanced control algorithms to compare the information collected by the sensors with the preset control commands and adjust the motion of the actuators to control the position, direction and attitude of the ship. The actuators, in turn, control the ship’s motion, including the main engine, rudder, thruster and other equipment, according to the commands of the control system.

DP system is widely used in offshore vessel mooring system and has many features. Firstly, DP system can cope with the harsh Labor Costs and ensure that the ship can maintain a stable position even under the conditions of strong wind and waves. Secondly, DP system has high accuracy and high efficiency, which can monitor and control dynamic parameters such as ship's position, direction, speed and attitude in real time. In addition, DP system can adapt to different labor costs and shipping needs and be flexibly applied to various offshore ship mooring systems. The application of DP system makes the offshore vessel mooring system have better control capability and flexibility. However, the roll and pitch of PSVs and MTVs in oceans are difficult to control, which still makes the ship-to-ship mooring remain big challenge. The safety of the mooring cannot be guaranteed with advanced technologies, while human remains as the most dominant factor.

3.2. Sustainability indicator system for ship-to-ship mooring

For the safety assessment of the offshore ship-to-ship mooring system, it is necessary to select suitable indicators to evaluate the system. The following are the four major primary indicators, namely human factors, environmental factors, DP System Factors, Maneuverability of MTVs and accident factors, and their corresponding secondary indicators.

Table 3.1. ship-to-ship mooring indicator system

objective	Layer 1	Layer2
Sustainability of Mooring analysis	Human Factors	Communication skills
		Mooring operation quality
		Design and construction quality
		Maintenance quality
		Duty arrangement
		Operating procedures
		Nautical expertise
		Crew physical condition
		Crew mental condition
	Economic Factors	Infrastructure Investment
		Operational Efficiency
		Labor Costs
		Maintenance and Upkeep
		Risk Management and Insurance
		Market Demand and Competition
	DP System Factors	DP sensor system
		DP propulsion system
		Ship electrical system
		DP system responsiveness
		DP system design and configuration
		Mooring ropes
		Buffer cushions
		Vessel equipment mechanical failure
	Maneuverability of MTV	Ship age
		Ship type
		Bow height
		Fullness of the bow

		Hull center of gravity position
		Displacement
		Mooring distance
		Mooring speed
	Accident Factors	Natural disasters
		Equipment failure

1) Human factors

Human factors, referring to the human-related first-level indicators, are closely related to the technical level, professional ability and experience of personnel. It has an important impact on the safety and reliability of the system. Therefore, the analysis from the perspective of human factors can assess the technical level, professional competence and experience of personnel and determine whether personnel training and management need to be enhanced to improve the safety and reliability of the system. The human factors considered in this section are divided into nine secondary indicators.

A. Communication skills

Good communication skills contribute to effective communication and understanding between crew members, thus ensuring safe and coordinated vessel mooring operations. The ability to pass information, instructions and guidance clearly between crew members reduces misunderstandings and errors, ensuring accuracy and consistency of operations. In emergency situations, good communication skills can help the crew to quickly and effectively communicate key information and instructions, as well as coordinate actions in response to emergency situations. Clarity and timeliness of communication are critical to the safety and protection of crew members' lives. The ship's commander or leader needs to have good communication skills to effectively communicate tasks, objectives and instructions to ensure that the crew understands and performs operations as required. Therefore, good communication skills have an important role in a ship's mooring safety system. It promotes safe and coordinated operations, supports emergency response, improves the efficiency of teamwork, facilitates cross-cultural communication, and effectively manages and directs the crew.

B. Mooring operation quality

The necessity of this indicator is that the quality of mooring operation is directly related to the stability and reliability of the system. Reasonable operation procedures and professional operators can ensure the safety and effectiveness of mooring operation and reduce the influence of human factors on the safety of the system.

C. Design and construction quality

The necessity of this indicator is that design and construction quality directly affect the stability and reliability of the mooring system. Reasonable design and excellent construction quality can ensure the good operation of the system and reduce the risk of accidents. Maintenance quality

D. Maintenance quality

The necessity of this indicator is that the quality of maintenance has an important influence on the long-term stability and reliability of the mooring system. Regular maintenance and servicing can identify and solve system problems in time and improve the safety and reliability of the system.

E. Duty arrangement

Duty arrangement refers to the arrangement of work and rest time of crew members on board the vessel. The unreasonable shift arrangement may lead to the crew's fatigue and poor mental state, which may affect their sensitivity and reaction speed to the mooring and docking operation, thus increasing the hazards when the ship is moored and docked.

F. Operation process

Operation process refers to the operation procedures and processes that crew members need to follow in the process of mooring and docking the ship. If the operation process is unreasonable or the crew is not familiar with the operation process, it may lead to operation error and confusion, thus increasing the risk when the ship is moored and docked.

G. Nautical expertise

Nautical expertise refers to the necessary professional knowledge of crew members, including oceanography, navigation, navigation technology and other aspects. Lack of necessary nautical expertise may lead to improper operation or errors, which may affect the safety of the ship's mooring and docking.

H. Crew physical condition

Crew physical condition refers to the physical health condition of the crew. If crew members are not in good physical condition, it may lead to fatigue, fainting, dizziness, etc. during the operation of the ship mooring, thus increasing the risk of the ship mooring and docking.

I. Crew Mental Condition

Crew Mental Condition refers to the mental state of the crew, including aspects such as emotional stability, tension, and willpower. If the crew's mental condition is poor, it may affect their judgment and decision-making ability in operating the ship mooring process, thus increasing the risk when the ship mooring and docking.

2) Economic Factors

Economic Factors, the first-level indicators related to the indicator system, can be analyzed from the perspective of Economic Factors to assess the adaptability and resilience of the system and determine whether the system design and configuration can meet the requirements.

A. Infrastructure Investment

This layer involves evaluating the initial capital investment required to establish suitable infrastructure for ship-to-ship mooring. This includes constructing mooring stations, installing necessary equipment, and creating a safe and efficient environment for vessels to dock. The cost of infrastructure development and maintenance influences the overall economics of the mooring system.

B. Operational Efficiency

The efficiency of ship-to-ship mooring operations directly impacts costs. Factors such as turnaround time for vessel mooring and unmooring, equipment reliability, and ease of navigation contribute to operational efficiency. A well-optimized system reduces idle time for vessels, minimizing associated expenses.

C. Labor Costs

The employment of skilled personnel for mooring operations is an economic consideration. Skilled crew members, including mooring masters and deckhands, ensure safe and timely mooring procedures. Labor costs include wages, training, and possibly overtime pay during complex or adverse conditions.

D. Maintenance and Upkeep

Regular maintenance of mooring equipment and infrastructure is essential for safety and operational efficiency. This layer encompasses costs associated with inspections, repairs, and replacement of mooring lines, fenders, buoys, and other equipment. Adequate maintenance prevents downtime and accidents that could result in financial losses.

E. Risk Management and Insurance

Economic Factors also include risk assessment and mitigation strategies. Insurance premiums, liability coverage, and compliance with safety regulations impact the overall cost structure. A robust risk management plan reduces potential financial losses due to accidents, damage, or environmental incidents.

F. Market Demand and Competition

The demand for ship-to-ship mooring services is influenced by global shipping trends and trade patterns. Understanding market demand helps optimize pricing strategies. Competition among mooring service providers can impact pricing and service quality, requiring careful economic analysis to remain competitive.

3) DP System Factor

DP positioning system factor, which is one of the key technologies in offshore floating platform mooring system, is also the first level indicator directly related to the stability of ship-to-ship mooring. The analysis from the perspective of DP system can assess the accuracy and stability of the system and determine whether higher accuracy sensors and equipment are needed to improve the safety and reliability of the system. In terms of DP system, it is divided into three secondary indicators, system performance, sensors and equipment, and system design and configuration.

A. DP Sensor system

The DP sensor system can provide accurate position and motion information, including the ship's longitude, latitude, heading, speed, inclination, etc., thus ensuring that the ship always remains in its predetermined position or within its designated working area. Based on the data provided by the DP sensor system, the ship can be adjusted in real time by the automated control system to maintain the stability of the ship's position. This is essential for ships that need to stay in a specific position for a long time or perform complex operations, such as offshore construction vessels, as well as two-ship berthing units. Therefore, DP sensor systems have an important role in the ship mooring safety system, which ensures ship stability and safe mooring by monitoring and controlling ship position, motion and environmental conditions in real time, providing reliable support for ship operations and reducing the risk of accidents.

B. DP propulsion system

DP propulsion system is a technical system that uses equipment such as thrusters and rudders to maintain the stability of a ship in a given position or designated area by automatically controlling the ship's propulsion force and rudder angle. DP propulsion system can maintain a ship in a predetermined position or designated working area by adjusting the propulsion force and rudder angle. It can make real-time ship attitude adjustment based on the position and motion information provided by DP sensor system to ensure the ship remains stable in the specified position. DP propulsion system can automatically adjust the propulsion force and rudder angle according to the change of environmental conditions, such as Risk Management and Insurance, Maintenance and Upkeep and sea current, to meet different environmental challenges. The automatic control function of DP propulsion system can improve the efficiency of ship mooring operation and accuracy, reduce human errors and labor cost, and improve work efficiency. Therefore, DP propulsion system has an important role in the ship mooring safety system to maintain the stability and safe mooring of the ship by precisely controlling the ship's propulsion force and rudder angle.

C. Ship electrical system

Ship electrical system refers to the electrical equipment, power supply and distribution system on the ship, which is used to supply, control and drive the normal operation of each system and equipment on the ship. Ship electric system can provide stable power supply to ensure the normal operation of each system and equipment. This includes ship power system, navigation equipment, communication equipment, life-saving equipment, ship control system, etc. A good power supply guarantees the operational safety and efficiency of the ship. The ship electric power system can detect the operation status of the electric power system in real time through monitoring and protection devices, including current, voltage, frequency, temperature and other parameters. The safety of the ship's electric power system is the key to ensure that the electric power supply is stable, reliable and free from external interference. In addition, the electric power system should have emergency capability and be able to provide backup power and emergency power supply in emergency to ensure the safe operation of the ship in emergency. Therefore, the ship electric power system has an important role in the ship mooring safety system. It provides stable power supply to ensure the normal operation of each system and equipment; it monitors the operation status of the power system in real time through monitoring and protection devices to guarantee the safety and reliability of the system.

D. DP system responsiveness

The need for this indicator lies in the fact that sensors and equipment are the core components of the DP positioning system and affect the accuracy and reliability of the system. Accurate and reliable sensors and equipment can ensure the good operation of the DP positioning system and improve the safety and stability of the system.

E. DP system design and configuration

The necessity of this indicator lies in the fact that system design and configuration determine the overall performance of the DP positioning system. Reasonable system design and configuration can better meet the needs of the system and improve the safety and stability of the system.

F. Mooring ropes

The mooring rope is a key element in ship mooring operations, connecting the ship to a fixed structure such as a quay or anchorage. A good quality mooring rope can provide sufficient strength and stability to ensure that the ship remains stable during mooring and prevent the ship from drifting to ensure mooring safety. The mooring rope needs to be durable and reliable enough to withstand the tension, friction and external environment during the mooring of the ship. Good quality mooring rope can reduce the risk of breakage, wear and aging, and ensure its long-term reliable support of ship mooring operations. The mooring rope should have a certain degree of elasticity and elongation to absorb the impact forces and dynamic loads during ship mooring operations. The mooring rope should have good corrosion resistance to resist seawater, oxidation and other environmental factors. Therefore, the mooring rope has an important role in the ship mooring safety system. It guarantees the safety of mooring operation, provides stable mooring connection, has durability, reliability and corrosion resistance.

G. Buffer cushions

Buffer cushions can provide vibration damping and shock absorption when a ship comes into contact with a dock or other vessel. They can reduce the shock and vibration caused by vessel motion during mooring operations, protect the vessel and the structure of the quay or other vessel, and reduce potential damage and collision accidents. The cushion has a certain elasticity and elasticity, which can deform and rebound adaptively when the ship is in motion. Punch buffer cushions enhance the safety of mooring operations as part of a vessel's mooring system. They can provide additional protection and safety boundaries to prevent collisions when a vessel comes too close. The use of buffer cushions can also provide benefits in terms of occupant comfort and safety. During mooring operations, they can reduce vessel sway and bumps, providing a smoother ride and reducing occupant discomfort and the risk of accidents such as slips and falls. Therefore, buffer cushions have an important role in a ship's mooring safety system. They damp and reduce shock, provide elasticity and bounce, enhance mooring safety, improve operational efficiency, and provide comfort and occupant safety.

H. Vessel equipment mechanical failure

Vessel equipment mechanical failure can lead to safety hazards and accident risks in mooring operations. For example, faulty propulsion systems, moorings or cable equipment may result in the inability of a vessel to moor stably or break away from the quay, increasing the occurrence of collisions, drift and other hazardous situations. Vessel equipment mechanical failure can affect the reliability and continued operation of the vessel's equipment. Faulty equipment may result in equipment not working as expected, affecting smooth mooring operations and even causing stoppages and delays. Vessel equipment mechanical failure may have a negative impact on the economics of ship operations. Losses caused by ship stoppages and repairs include downtime losses, increased operating costs, repair costs and equipment replacement costs. Mechanical failure of ship equipment reminds ship managers and operators of the importance of maintenance and management of equipment. Therefore, mechanical failures of ship equipment have an important significance in the ship mooring safety system. Through regular maintenance and inspection of equipment, preventive measures, timely detection and repair of faults, the risk of accidents can be reduced, the safety and reliability of the ship can be improved, and the smooth mooring operation can be ensured.

4) Maneuverability of MTV

A. Ship age

As the age of the ship increases, the ship equipment will gradually age, including the ship engine, electrical system, rudder, hull corrosion, etc. These aging problems may lead to unstable ship operation or operation failure.

B. Ship type

The ship type is an important factor affecting the flexibility of the ship. Generally speaking, the rounded ship shape is more suitable for driving in waves, but it will be more difficult to cut the surge, while the narrow and long ship shape has better ability to cut the surge, but it may not be as stable as the rounded ship shape.

C. Bow height

The bow height is the superstructure of the bow and its height will have an effect on the flexibility of the ship. A higher bow will make the bow more susceptible to wind and waves, thus reducing the flexibility of the ship.

D. Fullness of the bow

Bow fullness refers to the ratio of the width of the bow to the height of the ship. Smaller bow fullness can improve the ship's surge cutting ability, but it will also increase the resistance and drag.

E. Hull center of gravity position

The hull center of gravity position is a key parameter that affects the stability and flexibility of the ship. Generally speaking, the lower the center of gravity position is, the more stable the ship is, but it also affects the maneuverability of the ship.

F. Displacement

Displacement is a key parameter of ship buoyancy. Larger displacement can improve the stability of the ship, but at the same time, it can also increase the resistance and force of resistance of the ship and reduce the flexibility of the ship.

G. Mooring displacement

Mooring distance refers to the distance between a ship and a quay or other ships when it is docked. The size and accuracy of the mooring distance have an important influence on the safety and accuracy of the ship's mooring. If the mooring distance is too large or too small, it will increase the collision and danger in the process of ship mooring.

H. Mooring speed

Mooring speed is the speed of the ship when it is close to the mooring position. The size and stability of the mooring speed have an important influence on the accuracy and safety of the ship's mooring. If the mooring speed is too fast or the speed changes too much during the mooring, it will increase the risk during the mooring of the ship.

5) Accident Factors

Accident factors are one of the main sources of safety problems for offshore floating platform mooring systems, including hull collisions, natural disasters and equipment failures. These accidents are usually sudden and unpredictable and have a direct impact on the safety and reliability of the system. Therefore, analysis from the perspective of accidents can assess the system's disaster resilience and safety precautions and determine whether accident prevention and response capabilities need to be enhanced to improve the safety and reliability of the system. The accident factors are divided into two secondary factors, natural disaster indicators and equipment failure.

A. Natural disasters

The necessity of this indicator lies in the fact that natural disasters are one of the important causes of accidents in mooring systems. For different natural disasters, different counter-measures are needed to mitigate the impact of accidents and guarantee the safety of the system.

B. Equipment failure

The necessity of this indicator is that equipment failure is one of the major causes of accidents in mooring systems. For different equipment failure, different countermeasures need to be taken to mitigate the impact of the accident and guarantee the safety of the system.

3.3. Case study: Safety assessment of ship-to-ship mooring

3.3.1. Rules for expert consultation

The final set of indicators developed for the sustainability of maritime transport indicator system underwent an expert review for validation. The methodology for expert consultation consisted of the following steps:

1. Sampling experts

In this step, a selection of experts with relevant knowledge and experience in the field of maritime transport and sustainability is identified. These experts could come from various backgrounds such as academia, industry, research institutions, regulatory bodies, and non-governmental organizations (NGOs). The goal is to have a diverse group of experts who can provide comprehensive insights and perspectives.

2. Drafting the questionnaire

A questionnaire is prepared to gather opinions, feedback, and insights from the selected experts. The questions in the questionnaire should be well-structured, clear, and targeted at evaluating the relevance, feasibility, and comprehensiveness of the proposed indicators. The questionnaire could include open-ended questions as well as scaled responses for more quantitative analysis.

3. Contacting experts

The identified experts are then contacted, and their participation in the expert review process is sought. This could be done through email, formal invitations, or other communication methods. The experts should be provided with a clear explanation of the purpose of the review, the importance of their input, and the expected time commitment.

4. Collecting data and output results

Once the experts have agreed to participate, they are provided with the questionnaire. The experts' responses are collected and analyzed. The analysis involves synthesizing the qualitative feedback and quantifying the scaled responses. This step aims to identify trends, patterns, and areas of agreement or divergence among the experts' opinions.

The ultimate goal of this methodology is to ensure that the indicators developed for the sustainability of maritime transport are well-grounded, relevant, and capable of effectively measuring and assessing the various dimensions of sustainability in the context of maritime transportation. The expert review process helps validate the indicators, provides valuable insights for potential improvements, and enhances the overall credibility and usefulness of the indicator system.

3.3.2. Safety assessment procedures

The AHP method is used to calculate the weights of indicators in the following four steps.

(1) Establishing a hierarchical system model

According to the hierarchical relationship, there are three levels in the evaluation system.

- The highest level: it is the objective to be achieved in the system and is the main criterion for the evaluation.
- The second level: It is the selected criterion to achieve the highest level.
- The bottom level: It is also called the action level. It is the various means needed to achieve the goal.

(2) Establishing a judgment matrix

For the evaluation factors in the same level, the factors in the upper level are compared one by one and the corresponding scminerals are given to construct a judgment matrix. Comparing the importance of n factors B = (B1, B2, Bn) to factor A; a_{ij} is the ratio of the importance of factor B_i to factor B_j to factor A (see Table 3.2):

Table 3.2 Judgment matrix [53]

A	B_1	B_2	$\cdots$	B_n
B_1	a_{11}	a_{12}	$\cdots$	a_{1n}
B_2	a_{21}	a_{22}	$\cdots$	a_{2n}
$\cdots$	$\cdots$	$\cdots$	a_{ij}	$\cdots$
B_n	a_{n1}	a_{n2}	$\cdots$	a_{nn}

Call A=(a_{ij}) the judgment matrix. a_{ij} is the ratio of the relative importance of element i to element j in A, and has the following relationship (opposite matrix):

$$a_{ij} \neq 0, a_{ij} = \frac{1}{a_{ji}}, a_{ii} = 1, ij = 1, 2, \cdots n \tag{3-1}$$

The importance of i is proportional to the ratio, i.e., the larger the ratio, the more important it is.

To visualize the comparison, the relative importance of each factor was scaled according to 1-9 (see Table 3.3).

Table 3.3 Meaning of scaling methods [53]

Scale	Definition and description
1	Two elements are equally important for an attribute
3	When two elements are compared, the former element is slightly more important than the latter element
4	When two elements are compared, the former element is significantly more important than the latter element
7	Two elements are compared in which the former element is much more important than the latter element
9	Comparing two elements, the former element is extremely important than the latter element
2,4,6,8	The former element is more important than the latter element between the calibrated criteria
$1/a_{ij}$	Inverse comparison of two elements

(3) Calculation of weights

1) Calculate the estimated value of the feature vector using the root method.

$$\omega_i = \frac{(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}}{\sum_{i=1}^{n}(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}}, ij = 12kn \tag{3-2}$$

2) normalize it to obtain the weight vector $W = (\omega_1, \omega_2, \cdots \omega_n)^T$ 。

(4) Consistency check

In order to find the correct and realistic weight vector, the consistency test is also needed.

Calculate the consistency indicator C.I.

$$C.I. = \frac{\omega_{max} - n}{n-1} \qquad (3-3)$$

Where:

$$\omega_{max} = \sum \frac{(AW)_i}{n\omega_i} \qquad (3-4)$$

The error of C.I. is proportional to the value of n.
Therefore, the randomness consistency ratio C.R. is introduced in the validation.
When n=1~15, the magnitude of R.I. is shown in the following Table 3.4.

Table 3.4 value of R.I.

Number of steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58	1.59

When $C.R. = \frac{C.I.}{R.I.} < 0.1$,Otherwise, some elements of the judgment matrix are adjusted appropriately until the consistency test is passed.
(5) Calculation of comprehensive importance
The solution with the greatest weight is the optimal choice for achieving the goal.
In order to identify the risk factors of ship-to-ship mooring in oceans, AHP method is applied to conduct safety assessment. The developed assessment indicator system is provided to several experts, and the experts are asked to fill in weighting tables. By calculating the weighting tables from several experts, the weight of each indicator can be obtained. One of the experts' score is used as an example to calculate the weight Table 3.5.

Table 3.5 The importance of the three indicators to the overall goal

	C1	C2	C3
C1	1	3	4
C2	1/3	1	3
C3	1/4	1/3	1

A comparison matrix can be obtained from Table 3.5:

$$A = \begin{bmatrix} 1 & 3 & 4 \\ \frac{1}{3} & 1 & 3 \\ \frac{1}{4} & \frac{1}{3} & 1 \end{bmatrix} \qquad (3-5)$$

The next step is to calculate the product of the values of each row of the comparison matrix W_i, and calculate its 3rd root. $W_i = \sqrt[3]{M_i}$ the following results are obtained:

$$W_1 = \sqrt[3]{1 \times 3 \times 4} = 2.290 \qquad (3-6)$$

$$W_2 = \sqrt[3]{\frac{1}{3} \times 1 \times 3} = 1 \qquad (3-7)$$

$$W_3 = \sqrt[3]{1 \times \frac{1}{3} \times \frac{1}{4}} = 0.437 \qquad (3-8)$$

The next step is to normalize them:

$$\sum W_i = 2.290 + 1 + 0.437 = 3.727 \qquad (3-9)$$

$$W = \frac{W_i}{\sum W_i} \qquad (3-10)$$

Next step is to normalized weight matrix is obtained as:

$$W1 = [0.614 \;\; 0.268 \;\; 0.117]^T \qquad (3-11)$$

$$AW1 = [1.886 \;\; 0.824 \;\; 0.360]^T \qquad (3-12)$$

Calculate the maximum characteristic root of the judgment matrix λ_{max}:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)i}{(nWi)} = \frac{1.886}{3 \times 0.614} + \frac{0.824}{3 \times 0.268} + \frac{0.36}{3 \times 0.117} = 3.074 \qquad (3-13)$$

Lastly consistency test can be performed:

$$CI1 = \frac{\lambda_{max} - n}{n - 1} = \frac{3.074 - 3}{3 - 1} = 0.037 \qquad (3-14)$$

$$CR1 = \frac{CI1}{RI1} = 0.064 < 0.1 \qquad (3-15)$$

Therefore , the consistency is acceptable.

The same calculation was performed for the importance of the criterion level of other experts, and the weights whose consistency was unacceptable were deleted, resulting in a standard matrix R of the importance cases of the three indicators for the overall objective as:

$$R1 = (W1, W2, W3, W4) = \begin{bmatrix} 0.6144 & 0.2970 & 0.3333 & 0.4161 \\ 0.2684 & 0.5396 & 0.3333 & 0.4579 \\ 0.1172 & 0.1634 & 0.3333 & 0.1260 \end{bmatrix} \qquad (3-16)$$

W_i is the acceptable guideline layer weights for consistency.

The weights of the indicators in economy, technology, and environment are derived separately using the same calculation method of the above equation, and the criteria matrices R2, R3, and R4 are filtered out after consistency calculation.

$$R2=\begin{bmatrix}0.021364 & 0.548031\\0.001089 & 0.018268\\0.139764 & 0.062475\\0.143015 & 0.006702\\0.680058 & 0.00722\\0.000323 & 0.180208\\0.000929 & 0.170286\\0.006729 & 0.001805\\0.006729 & 0.005006\end{bmatrix} \quad (3-17)$$

$$R3=\begin{bmatrix}0.001023 & 0.000081 & 0.001961461\\0.000492 & 0.000279 & 0.023537537\\0.008512 & 0.000279 & 0.016320017\\0.064349 & 0.000279 & 0.029655438\\0.001364 & 0.002111 & 0.118621754\\0.318715 & 0.002928 & 0.014827719\\0.002252 & 0.04256 & 0.037363511\\0.058465 & 0.085119 & 0.15543847\\0.004504 & 0.085119 & 0.135788011\\0.008185 & 0.059018 & 0.149454044\\0.106238 & 0.046843 & 0.1958402\\0.424954 & 0.03192 & 0.118621754\\0.000946 & 0.643462 & 0.002570242\end{bmatrix} \quad (3-18)$$

$$R4=\begin{bmatrix}0.001518 & 0.005081 & 0.031671\\0.000557 & 0.002308 & 0.150199\\0.002317 & 0.000156 & 0.150199\\0.007649 & 0.000157 & 0.150199\\0.198573 & 0.34988 & 0.004434\\0.011032 & 0.215959 & 0.000467\\0.000835 & 0.04736 & 0.348581\\0.008756 & 0.367351 & 0.000589\\0.180415 & 0.003401 & 0.000742\\0.007955 & 0.002358 & 0.15961\\0.099286 & 0.004032 & 0.003197\\0.481107 & 0.001957 & 0.000111\end{bmatrix} \quad (3-19)$$

Because experts' ideas may differ due to their subjective factors, information entropy assignment and gray correlation clustering are then used in order to give greater weight to the

categories where consensus exists among experts, so as to balance the ideas of each expert and realize the principle that precision is better than fuzziness.
The matrix R consisting of the judgment matrix of m experts:

$$R = (W_1, W_2, \dots, W_m)\begin{bmatrix} \omega_{11} & \omega_{12} & \cdots & \omega_{1m} \\ \omega_{21} & \omega_{22} & \cdots & \omega_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ \omega_{n1} & \omega_{n2} & \cdots & \omega_{nm} \end{bmatrix} \qquad (3-20)$$

The absolute gray correlation is then calculated:

$$e_{ij} = \frac{1 + S_i + S_j}{1 + S_i + S_j + |S_i - S_j|} \qquad (3-21)$$

$$S_i = \sum_{k=2}^{n-1} \omega_{ki} + \frac{1}{2}\omega_{ni} \qquad (3-22)$$

The gray correlation matrix of the panel was obtained:

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1m} \\ e_{21} & e_{22} & \cdots & e_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ e_{n1} & e_{n2} & \cdots & e_{nm} \end{bmatrix} \qquad (3-23)$$

A threshold value between 0 and 1 is taken, and when e_{ij} is not less than the threshold value indicates that the weights are of the same kind.
Then m experts are divided into classes, and the kth (k=1, 2,...,t) class contains ℓ_k experts, and β_k is the inter-class weight, then we have:

$$\beta_k = \frac{\ell^2{}_k}{\sum_{k=1}^{t} \ell^2{}_k} \qquad (3-24)$$

In an assessment problem with n indicators and m evaluators, the definition of the information entropy of the jth evaluator:

$$H_{(j)} = -\frac{1}{\mathrm{In}(m)} \sum_{i=1}^{n} f_{ij} \mathrm{In}(f_{ij}), \quad j = 1, 2, \dots, m \qquad (3-25)$$

$$f_{ij} = \omega_{ij} / \sum_{j=1}^{m} \omega_{ij} \qquad (3-26)$$

Define the class weights of the experts in class k as:

$$\alpha_{kj} = \frac{1 - H_k(j)}{\sum_{j=1}^{\ell_k} [1 - H_k(j)]} \qquad (3-27)$$

This allows the calculation of the intra-class weights in the kth class.

Finally, based on the above results, the total weight vector $\Lambda=(\lambda_1, \lambda_2,...\lambda_m)$ of m experts is first calculated using linear weighting, where:

$$\lambda_j=\beta_k\alpha_{kj}, \quad j=1,2,...m \tag{3-28}$$

Finally, the weights of the n indicators are calculated:

$$p=(p_1, p_2,...p_n)^T=R\cdot\Lambda^T \tag{3-29}$$

Calculated using R1 as an example:

$$R1=(W1, W2, W3, W4)=\begin{bmatrix}0.6144 & 0.2970 & 0.3333 & 0.4161\\ 0.2684 & 0.5396 & 0.3333 & 0.4579\\ 0.1172 & 0.1634 & 0.3333 & 0.1260\end{bmatrix} \tag{3-30}$$

The absolute gray correlation is then calculated:

$$S_1=0.32, \ S_2=0.62, \ S_3=0.49, \ S_4=0.52 \tag{3-31}$$

The gray correlation matrix of the panel was obtained:

$$E=\begin{bmatrix}1 & 0.866 & 0.914 & 0.902\\ ... & 1 & 0.942 & 0.955\\ ... & ... & 1 & 0.985\\ & & & 1\end{bmatrix} \tag{3-32}$$

Taking a threshold of 0.9, the 4 experts are then divided into 2 categories,{ (1, 3, 4), (2) }.

Then the inter-class weights are calculated as 9/10, 9/10, 9/10, 1/10.

The information entropy is:

$$\begin{aligned} &f_{11}=0.168, \ f_{12}=0.168, \ f_{13}=0.168, \ f_{14}=0.168,\\ &f_{21}=0.168, \ f_{22}=0.168, \ f_{23}=0.168, \ f_{24}=0.168,\\ &f_{31}=0.168, \ f_{32}=0.168, \ f_{33}=0.168, \ f_{34}=0.168.\end{aligned} \tag{3-33}$$

$$H_1=0.873, \ H_2=0.918, \ H_3=0.918, \ H_4=0.916 \tag{3-34}$$

First category: (1,3,4),weights separately are 0.339,0.219,0.224;

Second category (2),weight is 1.

The total expert weights are then calculated as follows:

$$\Lambda=[0.355,0.197,0.202,0.246] \tag{3-35}$$

Finally, the weights of the indicators are calculated:

$$p1=(p_1, p_2,...p_n)^T=R\cdot\Lambda^T=[0.44,0.4,0.16] \tag{3-36}$$

$$P2 = \begin{bmatrix} 0.294 & 0.009 & 0.101 & 0.071 & 0.344 & 0.08 & 0.081 & 0.008 & 0.012 \end{bmatrix}^T \quad (3-37)$$

$$P3 = \begin{bmatrix} 0.001 & 0.008 & 0.008 & 0.023 & 0.023 & 0.0103 \\ 0.09 & 0.15 & 0.072 & 0.101 & 0.116 & 0.197 & 0.201 \end{bmatrix}^T \quad (3-38)$$

$$P4 = \begin{bmatrix} 0.013 & 0.051 & 0.051 & 0.052 & 0.184 & 0.086 \\ 0.108 & 0.118 & 0.081 & 0.057 & 0.04 & 0.16 \end{bmatrix}^T \quad (3-39)$$

Table.3-6 shows the final summary of the weights made, while the composite weight is the product of the indicator weight and the criterion weight.

Table.3-6 Summary of weights

Indicator Name	Indicator Weight	Combined Weight
Human Factors	**0.14**	
Communication Skills	0.294	0.0412
Mooring operation quality	0.009	0.0013
Design and construction quality	0.101	0.0141
Maintenance quality	0.071	0.0099
Duty Arrangement	0.344	0.0482
Operating procedures	0.08	0.0112
Nautical expertise	0.081	0.0113
Crew Physical Condition	0.008	0.0011
Crew Mental condition	0.012	0.0017
Environmental Factors	**0.18**	
Infrastructure Investment	0.15	0.0270
Operational Efficiency	0.22	0.0396
Labor Costs	0.05	0.0090
Maintenance and Upkeep	0.38	0.0684
Risk Management and Insurance	0.07	0.0126
Market Demand and Competition	0.13	0.0234
DP System Factors	**0.24**	
DP Sensor System	0.078	0.0187
DP Propulsion System	0.164	0.0394
Ship electrical system	0.118	0.0283
DP system responsiveness	0.076	0.0182
DP system design and configuration	0.079	0.0190
Mooring ropes	0.072	0.0173
Buffer cushions	0.144	0.0346
Vessel equipment mechanical failure	0.269	0.0646
Maneuverability of MTV	**0.38**	
Ship Age	0.12	0.0456
Ship Type	0.265	0.1007
Bow height	0.07	0.0266
Fullness of the bow	0.095	0.0361
Hull center of gravity position	0.08	0.0304

Displacement	0.13	0.0494
Mooring distance	0.055	0.0209
Mooring speed	0.185	0.0703
Accident Factors	**0.06**	
Natural Disasters	0.63	0.0378
Equipment failure	0.37	0.0222

From the table, it can be seen that the weight value of DP system accounts for 24% and MTV maneuverability accounts for 38%. In the human factor criterion layer, the weight of Duty Arrangement (0.344) is the largest, followed by Communication Skills (0.294). The third weight is Design and construction quality (0.101), while other indicators accounted for less than 0.1. Overall, it can be seen that in Human Factors, Duty Arrangement is the most important, followed by Communication Skills.

In the Environmental Factors criterion layer, Maintenance and Upkeep (0.38) and Operational Efficiency (0.22) account for the largest proportion, followed by Infrastructure Investment (0.15), and other indicators have relatively small weights. Maintenance and Upkeep has a great influence in Environmental Factors, so we must measure and estimate the suitable Maintenance and Upkeep in advance before mooring.

In DP System Factors criterion layer Vessel equipment mechanical failure (0.269) has the highest weight, DP Propulsion System (0.164) is observed the second highest weight and Buffer cushions (0.118) the third highest weight. So the damage rate of equipment should be strictly controlled and necessary maintenance and repair should be done, which is not negligible for the safety of ship-to-ship mooring.

In the maneuverability of MTV criterion layer, the weight of Ship Type is the largest (0.265), the weight of Mooring speed is the second (0.185), and the rest of the weights are smaller than 0.1. Therefore, in the maneuverability of MTV, the awareness of ship type and reasonable control of mooring speed are important for the safety of ship-to-ship mooring.

3.4. Conclusions

In this chapter historical records of bulk vessel accidents were analyzed and the safety assessment of ship-to-ship mooring was conducted. From the accident analysis, it is found that machinery damages/failure is the most common reason for bulk vessel accidents in recent years. Furthermore, since traditional mooring solutions are not applicable in ship-to-ship mooring between a PSV and a MTV, DP systems were analyzed in details and safety concerns for ship-to-ship mooring process were discussed. Lastly, the safety assessment of ship-to-ship mooring was conducted by applying the AHP method. It was found that maneuverability of MTV is considered to be the most important indicator for the safety of ship-to-ship mooring between MTVs and PSVs.

4. Sustainability of ship-to-ship minerals transfer

After successful mooring of a minerals transport vessel (MTV) to a production support vessel (PSV), the transfer operation of marine minerals from the PSV to the MTV will be carried out. Sustainable ship-to-ship marine minerals transfer should be achieved in order to minimize the environmental impact as well as to lower the cost of transfer process. This chapter will look into the details of ship-to-ship transfer and conduct sustainability assessment of the transfer process.

4.1. Types of ship-to-ship minerals transfer

4.1.1. Mother ship direct transfer with boom conveyor

The direct transfer method of the mother ship with its own boom conveyor is a sub-barging method using the ship's boom. For a bulk carrier with its own boom, it can transfer the dry bulk cargo to another ship through the boom. This barging form is the most widely used anchorage barging method in Southeast Asian countries and regions [54].

Its advantages are:

- No need to configure floating cranes or professional barging platforms, saving the cost of related auxiliary facilities.
- The efficiency of transfer is basically matched with the unloading capacity of the mother ship, which will not cause waste of barging capacity or unloading capacity of the mother ship.
- It has good flexibility in operation and response to unexpected events.

Its disadvantages are:

- It is affected by sea conditions (especially stormy monsoon) and cannot be operated continuously.
- Due to the limitation of boom outreaching capacity, it takes longer time for the mother ship to transfer the bulk cargo to another ship if the other ship is moored in the wrong place.

4.1.2. Floating crane transfer method

Floating crane transfer method utilizes floating cranes as transfer manners. Floating cranes are generally customized from fixed cranes on deck barges. It is mainly used for large and medium-sized ships without ship booms [55]. Its advantages are as follows.

- The structure of the floating crane is simple and the construction cost is relatively low.
- Two floating cranes can be used for simultaneous transfer operations on both sides of the mother ship to improve transfer efficiency.
- The transfer capacity of floating cranes can be customized according to the unloading capacity of ships, so that the transfer capacity at sea can be better matched with the unloading capacity of ships.

Disadvantages of floating crane transfer method can be: compared with the mother ship with its own boom direct transfer, floating crane transfer operation is less resilient to wind and wave impact.

4.1.3. Barging platform method

Barging platform is a specialized large-scale barging equipment, generally transformed from large bulk carriers or barges, and equipped with ship loading and unloading equipment and belt conveyors on board, with a number of functions such as marine unloading, loading and storage as one. The barging platform facilities are subject to the use of barging facilities and other relevant conditions. The design and construction of the barging platform is customized by considering the efficiency, cost, duration and constraints. The service targets are mainly for large and medium-sized vessels without transfer booms.

The main advantages are:

- Specialized barging equipment can be installed, and the barging capacity is high.
- The barging platform can be transformed from a large bulk carrier and has a high wind and wave resistance.
- The barging platform has the function of storage, so it can load or unload ships without the need of large and small ships berthing at the same time.

Limitations are:

- The barging platform is specialized equipment and the construction cost is relatively high.
- Considering that the area where the barging platform is located and affected by climate and tropical cyclone, the barging platform also needs to consider the problem of storm avoidance.

4.2. Sustainability indicator system for ship-to-ship minerals transfer

There are limited literature available for the sustainability assessment of ship-to-ship transfer [24]. This section analyzes the sustainability of ship-to-ship transfer in three steps: ① to construct an assessment indicator system for the sustainability of ship-to-ship transfer; ② to consult experts to determine the weights of different indicators. ③ to discuss the importance of the indicators and formulate guidelines for sustainable ship-to-ship transfer.

The ship-to-ship transfer sustainability indicator system developed in this report are summarized after reviewing a large amount of literature and inspired by the sustainability indicators of other operations, in which three main aspects of environment, economy and technology are considered, and the specific three-level indicators are shown in the following Table 4.1.

Table 4.1 Ship-to-ship transfer sustainability indicator System

objective Indicator (A)	Secondary indicators (B)	Tertiary indicators (C)
Sustainability indicators for ore transfer units (A)	Environmental Indicators(B1)	Noise(C1)
		Water pollution(C2)
		Carbon Emission(C3)
		Resource consumption(C4)
		Waste generation(C5)
		Marine pollution area (C6)
		Dust control (C7)

		Renewable Energy Utilization (C8)
		Energy saving technology and equipment (C9)
		Water consumption per unit of transshipment (C10)
	Economic indicators(B2)	Annual transfer volume (C11)
		Energy consumption per unit transfer volume (C12)
		Equipment procurement cost (C13)
		Operation and maintenance cost (C14)
		Economic efficiency (C15)
		Uncertainty (C16)
		Equipment replacement rate (C17)
		Environmental investment (C18)
	Technical indicators (B3)	Transit accident rate (C19)
		Equipment reliability (C20)
		Sustainability (C21)
		Technical Feasibility(C22)
		Technical operability(C23)
		Technical Maturity(C24)
		Technological Innovation (C25)
		Contingency Management (C26)

(1) Environmental indicators

A. Noise

The generation of noise may be harmful to staff and creatures in the working environment if the noise level is too high. So the noise is included as one of the environmental indicators. Use environmental noise detection and measurement instruments or automatic environmental noise monitoring instruments. Before and after the measurement of the use of acoustic calibrator to calibrate the measuring instrument deviation of the indicated value shall not be greater than 5dB, otherwise the measurement is invalid.

B. Water pollution

In the process of ship-to-ship transfer, some sewage or waste will be discharged and cause some pollution to the sea, so it will be considered in the sustainable environmental indicators. It is possible to sample the water body in the working area of ship-to-ship transfer and measure the excessive content or harmful substances in the water body.

C. Carbon emission

Emission of gases such as CO2 (complete combustion) and CO (incomplete combustion) are produced mainly during work (in this case, mainly during the operations of engines) due to the combustion of fuel. Excessive carbon emission will make the carbon content in the air too high, producing greenhouse effect and causing certain pollution to the environment. Actual measurement method: A measurement method to estimate carbon emission produced by traditional fossil energy sources, natural gas, etc. By measuring the actual concentration, flow rate of the emitted gases using relevant detection means (gas detector) and using recognized measurement data.

D. Resource consumption

Resource consumption refers to the transfer of cost value between departments and can be traced from the product to the final resources consumed by this product. The inclusion of resource consumption into environmental indicators can reflect the completion of the required work with the most reasonable resource utilization. In one working cycle, resource consumption is the total amount of resource required to complete a ship-to-ship transfer (including the cost of materials, labor, maintenance, transporting machinery to the job site, etc.).

E. Waste generation

Waste generation is the emission of waste gases, liquids and solids which are released into the environment. Waste generation will undoubtedly have a negative impact on the environment, so we have to consider waste generation as an indicator. Solid waste can be measured by multiplying the daily production of solid waste by the number of working days to get the total amount of solid waste generated; liquid waste is measured if there is no reuse of wastewater, then the emissions are equal to the amount generated at work; exhaust gas is measured as the emission rate multiplied by the number of production days and then multiplied by the daily working hours.

F. Sea pollution area

Due to human activities or maritime accidents, harmful substances can be put into the sea causing sea pollution. In the polluted sea, marine life is affected. This makes it an important indicator under the environment. The measurement of sea pollution area usually uses GPS to determine the geographic coordinates of the boundary location points of the sea area to be measured at regular intervals, and then seek the area of the irregular area enclosed by it.

G. Dust control

In each process operation is accompanied by the generation of dust, which is suspended in the air and brings serious pollution to sea. Dust concentration in the work area can be measured using a dust detector or a real-time dust detection system.

H. Utilization of renewable resources

Increasing the utilization rate of renewable resources (such as wind energy, solar energy, etc.) can effectively reduce the pollution to the environment. So the utilization rate of renewable resources is used as one of the environmental indicators. The utilization rate of renewable energy can be determined by dividing the amount of electricity generated from renewable energy (kWh) used for ship-to-ship transfer by the total amount of electricity used for ship-to-ship transfer each year.

I. Energy-saving technologies and equipment

Conservative use of energy is also an important measure to protect the environment. Under the premise of ensuring the completion of the task, energy saving is beneficial for the protection of the environment.

J. Water consumption

The ratio between the total amount of water required to complete the transfer process and the total amount of ore transferred in one cycle. We can read the value of water flow meter installed on the machine and divide the total amount of water consumption in a certain cycle by the total amount of ore transferred to get the specific water consumption per unit of transfer.

(2) Economic indicators

A. Annual operation volume

Taking one year as a cycle, the sum of ore volume transported from a PSV to a port is the annual transfer volume. Generally speaking, the greater the annual operation volume, the higher the efficiency, and vice versa. So it is listed as one of the economic indicators. Measurement method: Record the total amount of ore running in a year.

B. Energy consumption per unit of transit volume

Unit energy consumption is the main indicator reflecting the level of energy consumption and the status of energy saving and consumption reduction, and is an indicator of energy utilization efficiency. In this context, it refers to the degree of energy utilization in the ore transfer system, i.e. the total energy consumption of one operation compared to the total operation volume. The energy consumption per unit of operation reflects the degree of energy utilization in the process of ore transfer, if the degree of utilization is high, it can cost less in terms of energy consumption, and vice versa. For the sake of simple calculation, the energy consumption unit can be calculated by using the electricity (kWh) spent per ton of transfer, i.e., dividing the electricity consumed in a working cycle by the amount of ore transferred (tons) in this cycle to get the energy consumption per unit of transfer.

C. Equipment procurement costs

Equipment procurement costs refer to the costs associated with the purchase of raw material components for equipment, including purchase order costs, management costs for personnel who develop procurement plans, and management costs for procurement personnel. The funds spent on the purchase of equipment during the completion of a project can be added together to get a total amount that is the cost of equipment procurement.

D. Operation and maintenance costs

The main work of the maintenance part includes: 1) monitoring: real-time monitoring of the operation status to detect abnormal operation and resource consumption at any time; 2) troubleshooting: timely handling of any abnormality in the service to avoid the expansion of the problem or even suspension of the service as far as possible. The cost of operation and maintenance is the money consumed in these two parts. You can record the O&M cost during the whole operation period or record the maintenance cost in one year as a unit.

E. Economic efficiency

Economic efficiency is a comparison between cost expenditures and useful production results, i.e. the proportional relationship between gross product and production costs. Economic efficiency is whether the monetary gain is obtained after going to complete a project (or other operation), and whether the gain obtained is proportional to the payment, which makes it necessary to take it into account within the economic indicators. Economic efficiency is more suitable for a year or longer cycle to do a calculation, that is, in a cycle will be obtained in the total amount of money income and then subtracted from the total amount of money paid that is the economic efficiency of a cycle.

F. Uncertainty

Uncertainty refers to the fact that economic investors do not know exactly the outcome of a decision they make in advance. The presence of uncertainty may produce uncertain economic consumption in the work process. Measurement process: Construct or describe the probabilistic process of random variables - Sampling from the constructed probability distribution - Perform multiple simulations to generate the sampling results. After several simulations, the results are estimated unbiased and the random probability solution of the problem is obtained statistically.

G. Equipment renewal rate

Equipment renewal rate is the ratio of the total number of new equipment to the total number of all equipment. It is an indicator which reflects the status of equipment replacement in the work system. The equipment replacement rate is used to reflect the scale and speed of the enterprise equipment replacement. Renewal forecasting: Various equipment life cycle cost forecasting algorithms are analyzed, the main points of which are the "gray system method" and the "trend extrapolation" forecasting algorithms. In a cycle, the number of renewed equipment divided by the total number of equipment in operation is the equipment renewal rate.

H. Environmental protection investment

Environmental protection investment is the general term for all kinds of actions taken by human beings to solve real or potential environmental problems, to coordinate the relationship between human beings and the environment, and to guarantee the sustainable development of economy and society. While meeting the work requirements, the protection of the environment is also indispensable, which necessitates investment in environmental protection, which is part of the economic consumption of completing a project, making environmental investment a small indicator under the economic indicator. Record the total investment in environmental protection in a cycle that is the environmental protection investment.

(3) Technical indicators

A. Transit accident rate

Accident rate is also called "accident frequency", a statistical indicator of the probability of accidents. In a cycle, the number of accidents is divided by the total number of operations is the transit accident rate.

B. Equipment reliability

The ability or possibility of the equipment to perform the specified function without failure in a certain period of time and under certain conditions. The reliability of equipment can be evaluated by reliability, failure rate, and average failure-free interval. The reliability of equipment is closely related to the development of technology. According to the basic rated life of the same batch of equipment, the number of equipment with longer or equal to the rated life divided by the total number of equipment is the equipment reliability.

C. Sustainability

Sustainability refers to the conservation of natural resources as a long-term goal, and economic development as a means to gradually improve human living standards while protecting natural resources from over-exploitation, and ultimately achieving a dynamic balance between the total demand for resources and the quality of life of different generations. Sustainability is a hot topic of discussion, which involves many aspects, but in the final analysis, to achieve sustainability, we need to start from technical means, so it is included as one of the technical indicators. Constructing a system of sustainability indicators - Calculating weights through hierarchical analysis - Analyzing the importance of each indicator according to its weight - Improving relevant measures to achieve sustainability.

D. Technical Feasibility

Technical feasibility means that the technology of the decision and the technology of the decision program cannot break the boundary of the technical resource conditions possessed by the organization or mastered by the personnel concerned. It mainly includes the following aspects: whether the functional objectives can be achieved under the constraints; whether the performance objectives can be achieved using existing technologies; the requirements for the number and quality of developers and whether they can be met; and whether the development can be completed within the specified period.

E. Technical operability

The definition of technical operability should be observable, repeatable, and directly operable; the suggested measurement or operation must be feasible; it can start from both operation and measurement. Research methods: ① Literature research, refer to relevant research literature and research results to find the relevant literature and research status and direction of technical operability. ②Comparative analysis research, statistics on different fields of operational technology and analyze the differences in them for comparative analysis.

F. Technology maturity

Technology maturity refers to the practical degree of industrialization in terms of technology level, process flow, supporting resources and technology life cycle of scientific and technological achievements. The earliest time of technology emergence and technology penetration rate can assess the maturity of a technology.

G. Technological innovation

Technological innovation refers to the innovation of production technology, including the development of new technology, or the application of existing technology to innovation. The number of patents of a technology can be used to assess whether the technology is innovative.

H. Emergency management

Emergency management refers to the process of transit in the prevention of emergencies beforehand, response to the incident, disposal during the incident and recovery after the process, through the establishment of the necessary response mechanism, take a series of necessary measures, the application of science, technology, planning and management and other means to protect public life, health and property security. Emergency management is to be whether a plan for emergency management is made before starting a certain work, and the degree of executability of the plan.

4.3. Case study: Sustainability assessment of ship-to-ship minerals transfer

In the indicator system developed for the sustainability assessment of ship-to-ship transfer, as shown in Table 3.1. ship-to-ship mooring indicator system, there are ten indicators for environment B1, including noise C1, water pollution C2, carbon emission C3, resource consumption C4, waste generation C5, sea area pollution C6, dust control C7, renewable energy utilization C8, energy-saving technology and equipment C9, water consumption per unit of transfer C10. There are eight indicators for economic indicator B2, including annual operation C11, energy consumption per unit of transfer capacity C12, equipment procurement cost C13, operation and maintenance cost C14, economic efficiency C15, uncertainty C16, equipment replacement rate C17, environmental protection investment C18. There are eight indicators for technical indicators B3, including transfer story rate C19, equipment reliability C20, sustainability C21, technical feasibility C22, technical operability C23, technical maturity C24 , technological innovation C25, and emergency management C26.

Calculation of weight for each indicator is the key for the sustainability assessment of ship-to-ship transfer. This is done by scoring the sustainability indicator system with consultation of a group of experts and calculating the weight of each indicator by applying the AHP method.

Firstly, the determination of the weight for each indicator of layer 1 in the sustainability indicator system is carried out. According to the scale of the judgment matrix, the comparison matrix was filled by an expert:

$$A_1 = \begin{bmatrix} \frac{1}{1} & \frac{1}{5} & \frac{1}{5} \\ \frac{5}{1} & \frac{1}{1} & \frac{3}{1} \\ \frac{5}{1} & \frac{1}{3} & \frac{1}{1} \end{bmatrix} \tag{4-1}$$

The next step is to calculate the product of the elements of each row in the matrix. The next step is to calculate its 3rd power root, $\omega_i = \sqrt[3]{M_i}$ which can be obtained from as:

$$\omega_1 = \sqrt[3]{1 \times \frac{1}{5} \times \frac{1}{5}} = 0.341 \tag{4-2}$$

$$\omega_2 = \sqrt[3]{\frac{5}{1} \times \frac{1}{1} \times \frac{3}{1}} = 3.87 \tag{4-3}$$

$$\omega_3 = \sqrt[3]{\frac{5}{1}\times\frac{1}{3}\times\frac{1}{1}} = 1.29 \quad (4-4)$$

$$\sum \omega_i = 5.50 \quad (4-5)$$

$$W = \frac{\omega_i}{\sum \omega_i} \quad (4-6)$$

Therefore the weight matrix is:

$$W_1 = [0.062, 0.703, 0.234]^T \quad (4-7)$$

and

$$A_1 W_1 = [0.249, 1.72, 0.778]^T \quad (4-8)$$

Maximum characteristic root ω_{max}:

$$\omega_{max} = \sum \frac{(A_1 W_1)_i}{n\omega_i} = \frac{0.249}{3\times 0.062} + \frac{1.72}{3\times 0.703} + \frac{0.778}{3\times 0.234} = 3.06 \quad (4-9)$$

Consistency test:

$$C.I. = \frac{\omega_{max} - n}{n-1} = 0.03 \quad (4-10)$$

Consistency ratio:

$$C.R. = \frac{C.I.}{R.I.} = 0.06 < 0.1 \quad (4-11)$$

Therefore, it is considered that the consistency in the comparison judgment matrix is acceptable and the weight vector W is acceptable, if C.R.>0.1,Then the judgment matrix should be modified appropriately.
Therefore, the weights of each sustainability indicator of layer 1 in the indicator system for ship-to-ship transfer is:

$$W_1 = [0.062, 0.703, 0.234]^T \quad (4-12)$$

According to the above steps, the indicator weights under expert 2, 3, 4 and 5 scoring can be obtained as:

$$W_2 = [0.132, 0.336, 0.551]^T \quad (4-13)$$

$$W_3 = [0.333, 0.333, 0.333]^T \quad (4-14)$$

$$W_4 = [0.163, 0.063, 0.774]^T \quad (4-15)$$

$$W_5 = [0.016, 0.084, 0.90]^T \quad (4-16)$$

Then the standard matrix R can be formed as shown below:

$$R = (W_1, W_2, \ldots, W_5) = \begin{bmatrix} 0.062 & 0.132 & 0.333 & 0.163 & 0.016 \\ 0.703 & 0.336 & 0.333 & 0.063 & 0.084 \\ 0.234 & 0.551 & 0.333 & 0.774 & 0.90 \end{bmatrix} \quad (4-17)$$

$$s_1=\sum_{k=2}^{2}\omega_{k1}+\frac{1}{2}\omega_{31}=\omega_{21}+\frac{1}{2}\omega_{31}=0.703+\frac{1}{2}\times 0.234=0.82 \quad (4-18)$$

Similarly, we can find: $s_2 = 0.612, s_3 = 0.50, s_4 = 0.45, s_5 = 0.534$

$$e_{12}=\frac{1+s_1+s_2}{1+s_1+s_2+|s_1-s_2|}=\frac{1+0.82+0.612}{1+0.82+0.612+0.208}=0.921 \quad (4-19)$$

Similarly, we can find: $e_{13} = 0.879, e_{14} = 0.860, e_{15} = 0.892, e_{23} = 0.95, e_{24} = 0.927, e_{25} = 0.965, e_{34} = 0975, e_{35} = 0.984, e_{45} = 0.959$

Then the grey correlation matrix E of the expert group is:

$$E=\begin{bmatrix}1 & 0.921 & 0.879 & 0.860 & 0.892\\ & 1 & 0.950 & 0.927 & 0.965\\ & & 1 & 0.975 & 0.984\\ & & & 1 & 0.959\\ & & & & 1\end{bmatrix} \quad (4-20)$$

Determine the queue value （$\theta = 0.92$） can obtain 3 categories：｛（1）（2）（3，4，5）｝。

The inter-class weights can be obtained from the formula：

$$\beta_1=\frac{\varphi_1^2}{\sum_{k=1}^{3}\varphi_k^2}=\frac{1}{11} \quad (4-21)$$

Similarly, we can find：$\beta_2 = \frac{1}{11}, \beta_3 = \frac{9}{11}$

From the formula, we can calculate the f_{11}:

$$f_{11}=\omega_{11}\Big/\sum_{j=1}^{5}\omega_{1j}=\frac{0.062}{0.062+0.132+0.333+0.163+0.016}=0.087 \quad (4-22)$$

Similarly, we can find：$f_{21} = 0.463, f_{31} = 0.083$

The information entropy of the first expert can be obtained from formula:

$$H(1)=-\frac{1}{\ln 5}\sum_{i=1}^{n}f_{i1}\ln f_{i1}=0.483 \quad (4-23)$$

The same equations (4-10) and (4-11) can be used to find the information entropy of the 2nd, 3rd, 4th and 5th experts as, H(2)=0.601,H(3)=0.584,H(4)=0.513,H(5)=0.380

That is, the information entropy of each expert is $H=[0.483, 0.601, 0.584, 0.513, 0.380]$

The intra-class weights of the first class of experts can calculated as:

$$\alpha_{11}=\frac{1-H_1(1)}{\sum_{j=1}^{1}[1-H_1(j)]}=1 \quad (4-24)$$

Similarly, we can find：$\alpha_{21} = 1, \alpha_{31} = 0.273, \alpha_{32} = 0.32, \alpha_{33} = 0.407$ ，$\alpha_{kj} = [1,1,0.273,0.32,0.407]$

From the formula we can find:

$$\lambda_1 = \beta_1 \alpha_{11} = \frac{1}{11} = 0.091 \quad (4-25)$$

Similarly, we can find: $\lambda_2 = 0.091$, $\lambda_3 = 0.223$, $\lambda_4 = 0.262$, $\lambda_5 = 0.333$

That is, the total weight vector position of 5 experts is

$$\psi = (0.091, 0.091, 0.223, 0.262, 0.333) \quad (4-26)$$

The weight vector of secondary indicators can be derived as:

$$P = R\psi^T = [0.142, 0.216, 0.642]^T \quad (4-27)$$

Using the same method, the weight vectors of each indicator of layer 2 can be obtained as shown in the following tables.

Table 4.2 Environmental indicator weights

Noise	Water pollution	Carbon emission	Resource consumption	Waste Generation	Marine pollution area	Dust control	Renewable energy utilization	Energy saving technology and equipment	Water consumption
0.221	0.124	0.172	0.101	0.069	0.070	0.062	0.051	0.045	0.085

Table 4.3 Economic indicators weights

Annual operating volume	Water consumption per unit of transfer volume	Equipment purchase cost	Operation and maintenance costs	Economic efficiency	Uncertainty	Equipment replacement rate	Environmental Investment
0.271	0.145	0.056	0.141	0.150	0.10	0.051	0.086

Table 4.4 Technical indicator weights

Transit accident rate	Equipment Reliability	Sustainability	Technical feasibility	Technical operability	Technology Maturity	Technology Innovation	Emergency Management
0.0482	0.134	0.126	0.251	0.156	0.130	0.055	0.10

Combined weights of each indicator for the ship-to-ship transfer operation of the deep-sea mining.

Based on the above calculations the weights of the indicators are tabulated as follows:

Table 4.5 Combined weight of each indicator

Indicator Name	Indicator weights	Combined weights
Environmental indicators	0.142	
Noise	0.221	0.0314
Water Pollution	0.124	0.0176
Carbon Emission	0.172	0.0244
Resource consumption	0.101	0.0143
Waste generation	0.069	0.00980
Marine pollution area	0.070	0.00994

Dust control	0.062	0.00880
Renewable Energy Utilization	0.051	0.00724
Energy saving technology and equipment	0.045	0.00640
Water consumption per unit transfer volume	0.085	0.0121

Economic Indicators	0.216	
Annual transfer volume	0.271	0.0585
Energy consumption per unit transfer volume	0.145	0.0313
Equipment purchase cost	0.056	0.0121
Operation and maintenance costs	0.141	0.0304
Economic efficiency	0.150	0.0324
Uncertainty	0.10	0.0216
Equipment replacement rate	0.051	0.0110
Environmental Investment	0.086	0.0186

Technical indicators	0.642	
Transit accident rate	0.0482	0.0309
Equipment Reliability	0.134	0.086
Sustainability	0.126	0.0809
Technical feasibility	0.251	0.161
Technical operability	0.156	0.100
Technology Maturity	0.130	0.0835
Technology Innovation	0.055	0.0353
Emergency Management	0.10	0.0642

The theoretical basis of AHP method is to divide the complex problem into multiple levels according to the control relationship, and each level contains various factors that are interrelated with each other. On this basis, a comparison method is used on a case-by-case basis to quantify the relevant importance among the factors and finally determine the relative importance of each factor.

Therefore, after establishing the sustainability indicators of ship-to-ship transfer, the weights of each indicator are calculated by hierarchical analysis, and then the indicators with the greatest impact on the sustainability of ship-to-ship transfer are analyzed, but the initial data of each indicator, i.e., the relative importance of each indicator, are required before the calculation.

The calculation of weights is the key to achieve sustainability assessment of ship-to-ship transfer, by scoring the sustainability indicator system by each expert and calculating the weights of each indicator. From Table 4-5 it is found that technical indicator (weight=0.642) is more important than environmental indicator (weight=0.142) and economic indicator (weight=0.216). This means that technical development is still the main concern of ship-to-ship transfer for deep-sea mining. Within the technical indicator, the technical feasibility, technical operability and equipment reliability are three most important indicators. It is considered that due to the harsh working environment of ship-to-ship transfer in oceans, the equipment must be feasible enough to meet different working conditions, and the equipment must be easy to operate, as well as have high reliability.

4.4. Conclusions

In this chapter technical solutions for ship-to-ship transfer of mined minerals from PSVs to MTVs were analyzed and sustainability indicators from environmental, economic and technical aspects are presented and discussed. In addition, the weights of these indicators were calculated by applying the AHP method. The weighting table of the sustainability indicators of the ship-to-ship transfer shows that the top five indicators that have a greater impact on sustainability are technical feasibility, technical operability, equipment reliability, technical maturity and sustainability, with a weight of 0.161, 0.100, 0.086, 0.0835 and 0.0809, respectively. Therefore, to improve the sustainability of the ship-to-ship transfer one should start from these five aspects of technical feasibility, technical operability, equipment reliability, technical maturity and sustainability, and strengthen the innovation of technology, assisted by environmental and Economic Factors, so that more sustainable ship-to-ship transfer solutions can be achieved.

5. Sustainability of shipping deep sea minerals

5.1. Overview of shipping

After the marine minerals are transferred from production support vessels to minerals transport vessels, the main part of maritime transport will be carried out which is to bring the mined minerals from deep-sea mining sites to ports for further processing of the minerals. For the maritime transport for deep-sea mining, limited research of economic modelling of transport cost has been done. Therefore, this chapter aims to develop an economic model for the maritime transport for deep-sea mining, with considerations of environmental impact and societal influence. A case study for shipping marine minerals from a deep-sea mining site in CCZ to China/Japan/Netherlands will be present to provide some insights into the proposed economic model.

Deep-sea mining is an emerging industry that targets mineral-rich deposits on the deep ocean floors. These deposits often contain valuable metals such as copper, nickel, and cobalt, which are in high demand for advanced technologies like electric batteries and renewable energy hardware. However, the mining of these deep-sea resources faces significant environment and economic challenges. Deep-sea mining is considered to be a kind of capital-intensive economic activities. For a typical deep-sea mining project, the capital expenditure can be tens of billions of dollars. for the purchase of production support vessels (PSVs), miners, construction costs of vertical lifting systems, chartering of minerals transport vessels (MTVs) and so on. The operation costs include the operations of MTVs, PSVs, maintenance and operation of mineral collection and vertical lifting systems, onshore mineral processing plant operations, and so on. Frimanslund [56] employed probabilistic cost estimation and Monte Carlo simulation using different sets of random variables to analyze the costs based on the commercial plan of Nautilus Minerals, providing an overview of average total development costs and operating costs at a macro level. Hong et al. [57] studied the economic feasibility of mining systems by dividing costs into capital cost (CAPEX) and operation cost (OPEX) and concluded that schemes involving hydraulic lifting and large-scale collectors are more economically valuable. In a report published in 2008 [58], the International Seabed Authority (ISA) provided an explanation of the proportion of CAPEX and OPEX in deep-sea mining projects and offered a glimpse into future developments. Duijnstee [59] conducted economic evaluation and sensitivity analysis, considering uncertainty factors in the economic feasibility of large sulphide deposits on the seafloor, including geological, mining, transportation, production, and shipping aspects. Sharma [24] presented cost breakdowns for different components of deep-sea mining projects, namely the mining system, transportation system, and production system, and concluded with an assessment of efficiency and environmental factors, providing a case study on investment return in a mining area. Lesage et al. [23] proposed an economic modular framework for deep-sea sulphide mining, estimating economic costs based on literature values for mining areas in the Mid-Atlantic Ridge, aiming to provide insights for development studies. Van Nijen et al. [60] analyzed price predictions for mineral commodities and further analyzed the Internal Rate of Return (IRR) for collecting polymetallic nodules from the Clarion-Clipperton Fracture Zone, demonstrating that deep-sea mining is more competitive than land-based mining. Furuichi et al.[61], from the perspective of operators, considers that shipping costs mainly include capital cost, special route fees, crew costs, maintenance costs, insurance costs, fuel costs, and port dues, among which special route fees, crew costs, maintenance costs, and insurance costs belong to the operating cost category.

For the economic analysis of deep-sea mining, the economic analysis of shipping transport is an important part. Firstly, regarding the route planning for deep sea minerals transport vessels, Agarwal et al. [54]proposed a route planning from the Clarion-Clipperton Zone to China for MTVs, including the selection of onshore ports, ocean routes, vessel types, and operational modes, conducting a simple planning study for mineral transportation routes of MTVs. Ma et al. [62] introduced a comprehensive multi-criteria decision-making method called the Fuzzy-ANN-ANP method for deep-sea mining transportation route planning, considering the multi-objective and uncertainty aspects of transportation plans. Due to the limited availability of specific literature on deep-sea mining route planning, attention should also be given to relevant literature on route planning. Zhang [63] conducted an upgrade study on container vessels for the China to Gulf of Mexico route, performing cost-benefit analysis of the route and drawing research conclusions on upgrading container vessels. Meng et al. [64] conducted a literature review on Arctic route planning and identified feasibility issues concerning the Arctic route. Current research on the economic analysis of deep-sea mining projects, the operation costs for minerals transport vessels have not been studied in details. Most studies uses estimates of CAPEX and/or OPEX based on relevant literature or companies' reports. However, since fuel price can experience large variation, a detailed economic model is required in order to calculate the shipping cost at an accurate level.

5.2. Sustainability indicator system for shipping

From environmental dimension, the burgeoning field of deep-sea mining shipping is intertwined with significant environmental challenges. Prioritizing environmental sustainability is imperative to ensure the long-term health of our oceans. Deep-sea mining operations should be guided by rigorous environmental impact assessments to evaluate potential ecological consequences. Preservation of unique and sensitive deep-sea ecosystems, such as hydrothermal vents and cold-water coral reefs, is critical. Implementing robust waste management practices to prevent harmful chemical releases and tailings disposal is essential. Collaborative efforts on an international scale are necessary to establish strict regulations that safeguard marine biodiversity and minimize ecosystem disruption, enabling deep-sea mining to coexist with the delicate balance of our oceans.

From economic and social dimensions, deep-sea mining shipping has the potential to revolutionize both the economy and society by unlocking valuable mineral resources. Economically, it can diversify resource supply chains, stimulate job creation, and drive technological innovation. However, equitable distribution of economic benefits and minimizing negative social impacts are paramount. Transparency in revenue sharing, community engagement, and sustainable development in regions hosting mining activities are crucial. Empowering local communities through education, job training, and capacity-building programs can ensure that the benefits of deep-sea mining are shared broadly, while avoiding social inequalities and negative societal disruptions.

From safety dimension, the extreme conditions of the deep sea pose formidable challenges to safety in mining shipping operations. Ensuring the safety of personnel, vessels, and equipment is non-negotiable. Rigorous safety protocols, stringent training, and well-prepared emergency response plans are essential to address the unique risks of working in deep-sea environments. Developing advanced technologies for remotely operated vehicles (ROVs), underwater communication systems, and real-time monitoring can enhance safety measures. Cross-industry collaboration and information-sharing are pivotal in continuously improving safety standards, preventing accidents, and responding effectively to emergencies.

From technological dimension, technology is the linchpin of successful deep-sea mining shipping operations. Innovations in robotics, automation, and data analytics play a pivotal role in precise mineral extraction. Advanced sensors and imaging technologies facilitate real-time monitoring and data collection, enabling informed decision-making. Sustainable energy solutions, such as utilizing renewable sources for power, are vital to minimize the environmental impact. Research and development efforts should be ongoing to refine mining techniques, enhance resource recovery efficiency, and reduce the carbon footprint. Collaborative platforms that promote technological advancements and knowledge sharing ensure that the industry remains at the forefront of innovation while upholding environmental and safety standards.

Within the intricate tapestry of deep-sea mining shipping, the economic dimension emerges as a linchpin, holding the key to the sustainability of this complex endeavor. The economic aspects encompass not only the financial prosperity that can be unlocked through mineral extraction but also the potential to drive responsible practices across environmental, social, safety, and technological spheres. Economic viability ensures ongoing investments in cutting-edge technologies, safety protocols, and sustainable operations. It paves the way for equitable distribution of benefits among stakeholders, empowering local communities and fostering societal advancement. As the engine that fuels innovation, economic considerations can incentivize the development of efficient extraction techniques, minimization of environmental impact, and the creation of resilient frameworks for collaborative international governance. By anchoring sustainability in the economic dimension, deep-sea mining shipping endeavors can chart a course toward harmonizing societal progress with environmental stewardship, redefining the future of maritime ventures on a global scale.

Cargo liquefaction is a major concern for the safety of shipping deep sea minerals [65]. Cargo liquefaction is a phenomenon that bulk materials inside cargo holders may move like liquid which can cause a bulk carrier to list or capsize [66]. The reason for cargo liquefaction is that with cycling loading due to vessel motion and engine vibration, fine particles form an easy-to-slide interface. Bulk materials above such interface would easily move to one side of the bulk carrier and cause the ship to list. To control cargo liquefaction, the International Maritime Solid Bulk Cargoes (IMSBC) by IMO regulate the Transportable Moisture Limit (TML) when bulk materials are loaded and carried [67]. Up to date, specific regulations on the TML of deep sea minerals have not been made in the IMSBC Code. Knowledge gap exists in the potentiality of liquefaction of deep sea minerals during shipping. Research on flowability of deep sea minerals is needed to fill in this knowledge gap.

Table 5.1. Shipping sustainability indicator system

Dimension	Criteria	Indicator	Unit
Environment	Impact on environment*	emissions of GHG	Tonnes of GHG equivalent/year

		Noise	db
		Extent of marine habitat positively/negatively impacted	Yes/no. if yes, specify
		Technologies applied to reduce noise, air pollutions	No. and type of technologies No./year
	Level of energy consumption*	Energy consumption	Tonnes of oil equivalent/year
		Energy demand met by green energy	% of total primary energy supply
	waste management*	Seafarers' waste generated and recycled	Tonnes of waste generated and recycled /year
		Wastewater generated and reused	Tonnes of wastewater generated and reused /year
		Ballast water recycled	Tonnes of ballast water recycled /year
		Technology available for solid waste, wastewater and ballast water treatment	Yes/no. if yes, specify
		Hazardous waste management guidelines and measures to handle hazardous substances	Yes/no. if yes, specify
Economic	Economic benefits*	Total revenue generated by shipping work	Million $ /year
	Economic viability	Gross value added*	Million $ /year
		Production of shipping	Tonnes of minerals shipped /year
		Specific investments in ships	Million $ /year
		Turnover*	Million $ /year
	costs	Average personnel costs	x1000 $/year
		Maintenance costs	x1000 $/year
		Charter fee	x1000 $/year

Social	employment	Direct and indirect jobs	No. of direct and indirect jobs x1000 persons/year
	Employment conditions	Average wage of employees*	$/year
		Presence and activeness of labour unions in the company*	Yes/no. if yes, specify
		Informal employment*	% informal employment of total employment
		Professional training	Hours of professional training /year
	Health management	Frequency of auditing by external health experts	No. of audits by external health experts /year
		Time of employees expose to hazardous substances	Hours of employees expose to hazardous substances during work
		Existence of policies and measures to combat occupational diseases and accidents	Yes/no. if yes, specify
Safety	Safety management	Accidents occurred during work	No. of accidents occurred during work /year
		Frequency of auditing by external safety experts	No. of audits by external safety experts /year
		Emergence plans and measures when accidents occur	Yes/no. if yes, specify
	Cargo liquefaction	The possibility of liquefaction for deep sea minerals during shipping	%
	Safety related hardware	Sufficient safety related hardware (helmet, shoes etc.) on site	No. of safety hardware per person

		Hazard detection system (camera, microphone, fire detector)	No. of hazard detection system per terminal
Technology	Equipment reliability	Time of onboard machines malfunction	Hours of unloading equipment malfunction /year
		Maintenance time	Hours of maintenance for shipping equipment /year
	Technology advancement	Whether the shipping equipment and technical solutions are out of date	Yes/no. if yes, specify
	KUP	Knowledge ,Understanding and Proficiency of the vessel's crew during the entire operation that will make a difference	Yes/no. if yes, specify
	Energy efficiency	The efficiency of energy system used in ships	%
		Measures taken to increase energy efficiency	Yes/no. if yes, specify

Note: criteria and/or indicators marked with * are adopted from [68].

5.3. Economic model of shipping deep sea minerals

5.3.1. Model framework

In this section, we will elaborate on the framework of the proposed deep sea minerals shipping cost model. Previous literature mainly divided shipping costs into two categories: capital cost (CAPEX) and operation cost (OPEX). In this section, we will provide a detailed explanation of the elements of CAPEX and OPEX for the proposed economic model. Table 5.2 shows the general elements of CAPEX and OPEX, as well as inclusion/exclusion of the element in the proposed economic model [56].

In our study, the rationale for employing charter costs as a central metric is twofold. Firstly, fluid dynamics of minerals during transport is indeterminate and depends on type. Given the absence of precedents in designing special vessels for theses minerals, the preemptive construction of dedicated vessels becomes economically unviable. Secondly, considering the significant initial costs of maritime shipping for PSVs, it is crucial to focus on cost-effective approaches. Mitigating the substantial expenditures related to the MTV segment takes precedence. It's important to note that while deep-sea mining projects are in the feasibility analysis stage, bulk carrier mineral transportation benefits from a well-established technological foundation. Consequently, the fluid dynamic of mineral will constitute the principal trajectory of our forthcoming investigational phase. Therefore, the charter type is to undertake an economic analysis to ascertain the additional value of transportation [61].

As an important part of the economic study for shipping deep sea minerals, market public data is used as much as possible to ensure the referentiality, credibility, and feasibility of the research results [63]. However, contents of contracts of chartering are complex and private so whether crew cost, maintenance cost and insurance cost are included in charter cost is unknown. Therefore, as shown in Table 5.2, the crew cost maintenance cost and insurance cost are included in the proposed economic model as part of charter fee.

Table 5.2. Components of economic modelling

Category of cost	Element	Inclusion/exclusion in the model
CAPEX	Charter cost	included
	Buying ship cost	excluded
OPEX	Handling cost	excluded
	Crew cost	included in charter fee
	Maintenance cost	included in charter fee
	Insurance cost	included in charter fee
	Fuel cost	included
	Port charge	included

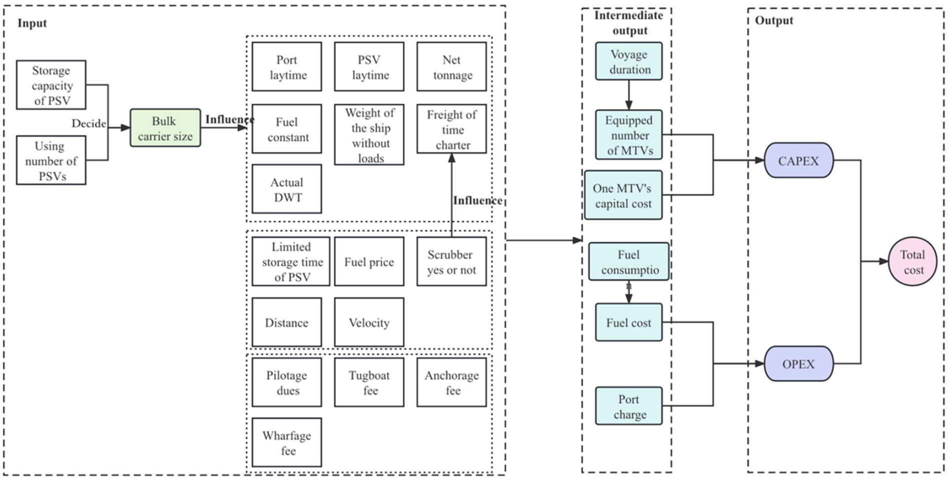

Fig 5.1. Framework for shipping economic model

Fig 5.1 illustrates the model framework for calculating the shipping cost of deep-sea mining. It mainly consists of three parts: input, intermediate output, and output. Firstly, the input part includes "storage capacity of PSV" and " number of PSVs," which jointly determine the selection of bulk carrier size, highlighted by the green colour. The bulk carrier size is the most significant influencing factor, which affects many specific inputs, and the "freight of time charter" is further affected by the scrubber equipment. Secondly, the intermediate output is the result produced by the input during the calculation process, which directly affects the final total cost result. Finally, based on the output part, the maritime transport cost model can be formulated as follows:

$$TC = C_{capex} + C_{opex} \quad (5-1)$$

in which TC refers to the total cost of deep sea minerals transport, C_{capex} represents the capital cost (CAPEX), while C_{opex} represents the operation costs (OPEX).
The detailed explanation of each cost is as follows.

5.3.2. CAPEX

The capital cost (CAPEX) includes loan interest, taxes, and depreciation, also known as ship acquisition cost. The ship's loan situation, depreciation rate, and other related information are internal data of the shipowner. Specific cost calculations require manual input of relevant data parameters.[69] However, to ensure the reference value of results, ship capital cost can be transformed into variable cost through time or bareboat chartering. The capital cost of time charter is equal to the ship time charter cost. Since the current market generally leases ships in the form of time charter, our economic model considers the deployment of time charter ships on the route.
In the C_{capex}, the most critical element is the number of MTVs which needs to be considered for the maritime transport. And one MTV’s capital cost needs to be multiplied by the number of MTVs to obtain the transport route capital cost. In the proposed model, the MTV transport route capital cost can be calculated as:

$$C_{capex} = N_{MTV} \times C_{occ} \quad (5-2)$$

where N_{MTV} is the number of MTVs, C_{occ} is one MTV’s capital cost.

To avoid the situation where the PSV must stop operation due to waiting for the MTV while storage cabin is fully loaded, the limitation of storage time of the PSV must be determined. This means that at least one MTV must arrive at the PSV to transfer the ore within the limited storage time of the PSV. Therefore, the number of MTVs required for the deep-sea mining project can be calculated by dividing the voyage duration by the limited storage time of the PSV, rounding up, and adding one. The number of MTVs for the shipping route can be calculated as follows:

$$N_{MTV} = \left\lceil \frac{T_v}{T_{ltPSV}} \right\rceil + 1 \quad (5-3)$$

T_v is the voyage duration, T_{ltPSV} is stand for the limited storage time of PSV.

The ship time charter cost is equal to the product of charting periods and freight of time charter (paying to chartering per day), so one MTV’s capital cost is:

$$C_{occ} = T_v \times F_{TC} \quad (5-4)$$

in which F_{TC} is the freight of time charter.

The voyage duration is composed of three parts: round-trip sailing time, port laytime, and laytime in the mining area with the PSV. In the case of multiple PSVs, the transport time between PSVs is negligible compared to the total sailing time and therefore ignored in this study. The calculation for the voyage duration is as follows:

$$T_v = \frac{d}{v \times 24} \times 2\ voyages + T_{pl} + T_{PSVl} \qquad (5-5)$$

where d is the distance of mineral area to port, v is the velocity of MTV, T_{pl} is the port laytime, T_{PSVl} stands for PSV laytime.

5.3.3. OPEX

The operation cost refers to the expenses incurred by a ship for a specific voyage, which includes fuel cost, port and canal fees, and handling costs. The handling costs mainly depend on the port handling rates and whether there is a handling contract signed with the corresponding port. In addition, some charter contracts may also include handling costs, and the specific situation needs to be determined based on the commercial contract or the internal price list of the port. Therefore, the operating cost model established in this paper refers to the one built by Zhang [63] and does not consider handling costs. The operation costs mainly include fuel cost and port charges, multiplied by the number of MTVs needed for the deep-sea mining project's voyage:

$$C_{opex} = (C_{fuel} + C_{pc}) \times N_{MTV} \qquad (5-6)$$

where C_{fuel} stands for fuel cost, and C_{pc} is port charge.

A. Fuel cost

The fuel cost refers to the sum of all fuel expenses incurred by the vessel during voyage, which is the main component of operation costs. When establishing a fuel cost model, the key point is to establish a formula for the vessel's fuel consumption. Velocity and actual DWT are two important factors which determine the vessel's fuel consumption. According to Xia et al. [70]the fuel consumption per nautical mile is used as the fuel consumption unit, and the influence of vessel velocity and actual DWT on fuel consumption is comprehensively considered. Based on Xia et al.[70], the fuel consumption can be calculated as follows:

$$\gamma = \beta v^3 (\omega + \varphi)^{\frac{2}{3}} \qquad (5-7)$$

where γ is the fuel consumption, β is the fuel constant which is detailed value depends on the bulk carrier size, ω is the weight of the ship without loads, tonnage, and φ is the actual DWT (Deadweight tonnage).

From Clarkson website[71], the corresponding fuel consumption rate at the optimal velocity of a vessel can be found. Based on the above Formula (5-7), the fuel consumption per unit time for different bulk carriers of different types can be estimated at different velocities and different loads.

Since the load of the MTVs will change during the round trip between the port and the mining area, the entire voyage is divided into two segments: one section from the port to the mining area and one section from the mining area back to the port. During the segment from the port to the mining area, the vessel is empty, $\varphi = 0$, and the fuel consumption rate is represented by γ_1:

$$\gamma_1 = \beta v^3 (\omega)^{\frac{2}{3}} \quad (5-8)$$

$\gamma_1$stand for the fuel consumption of the ship without load, when the route is from the port to the mining area, so the vessel is empty ($\varphi = 0$).

During the segment from the mining area back to the port, the vessel is loaded, $\varphi = \varphi_{PSV} * N_{PSV}$, and the fuel consumption rate is represented by γ_2:

$$\gamma_2 = \beta v^3 (\omega + \varphi_{PSV} * N_{PSV})^{\frac{2}{3}} \quad (5-9)$$

γ_2 is the fuel consumption of the ship with load, besides, φ_{PSV} is the storage capacity of PSV and N_{PSV} is the number of PSVs that the MTV visits during one trip.

On October 27th, 2016, the International Maritime Organization (IMO) officially announced that the 70th session of the Labor Costs Protection Committee had passed a resolution to enforce a global sulphur emission limit of 0.5% m/m for marine fuels from 2020[72]. In February 2018, the IMO confirmed that the global sulphur emission limit of 0.5% for marine fuels would not be changed from 2020 onwards [73]. On April 13, 2018, the IMO approved an amendment that requires all ships without installed sulphur scrubber systems to be prohibited from carrying fuel oil with sulphur content exceeding the 0.5% m/m limit after the global sulphur limit regulation comes into force in 2020. Therefore, this paper considers the way to achieve sulphur emissions as follows:

①Using very-low-sulphur fuel oil (VLSFO) which sulphur emission limit of 0.5% m/m, so the fuel cost can be calculated as:

$$C_{fuel} = \frac{d}{v} \times F_v \times (\gamma_1 + \gamma_2) \quad (5-10)$$

where F_v is the price of VLSFO.

②Installing a desulfurization equipment, scrubber, so the fuel cost can be calculated as:

$$C_{fuel} = \frac{d}{v} \times F_H \times (\gamma_1 + \gamma_2) \quad (5-11)$$

where F_H is the price of HSFO 380cst.

B. Port charges

Port charges refer to the fees charged by each port for providing services such as pilotage, towing, and anchorage, which may vary depending on the port. In this paper, the calculation model assumes proposed by Zhang[1],, which calculates port charge based on pilotage fees, tugboat fees, anchorage fees, and wharfage fees. That is, port dues are charged by multiplying the corresponding fee rates by the parameter units of the corresponding ships. Therefore, the port charge calculation model is:

$$C_{pc} = F_1 \times x \times 2\ times + F_2 + F_3 \times x \times T_{pl} + F_4 \times \varphi \times 2\ times \quad (5-12)$$

where F_1 is the pilotage fee, F_2 is the tugboat fee, F_3 is the anchorage fee, and F_4 is the wharfage fee, x is net tonnage about the ship, T_{pl} is the port laytime, and φ is the actual DWT.

5.4. Case study: economic analysis of shipping deep sea minerals from CCZ to CHina/Japan/Netherlands

Within this segment, the analysis employs distinct transport scenarios, notably centered on the transportation route spanning from the Clarion-Clipperton Zone (CCZ) situated in the Pacific Ocean to ports located in China, Japan, and Netherlands. These case studies serve the purpose of elucidating the cost estimation intricacies pertinent to marine mineral extraction and transportation.

5.4.1. Case selection

The main exploration contracts for polymetallic nodules in the international seabed is in the CCZ area in the eastern Pacific, at the longitude and latitude of 154°52.5′W and 11°7.5′N respectively. Therefore, the deep-sea mining route in this case is mainly based on the CCZ area in the eastern Pacific. As shown in Fig 5.2, seventeen of the ISA contracts are for polymetallic nodules in the CCZ [74]. The colors red, green, and yellow symbolize distinct mineral resources. Within this context, the CCZ region is associated with manganese nodules and stands as the locale with the highest number of exploration contracts issued by the ISA. A total of 18 nations or regions are actively engaged in exploration and exploitation endeavors within this area.

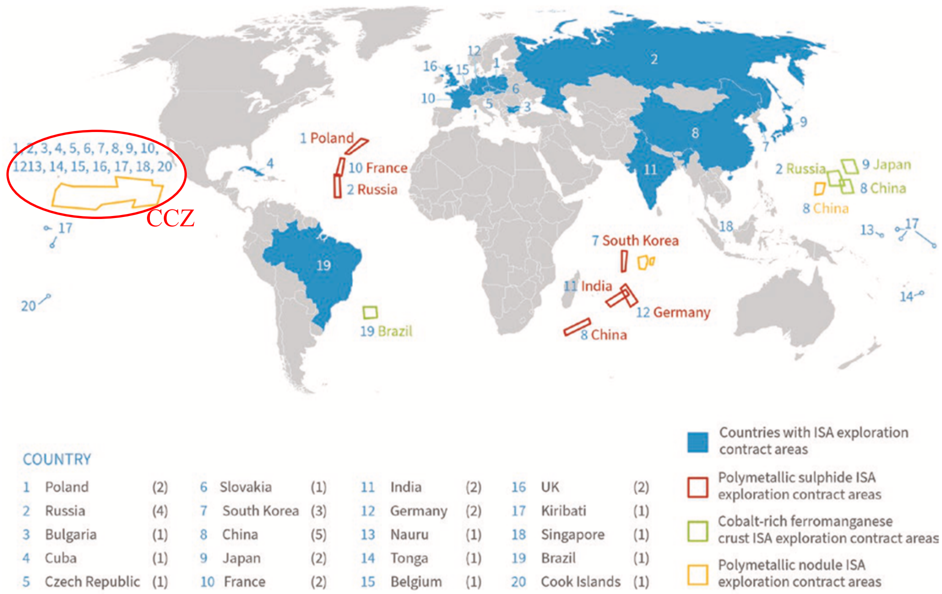

Fig 5.2. International exploration contracts from ISA. Source of image from [75]

Table 5.3. Maritime mineral import volumes in the world. Data from [76]

Country	2015	2016	2017	2018	2019	2020	2021	2022
China	939.1	1007.5	1057.8	1047.7	1047.4	1145.6	1107.4	1092.1
Japan	131.0	130.0	126.5	123.9	119.6	99.4	113.1	104.2
Korea	73.3	71.7	72.4	73.3	74.7	70.4	74.1	66.4
Germany	42.0	41.3	42.3	41.2	39.1	33.5	39.5	35.4
Netherlands	9.7	9.8	9.1	10.1	9.4	9.4	9.7	9.9

Table 5.3 presents the maritime import quantities of mineral for key countries involved in mineral extraction within the CCZ. Notably, China stands out as the largest importer of mineral,

both within Asia and globally, followed by Japan. In contrast, European countries, including Germany, exhibit lower overall mineral import volumes. Despite this, Germany is notably engaged in deep-sea mining exploration activities on a global scale.

Table 5.4. Ore input at the top ports in Asian and European Data mainly from [77]

Main mineral input port	Route distance (mile)	Limited DWT	Limited ship draft/length/width (m)	Remarks
Caofeidian port (CN)	5000	403880	25/362/65	The one of largest mineral receiving ports in China has 100.5 (2021) million tons imports.
Ningbo-Zhoushan port (CN)	4700	403880	23/368/65	Ningbo-Zhoushan port is a new deep-water port mainly engaged in sea going transshipments of dry bulk and oil cargoes.
Nagoya port (JP)	4000	327127	12.6/366/60	Its main imports include mineral, and nonmetallic minerals which is one of the important mineral ports.
Kashima port (JP)	3750	300000	19/340/60	It relates to an extensive port industrial zone, especially petrochemical and steel plants.
Busan port (KR)	4750	140000	15/350/61.5	The largest in South Korea, and receives shipments of cement, oil, timber, iron and general cargo, also is a major industrial center.
Pohang port (KR)	4800	250000	19.5/345/55	Main imports include mineral, coal and petroleum.
Rotterdam port (NL)	9200 (Panama) 13350 (Cape)	399821	23.6/400/65	It is the crucial link in the mineral supply chain for the steel industry in Germany, Austria and the Netherlands and 50 percent of all mineral throughput in Northwest Europe takes place.
Hamburg port (DE)	9500 (Panama) 13650 (Cape)	232606	15/400/62	The main dry bulk port of Germany and has received the most of grain, minerals and coal.

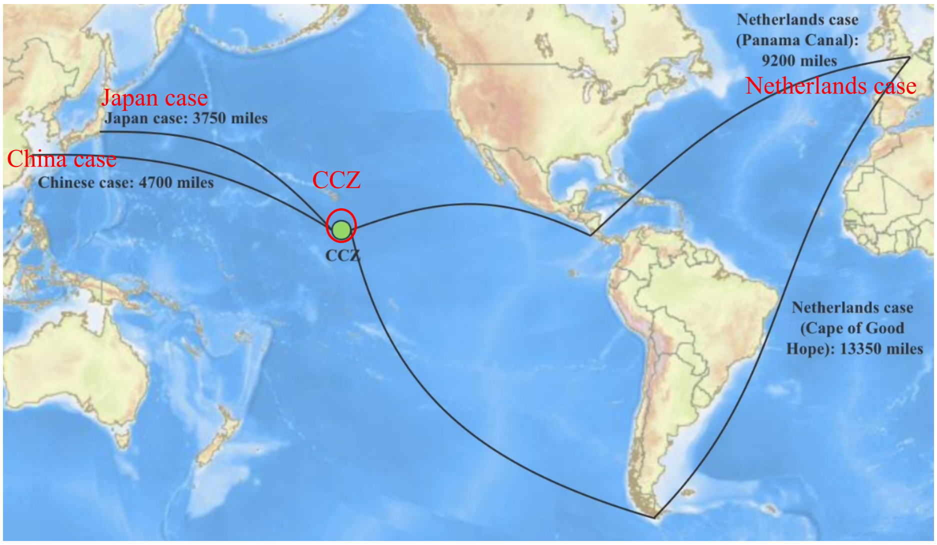

Fig 5.3. Shipping routes from mining area CCZ to ports in case study

Based on the selection of Asian and European countries, this case study designates the anchoring ports for investigation. By meticulously compiling data, we have identified key mineral import harbors in various countries, presenting details such as distances from mining regions to ports and harbor constraints, as shown in Table 5.3.

Within the Asian context, the Ningbo-Zhoushan Port in China (CN) emerges as a favorable choice, characterized by its optimal proximity and favorable conditions for loading, unloading, and berthing. For Japan (JP), the Kashima Port is chosen as the destination port, primarily due to its central position within Japan's port network. Turning to Europe, leveraging the route data from Clarksons and official information from the Port of Rotterdam, Rotterdam stands out as a pivotal mineral import harbor, serving both the Netherlands (NL) and Germany (DE). However, when considering the shipping route from the west coast of the Americas to Europe, it becomes evident that the transit capacity of the Panama Canal plays a pivotal role. As a result, two distinct routes are under contemplation. The first route involves traversing the Panama Canal, while the second circumvents the Cape of Good Hope. These two routes entail differing voyage distances due to the varying constraints imposed by their respective navigation pathways. ports shows the deep-sea mining routes in our cases.

From the CCZ, two reference routes are considered: one involving China and Japan for routes to Asia from the west coast of the Americas, and another with varying distances for European routes from the west coast of the Americas. In the forthcoming research, our primary focus will revolve around a comprehensive analysis of the Ningbo-Zhoushan Port, while the Kashima Port and Rotterdam Port will serve as supplementary comparative cases, thereby enriching our study through contrastive exploration.

5.4.2. Variable assumption

The selection of the ship size will be assumed under the maximum ship size restriction at case Ports, and the distance of the shipping route as shown in the

Table 5.5, it will be used as a parameter for calculating the transport cost.

Table 5.5. China case marine fuel prices and port charge rates

Port	HSFO 380st	VLSFO	Pilotage dues	Tugboat fee	Anchorage fee	Wharfage fee
Ningbo-Zhoushan port	472.75 ($/ton)	603 ($/ton)	0.06 ($/NT/times)	3190.62 ($)	0.01($/NT/day)	0.17($/ton/times)

In section 5.2, Formulas (5-10) and (5-11) are related to marine fuel prices. By querying the data from the Clarksons website [71], we obtained the prices for the Shanghai port. Since Ningbo-Zhoushan port is adjacent to Shanghai port, we took the fuel prices of Shanghai port as input data. The latest fuel price in May 2023 for reference. According to the "Port Fees Charging Methods" on the website of Chinese Ministry of Transport [78], the marine fuel price data and the port fees data is shown in

Table 5.5. China case marine fuel prices and port charge rates.

Table 5.6 Japan case marine fuel prices and port charge rates

Port	HSFO 380st	VLSFO	Pilotage dues	Tugboat fee	Anchorage fee	Wharfage fee
Kashima port	520.5($/ton)	606.5($/ton)	0.019($/GT/times)	6000($)	415.87($/day)	0.092($/GT/day

Table 5.7 Netherlands case marine fuel prices and port charge rates

Port	HSFO 380st	VLSFO	Port dues gross tonnage		Port dues cargo volume
			Switch percentage	GT tariff	Cargo tariff
Rotterdam port	436.69($/ton)	527.69($/ton)	133.7%	0.36($)	0.58($)

For the case scenarios involving Kashima Port and Rotterdam Port (shown in Table 5.6 and Table 5.7), the reference point for fuel price considerations is the most recent data available as of May 2023. Furthermore, the assessment of port charge rates are informed by data sourced directly from the official websites of these respective ports, Table 5.6 and Table 5.7 shown the both of ports marine fuel prices and port charge rates [78, 79]. Specially, Rotterdam port has their own port charge calculation and preferential policy, so the Rotterdam port charge calculation model is:

$$C_{pc}(R) = GT \times GT\ tariff + Min(GT \times Switch\ percentage \times Cargo\ tariff | \varphi \times Cargo\ tariff) \qquad (5-13)$$

where $C_{pc}(R)$ is presented port charge of Rotterdam port case, GT is the MTV's gross tonnage, GT tariff and Cargo tariff are the port charge rates from Rotterdam port, and φ is the actual DWT. Significantly, the port of Rotterdam offers an environmental ship index discount, specifically characterized by a 10% reduction in the port dues denoted as $C_{pc}(R)$. This reduction is pertinent to our investigation, as it pertains to option 5 which is outfitted with a scrubber system.

Regarding the PSV for deep-sea mining, this case assumes the use of the PSV ship type currently under construction in Chinese shipyards. The daily production capacity for this PSV is 3900 tons/day, and the PSV is equipped with minerals dewatering equipment. The 3900 tons of minerals produced is the weight of minerals after dewatering process. The maximum storage capacity for the PSV is around 40000 tons, and we can obtain from Formula (5-3) that T_{ltPSV} storage time. T_{ltPSV} represents the maximum storage time for the PSV, is approximately:

$$T_{ltPSV} = \frac{40000}{3900} \approx 10\ days \qquad (5-14)$$

Therefore, this case assumes that T_{ltPSV} is equal to 10 days which means that at least one MTV needs to arrive at the mining area to transfer the ore from the PSV within 10 days. Since the Formula (5-14), we can assume that:

$$\varphi_{PSV} = 10 \times 3900 = 39000\ tons \qquad (5-15)$$

which is the ore storage capacity of the PSV.

For the MTV used for shipping deep sea minerals, given that the maximum ore storage capacity of a single PSV is 39000 tons, the MTV must be able to meet the maximum mineral carrying capacity of 39000 tons for a single PSV transport. At the same time, this case also considers the scenario of visiting multiple PSVs during one trip. Therefore, the most important factor affecting the selection of the MTV is the number of PSVs. Thus, this study considers the following scenarios: N_{PSV} is 1 PSV, 2 PSVs, 3 PSVs, and 4 PSVs, respectively. According to the formula $\varphi_{PSV} * N_{PSV}$, the total MTV's carrying capacities are 39000 tons, 78000 tons, 117000 tons, and 156000 tons, respectively. Relevant ship parameters for the reference ship types were obtained mainly from websites such as www.shipxy.com and www.Hifleet.com. The ship charter rate was obtained from the Clarksons website [71].

For the MTV ship type mentioned earlier, the constant value for fuel consumption in Formula (5-7) was calculated by the data from the Clarksons website [71]. Furthermore, since the size of the MTV is different, and the laytime at the PSV or at the port are also different, assumptions were made about both of laytime. Table 5.8 shows the relevant calculation parameters about bulk carrier size in scenarios. In the bulk carrier ship type, both option types numbered 4 and 5 are considered with a capacity of 156000 tons, for 4 PSVs situation. The main difference between options 4 and 5 is that option 5 is equipped with a scrubber, which provides a special explanation for cost estimation under different fuel conditions in later sections.

Table 5.8 The relevant calculation parameters about bulk carrier size in scenarios

Option	Capacity (ton)	T_{pl} (day)	T_{PSVl} (day)	β	ω (ton)	F_{TC} ($/day)	x (NT)	GT
1	39000	3	0.5	0.0000003474	10688	13750	13623	29127
2	78000	6	1	0.0000002581	13500	15675	27336	44046
3	117000	9	1.5	0.0000002381	18147	17000	41224	84022
4	156000	12	2	0.0000002174	23976	17000	56833	87618
5	156000	12	2	0.0000002136	26978	19000	58907	94674

In addition to the input values of parameters related to the bulk carrier ship type listed in Table 5.8, other detailed scenario input parameters are listed in Table 5.9. In Table 5.9, the distance from CCZ to case ports are included three ports but 4 different routes, the range of values for velocity is 11 to 13 knots, the range of number of PSVs is 1 to 4, and the maximum storage time for the PSV are calculated for purpose of later result analysis.

Table 5.9 Other input parameters

Parameters	Value
d	[4700, 3750, 9200, 13350] (nm)
v	[11,13] (nm/h)
φ_{PSV}	39000(tons)
N_{PSV}	[1,4] (vessel)
T_{ltPSV}	10(day)

5.4.3. Results

The comprehensive assessment of shipping costs is influenced by a multitude of diverse variables. By systematically computing the corresponding expenditures across various scenarios, a platform is established for economic analysis and in-depth discussions concerning the aggregate cost of MTVs.

Initially, as the number of PSVs fluctuates from 1 to 4, a commensurate adjustment in the requisite count of MTVs ensues. For instance, in the case of a single PSV deployment, denoted as "option 1" in Table 5.10, a solitary MTV suffices to cater to the PSV's needs. Conversely, the scenario involving 4 PSVs, designated as "option 5" within shipping context, necessitates the employment of bulk carrier type of option 5 to cater to the demands of the 4 PSVs as same as option 4 but there is a scrubber difference in option 5. We posit that MTV option 5 conforms to the IMO 2020 sulphur emission regulations, having been equipped with a scrubber apparatus onboard. This configuration enables the utilization of high-sulphur fuel oil (HSFO) 380cst as the fuel source for option 5, while other option categories are constrained to employing very low sulphur fuel oil (VLSFO) with sulphur emissions below the threshold of 0.5% m/m. Furthermore, the vessel's cruising velocity exhibits variability in line with distinct PSV scenarios, spanning the range from 11 to 13 knots.

Subsequently, an inventory of total costs across diverse scenarios is presented in Table 5.10, accompanied by the fuel price computations predicated on the latest data available in May 2023. This framework sets the stage for a comprehensive evaluation of the financial implications associated with the considered shipping arrangements.

Table 5.10 Results of the total costs in China case with different number of MTVs and velocities

Velocity	Calculation results	Option 1	Option 2	Option 3	Option 4	Option 5
11knots	Total cost (million $)	314.93	469.28	561.02	609.75	628.56
12knots	Total cost (million $)	315.06	374.09	561.32	612.73	622.56
13knots	Total cost (million $)	316.65	380.55	563.86	626.65	628.01

Apart from the exhaustive analysis of Ningbo-Zhoushan Port, our investigation extends to encompass the Kashima Port and Rotterdam Port as additional cases. Pertinent data, inclusive of marine fuel prices and port charge rates, have been meticulously gathered and documented in Table 5.6 and Table 5.7.

Like Table 5.10, as the number of PSVs fluctuates from 1 to 4, a commensurate adjustment in the requisite count of MTVs ensues and the vessel's cruising velocity exhibits variability in line with distinct PSV scenarios, spanning the range from 11 to 13 knots. An inventory of total costs across diverse scenarios is presented in Table 5.11 and Table 5.12, accompanied by the fuel price computations predicated on both of Japan and Netherlands latest data available in May 2023. Specially, option 5 shows the scrubber situation under different velocities affecting total costs.

Table 5.11 Results of the total costs in Japan case with different number of MTVs and velocities

Velocity	Calculation results	Option 1	Option 2	Option 3	Option 4	Option 5
11knots	Total cost (million $)	254.74	314.25	374.94	522.17	549.49
12knots	Total cost (million $)	192.82	315.74	377.9	528.03	550.25
13knots	Total cost (million $)	195.45	318.45	382.3	428.69	442.19

Note: In Japan case, Kashima port is our terminal assumption.

Table 5.12 Results of the total costs in Netherlands case with different number of MTVs and velocities

Velocity	Calculation results	Option 1	Option 2	Option 3	Option 4	Option 5
11knots	Total cost (million $)	1140.32	1320.65	3208.86	3379.55	3506.3
12knots	Total cost (million $)	989.91	1305.29	2932.92	3085.35	3155.89
13knots	Total cost (million $)	995.99	1144.23	2686.68	2839.75	2864.33

Note: In Netherlands case, Rotterdam port is our terminal assumption and there are two shipping routes Panama Canal and Cape of Good Hope.

5.4.4. Scenario analysis

According to section 5.3.3, we analysis the relevant results table in this section.

(1) THE IMPACT OF SHIPPING VELOCITY ON MTV

Variations in total costs are observed across different velocities for the MTVs. This phenomenon is exemplified in Table 5.10, where the shipping costs exhibit sensitivity to velocity changes. The underlying cause for these substantial cost oscillations primarily stems from alterations in the requisite count of MTVs necessary for marine mineral transportation, itself contingent on the velocity parameter. This dynamic relationship results in marked cost fluctuations.

Table 5.13 The voyage duration and required number of MTVs according to varying velocity and number of PSVs in China case

Velocity	Calculation results	Option 1	Option 2	Option 3	Option 4	Option 5
11konts	Voyage duration（day）	39.11	42.61	46.11	49.61	49.61
	Equipped number of MTV (vessel)	4	5	5	5	5

12konts	Voyage duration（day）	36.14	39.64	43.14	46.64	46.64
	Equipped number of MTV (vessel)	4	4	5	5	5
13konts	Voyage duration（day）	33.63	37.13	40.63	44.13	44.13
	Equipped number of MTV (vessel)	4	4	5	5	5

The transformative effect of velocity on MTV requirements is explicated in Table 5.13, which delineates shifts in the requisite number of MTVs across diverse vessel quantities within velocity spans ranging from 11 to 13 knots. It is noteworthy that Option 5's data is presented in Table 5.13, as it aligns with Option 4 except for the presence of a scrubber, meriting exclusion from this comparative analysis.

Specifically, in the case of Option 2, elevating velocity from 11 to 12 knots engenders a reduction in MTV count from 5 to 4. This is predicated on the finding that the voyage duration of Option 2 diminishes from 42.61 days to 39.63 days with the escalated velocity, as delineated in Table 5.13. This temporal compression directly leads to a concomitant decrease in the requisite MTVs, attributed to the maximum PSV visiting interval of 10 days.

On contrast, when Options 1, 3, 4 and 5 augment their velocity, the imperative MTV count hasn't decreased obviously while the voyage duration is also diminished by escalated velocity. When Option 1 augments its velocity from 11 to 13 knots, the voyage duration decreases from 39.11 to 33.63 days. Analogously, Option 3 witnesses a reduction the voyage duration from 46.11 to 40.63 as its velocity progresses from 11 to 13 knots. Option 4 and Option 5 are same to each other's and conform to this trend, experiencing a decrease in the voyage duration from 49.61 to 44.13 with a velocity increment from 11 to 13 knots. Over the range of velocities spanning from 11 to 13 knots, the requisite number of MTVs remains unaltered, elucidating a distinct performance characteristic that distinguishes it from its counterparts.

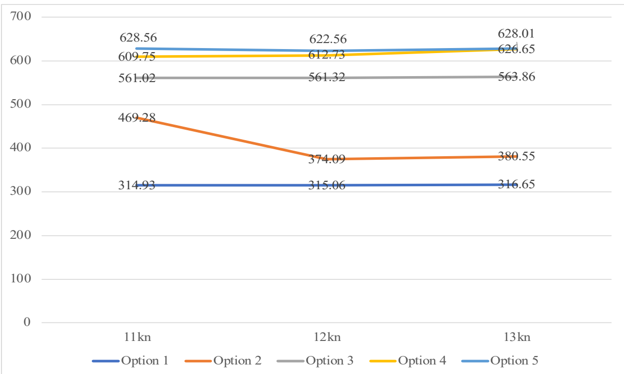

Fig 5.4 The total cost of different options varies with the change of velocity in China case

In synthesis, alterations in velocity engender consequential variations in the requisite count of MTVs, thereby directly imparting pronounced undulations to the total cost of shipping. This phenomenon is perceptibly depicted in Fig 5.4, wherein marked fluctuations in transportation costs manifest concomitantly with shifts in MTV requisites. The CAPEX component of MTVs, denoted by the period chartering cost, exhibits a moderated reduction because of abbreviated voyage durations resulting from elevated velocities. This reduction, however, encounters counterbalance in the escalated OPEX attributed to augmented fuel consumption in bulk carriers, concomitantly increasing fuel costs.

Consequently, as delineated by the trajectory of distinct options in Fig 5.4, excluding instances where the required MTV count undergoes alteration, the total costs evince a consistent ascent as velocity escalates. This pattern is discernible due to the insufficient offsetting capacity of reduced period time charter costs arising from heightened velocities, incapable of fully compensating for the amplified fuel expenditures. This resultant dissonance culminates in an incessant escalation of overall transportation costs. Particularly noteworthy is the observed propensity of Option 2, corresponding to scenarios wherein the PSV count stands at 2, exhibiting the most conspicuous and sustained decrease in total costs as velocity progresses. Besides, Option 4 and Option 5 have a high repeatability but in total costs Option 4 is lower than Option 5. Through the trajectory when the velocity continuously heightens total costs are adjacence thereby the increase in velocity results in a gradual surpassing of the cost of chartering vessels equipped with scrubber devices due to higher fuel expenses.

Table 5.14 The voyage duration and required number of MTVs according to varying velocity and number of PSVs in Japan case

Velocity	Calculation results	Option 1	Option 2	Option 3	Option 4	Option 5
11konts	Voyage duration（day）	31.91	35.41	38.91	42.41	42.41
	Equipped number of MTV (vessel)	4	4	4	5	5
12konts	Voyage duration（day）	29.54	33.04	36.54	40.04	40.04
	Equipped number of MTV (vessel)	3	4	4	5	5
13konts	Voyage duration（day）	27.54	31.04	34.54	38.04	38.04
	Equipped number of MTV (vessel)	3	4	4	4	4

Table 5.15 The voyage duration and required number of MTVs according to varying velocity and number of PSVs in Netherlands case

Velocity	Calculation results	Option 1	Option 2	Option 3	Option 4	Option 5
11konts	Voyage duration（day）	73.20	78.70	111.64	115.14	115.14
	Equipped number of MTV (vessel)	8	8	12	12	12
12konts	Voyage duration（day）	67.39	70.89	103.21	106.71	106.71
	Equipped number of MTV (vessel)	7	8	11	11	11
13konts	Voyage duration（day）	62.47	65.97	96.08	99.58	99.58
	Equipped number of MTV (vessel)	7	7	10	10	10

The impact of velocity on the requisites of MTVs in the contexts of Japan and Netherlands is elucidated through the scrutiny of Table 5.14 and Table 5.15, which furnish a comprehensive elucidation of shifts in the mandatory count of MTVs across diverse vessel quantities, encompassing velocity intervals from 11 to 13 knots.

Much akin to the China case, the Japan case similarly demonstrates that a direct alteration in velocity engenders a corresponding reduction in mandatory MTVs. In the Japan case, elevating velocity corresponds to a decrease in required MTVs. When Option 1 augments its velocity from 11 to 12 knots, the requisite number of MTVs reduced from 4 to 3 and the same trajectory with options 4 and 5.

In the Netherlands case, however, the reduction in MTV count is more conspicuous and recurring. For instance, in the scenario of Option 1, augmenting velocity from 11 to 12 knots begets a reduction in requisite MTVs from 8 to 7. This trend is a consequence of the protracted shipping routes inherent to the Netherlands case, spanning from the CCZ to Rotterdam port. Consequently, strategic acceleration of velocity intermittently proves more efficacious and cost-effective.

Analogously, the scenario mirroring Option 3, even though adopting the Cape of Good Hope route instead of the Panama Canal, involves extended shipping routes. Despite this, velocity increments lead to a fourfold reduction in MTVs required, successively diminishing from 12 to 11, and eventually to 10. This trend is predicated on the discovery that the temporal duration of voyages, across all scenarios, decreases with escalated velocities, as expounded in Table 5.14 and Table 5.15. Collectively, these reductions in the equipped MTV count exert substantial abatement on total costs.

<u>(2) SUMMARY OF THE VELOCITY</u>

Table 5.16 provides a comprehensive breakdown of cost comparisons across three distinct scenarios in China case, each illuminating typical instances of juxtaposed total cost situations. It predominantly elucidates the allocation of CAPEX, fuel costs, and port charges—constituting a vital component of OPEX—within the realm of deep-sea mining shipping costs. The scenarios delineated in the table contrast the shipping costs of Options 1 to 5, spanning velocities from 11 knots to 13 knots, to underscore the shifts in cost proportions stemming from velocity augmentation.

In Option 1, at a velocity of 11 knots, the cost distribution is dominated by CAPEX, accounting for nearly 70% of the total cost. Correspondingly, fuel expenses encompass a modest 27.79%, with port charges constituting a minimal proportion of 2.35%. With an elevation in velocity to 13 knots, a reduction in the number of MTVs leads to a significant 0.55% increase in the total cost. Evidently, the proportion of CAPEX decreases to 59.06%, while fuel costs experience a noteworthy surge, escalating to 38.61%. This alignment concurs with the economic cost model, which posits an ongoing ascent in fuel costs alongside velocity increments. The observations gleaned from Table 5.16 corroborate the paramountcy of CAPEX, especially chartering costs, within the shipping cost framework. It is pertinent to note the tandem escalation of fuel costs with MTV velocity, accentuating the imperative to optimize velocity to achieve a judicious OPEX equilibrium.

Notably, in Option 2, a transition from 11 knots to 12 knots yields a substantial 20.24% reduction in total cost. According to Table 13, this fluctuation is attributable to the decline in the equipped number of MTVs from 5 to 4, exerting a direct impact on the CAPEX component of total cost. As Table 5.16 demonstrates, the proportion of CAPEX reduces by 25.58%, while OPEX increases by 6.79%. Thus, increasing velocity to modulate the equipped number of

MTVs emerges as a more cost-effective strategy than simply elevating velocity to incur higher fuel costs within OPEX. Consequently, an optimum economic velocity for deep-sea mining shipping emerges as a focal point for future study.

Additionally, Table 5.16 underscminerals the marginal role of port charges within total cost and emphasizes the pivotal role of CAPEX, with fuel costs demonstrating heightened dependence on velocity as it aligns with a progressively larger percentage of the overall cost. Across Options 1 to 4, where velocity varies from 11 knots to 13 knots, fuel cost consistently increases by approximately 4%, with CAPEX being chiefly influenced by MTV charter rates and equipped numbers, albeit on a descending trajectory as velocity escalates.

Lastly, a comparison between Options 4 and 5 considers MTVs without and with a scrubber. Under an 11 knots velocity, the total cost disparity between the two options is evident. Specifically, Option 5 exhibits higher CAPEX at 75.57%, compared to 69.70% for Option 4, yet benefits from lower fuel costs with a difference of 18.83% (24.57% for Option 5 and 43.40% for Option 4). Despite Option 5 having a higher charter rate for MTVs, its reliance on the more economical HSFO 380st marine fuel results in a lower total cost compared to Option 4. As velocity increases, the differential advantage of total cost between scrubber-equipped and non-equipped options becomes progressively less pronounced. When the velocity reaches 13 knots, the cost difference narrows to 1.32 million dollars, indicating the significance of fuel cost within OPEX, causing the percentage of CAPEX to decrease by approximately 7%, in favor of OPEX.

In conclusion, our economic shipping model effectively determines the optimal economic velocity for distinct scenarios. For instance, in Option 1 with a single PSV, 11 knots emerges as the economic velocity within the 11 to 13 knots range, while being equipped with 4 MTVs. Similarly, in Option 2 with 2 PSVs, 12 knots is deemed economically optimum within the same velocity range, coupled with 4 MTVs. Parallel conclusions are drawn for Options 3 and 4 with 3 and 4 PSVs, respectively. Notably, in Option 5, which features 5 PSVs, 12 knots proves to be the optimal economic velocity within the 11 to 13 knots spectrum, while retaining 4 MTVs, albeit with the additional environmental advantage of the scrubber.

Table 5.16 Comparison of components of the total cost of MTV operating in China case (million $)

Option	Velocity/kn	CAPEX		Fuel cost		Port charge		OPEX		Total cost	
		Cost	Percentage	Cost	Percentage	Cost	Percentage	Cost	Percentage	Cost	Percentage
1	11	220.00	69.86%	87.53	27.79%	7.40	2.35%	94.93	30.14%	314.93	100%
	12	203.50	64.55%	104.17	33.06%	7.40	2.35%	111.57	35.41%	315.06	100%
	13	187.00	59.06%	122.25	38.61%	7.40	2.34%	129.65	40.94%	316.65	100%
2	11	337.01	71.81%	114.95	24.49%	17.32	3.69%	132.27	28.19%	469.28	100%
	12	250.8	67.04%	109.44	29.25%	13.85	3.70%	123.29	32.96%	374.09	100%
	13	238.26	62.61%	128.44	33.75%	13.85	3.64%	142.29	37.39%	380.55	100%
3	11	399.50	71.21%	135.71	24.19%	25.81	4.60%	161.52	28.79%	561.02	100%
	12	374.00	66.63%	161.50	28.77%	25.81	4.60%	187.31	33.37%	561.32	100%
	13	348.50	61.81%	189.54	33.61%	25.81	4.58%	215.35	38.19%	563.86	100%
4	11	425.00	69.70%	149.82	24.57%	34.94	5.73%	184.76	30.30%	609.75	100%
	12	399.50	65.20%	178.30	29.10%	34.94	5.70%	213.24	34.80%	612.73	100%
	13	382.50	61.03%	209.25	33.39%	34.94	5.58%	244.19	38.97%	626.69	100%
5	11	475.00	75.57%	118.37	18.83%	35.18	5.60%	153.55	24.43%	628.56	100%
	12	446.50	71.72%	140.87	22.63%	35.18	5.65%	176.05	28.28%	622.56	100%
	13	427.50	68.07%	165.33	26.33%	35.18	5.60%	200.51	31.93%	628.01	100%

Note: the marine fuel price is taken the latest data available in May 2023, HSFO 380cst: 472.75 $/ton, VLSFO: 603 $/ton.

The trajectory observed in the Japan case parallels that of the China case, with comparable short shipping routes, yet it also yields an economic velocity as presented in Table 5.17. In Option 1, involving a single PSV, the economically optimal velocity within the range of 11 to 13 knots is determined to be 12 knots, while being accompanied by the utilization of 3 MTVs. Likewise, for Option 2, featuring 2 PSVs, an economically optimal velocity of 11 knots is identified within the same velocity span, in conjunction with the deployment of 4 MTVs. The same conclusions apply for Option 3, which entails 3 PSVs. In Option 4, an economic velocity of 13 knots is established while employing 4 MTVs. Particularly noteworthy is Option 5, encompassing 5 PSVs, wherein an economic velocity of 13 knots emerges as optimal within the 11 to 13 knots range, while also retaining 4 MTVs. It is essential to emphasize that Option 5 additionally reaps the environmental benefits attributed to the inclusion of a scrubber.

Differing from both the Japan and China cases, the Netherlands case presents extended shipping routes, almost double the length of the China case. Furthermore, due to the constraints imposed by the size of MTVs, a Cape of Good Hope route is necessitated from CCZ to Rotterdam port, leading to even greater route lengths, as evident in Table 5.18. A distinctive trend is observed, wherein longer shipping routes and alterations in velocity proportionally impact the equipped number of MTVs, consequently inducing fluctuations in CAPEX. Instances such as Options 3 and 4 showcase how velocity alterations from 11 knots to 13 knots result in twice the influence on the total cost. This substantiates the conclusion that planning an economic velocity is imperative for longer shipping routes.

In Option 1, involving a single PSV, the optimal economic velocity within the 11 to 13 knots range is ascertained to be 13 knots, in tandem with the utilization of 7 MTVs. Similarly, for Option 2, featuring 2 PSVs, an economically optimal velocity of 13 knots is identified within the same velocity span, with the deployment of 7 MTVs. Option 3, entailing 3 PSVs and equipped with 10 MTVs, applies a velocity of 13 knots. In Option 4, an economic velocity of 13 knots is established while employing 10 MTVs. Particularly noteworthy is Option 5, encompassing 5 PSVs, wherein an economic velocity of 13 knots emerges as optimal within the 11 to 13 knots range, while retaining 10 MTVs. It is imperative to underscore that Option 5 derives additional environmental advantages through the inclusion of a scrubber. Our research highlights that longer shipping routes, when navigated at a comparable higher speed, amplify the significance of economic velocity fluctuations, a characteristic not as pronounced in shorter route scenarios.

Table 5.17 Comparison of components of the total cost of MTV operating in Japan case (million $)

Option	Velocity/kn	CAPEX		Fuel cost		Port charge		OPEX		Total cost	
		Cost	Percentage	Cost	Percentage	Cost	Percentage	Cost	Percentage	Cost	Percentage
1	11	176.00	69.09%	70.24	27.57%	8.50	3.34%	78.74	30.91%	254.74	100%
	12	123.75	64.18%	62.69	32.51%	6.37	3.30%	69.06	35.82%	192.82	100%
	13	115.50	59.09%	73.58	37.65%	6.37	3.26%	79.95	40.91%	195.45	100%
2	11	225.72	71.83%	73.80	23.48%	14.73	4.69%	88.53	28.17%	314.25	100%
	12	213.18	67.52%	87.83	27.82%	14.73	4.67%	102.56	32.48%	315.74	100%
	13	200.64	63.01%	103.08	32.37%	14.73	4.63%	117.81	36.99%	318.45	100%
3	11	265.20	70.73%	87.12	23.24%	22.61	6.03%	109.73	29.27%	374.94	100%
	12	251.60	66.58%	103.69	27.44%	22.61	5.98%	126.3	33.42%	377.9	100%
	13	238.00	62.25%	121.69	31.83%	22.61	5.91%	144.3	37.75%	382.30	100%
4	11	365.50	70.00%	120.23	23.03%	36.44	6.98%	156.67	30.00%	522.17	100%
	12	348.50	66.00%	143.08	27.10%	36.44	6.90%	179.52	34.00%	528.03	100%
	13	265.20	61.86%	134.34	31.34%	29.15	6.80%	163.49	38.14%	428.69	100%
5	11	408.50	74.34%	103.99	18.92%	37.00	6.73%	140.99	25.66%	549.49	100%
	12	389.50	70.79%	123.75	22.49%	37.00	6.72%	160.75	29.21%	550.25	100%
	13	296.4	67.03%	116.19	26.28%	29.6	6.69%	145.79	32.97%	442.19	100%

Note: the marine fuel price is taken the latest data available in May 2023, HSFO 380cst: 520.5 $/ton, VLSFO: 606.5 $/ton.

Table 5.18. Comparison of components of the total cost of MTV operating in Netherlands case (million $)

Option	Velocity/kn	CAPEX		Fuel cost		Port charge		OPEX		Total cost	
		Cost	Percentage	Cost	Percentage	Cost	Percentage	Cost	Percentage	Cost	Percentage
1	11	1124.80	81.75%	210.36	15.29%	40.83	2.97%	251.19	18.26%	1375.98	100%
	12	904.40	78.02%	219.05	18.90%	35.72	3.08%	254.77	21.98%	1159.17	100%
	13	837.9	74.10%	257.08	22.74%	35.72	3.16%	292.8	25.90%	1130.7	100%
2	11	1170.40	78.70%	259.58	17.46%	57.11	3.84%	316.69	21.30%	1487.09	100%
	12	1079.20	74.67%	308.92	21.38%	57.11	3.95%	366.03	25.33%	1445.23	100%
	13	877.80	70.51%	317.23	25.48%	49.97	4.01%	367.2	29.49%	1245.01	100%
3	11	2553.60	76.85%	659.33	19.84%	110.10	3.31%	769.43	23.15%	3323.03	100%
	12	2173.60	72.60%	719.27	24.03%	100.92	3.37%	820.19	27.40%	2993.79	100%
	13	1843.00	68.20%	767.40	28.40%	91.75	3.40%	859.15	31.80%	2702.15	100%
4	11	2366.40	70.02%	893.76	26.45%	119.38	3.53%	1013.1	29.98%	3379.55	100%
	12	2000.90	64.85%	975.02	31.60%	109.44	3.55%	1084.5	35.15%	3085.35	100%
	13	1700.0	59.86%	1040.26	36.63%	99.49	3.50%	1139.8	40.14%	2839.75	100%
5	11	2644.80	75.43%	745.40	21.26%	116.10	3.31%	861.5	24.57%	3506.30	100%
	12	2236.30	70.86%	813.16	25.77%	106.42	3.37%	919.58	29.14%	3155.89	100%
	13	1900.00	66.33%	867.58	30.29%	96.75	3.38%	964.33	33.67%	2864.33	100%

Note: the marine fuel price is taken the latest data available in May 2023, HSFO 380cst: 436.69 $/ton, VLSFO: 527.69 $/ton

5.5. Social and environment dimensions of shipping

5.5.1. Social dimension

Firstly, marine transport plays an important role in terms of employment opportunities. The industry provides a large number of jobs, involving crew members, dock workers, shipping agents and many other employment. These employment opportunities create jobs for local communities and contribute to economic growth and social development. In addition, maritime transport also brings business and service development to port cities, further enhancing local employment levels.

Secondly, maritime transportation is important for economic benefits. By transporting and importing mineral resources, the country can earn foreign exchange income and promote economic growth and development. At the same time, the development of the industry also drives the rise of related industries, such as shipbuilding, shipping logistics, maintenance services. The new economic industry creak wealth and employment opportunities for the country and society.

However, maritime transport also needs to face some social challenges and problems. One of them is the conflict between resource exploitation and environment. Maritime transport involves the development and utilization of natural resources, so it needs to balance the relationship between resource exploitation and environmental protection. In the process of resource exploitation, the sustainability of deep-sea mining, environmental impact assessment and ecological protection need to be considered to ensure the rational use of resources and environmental sustainability.

In addition, maritime transport has certain impacts on local communities. This includes noise, traffic congestion, and the construction of port infrastructure. To mitigate these impacts, community engagement and communication are needed to understand and address community concerns and ensure the alignment of offshore mineral shipping activities with community interests.

In terms of safety and risk management, offshore mineral shipping involves risks in terms of vessel safety and cargo security. Therefore, it is necessary to establish an effective safety management system, including measures and norms for navigation safety, cargo safety and personnel safety, to ensure the safety and reliability of the transport process.

In addition, maritime transport also needs to strengthen international cooperation, policy and regulations. Maritime transport is an important part of international trade and cooperation. In order to ensure smooth transport activities, policies and regulations for international cooperation need to be developed and complied with. This includes international agreements and laws and regulations on ship safety standards, Labor Costal protection, labor rights protection. Through international cooperation, regulation and management can be strengthened to promote the sustainable development of maritime transport.

In addition to the above-mentioned factors and impacts, maritime transport also requires social responsibility and attention to sustainable development. Industry participants should observe labor rights and interests, maintain labor safety, and promote social justice and equity. It is also necessary to actively promote sustainable development, take measures to reduce the adverse environmental impact of the shipping industry, improve energy efficiency and reduce carbon emissions, and promote green shipping and environmental awareness.

In terms of education and training, the maritime transport industry needs to develop highly qualified personnel and skills. In order to meet the business needs, education and training in related fields need to be strengthened to cultivate professionals and provide skills training to improve the quality and technical level of practitioners.

In summary, the social aspects of maritime transport need to consider factors and impacts such as employment opportunities, economic benefits, resource development and environmental conflicts, community impacts, safety and risk management, international cooperation and policies and regulations. By considering these aspects comprehensively, the sustainable development of maritime transport can be promoted, and socio-economic coordination and win-win situation can be achieved.

5.5.2. Environment dimension

The environmental considerations and impacts of maritime transport are critical. The development and operation of this industry has direct and indirect impacts on marine ecosystems and the natural environment. The following is an overview of the environmental considerations and impacts of maritime transport.

Firstly, maritime transport has potential impacts on marine ecosystems and biodiversity. Vessels at sea generate noise, vibration and waste-water discharge. These factors may negatively affect aquatic organisms by interfering with their physiological functions, behavior and migration. In addition, the loading and unloading process of mineral may cause the release of suspended matter and destruction of benthic habitats. Therefore, in maritime transport, measures are needed to reduce noise and wastewater discharges and prevent adverse impacts on marine ecosystems.

Secondly, mineral shipping also involves the construction of navigation channels and port infrastructure. These activities may have impacts on shorelines and coastal ecosystems. For example, port construction may lead to coastal erosion, wetland and estuarine ecosystem destruction. Therefore, environmental impact assessment needs to be conducted when planning and building port infrastructure, and appropriate protection and restoration measures need to be taken to reduce the impact on coastal ecosystems.

In addition, maritime mineral shipping has an impact on the atmospheric environment. The combustion of ship fuel produces atmospheric pollutants such as sulfur dioxide (SO2) and nitrogen oxides, which can have adverse effects on air quality and human health. To reduce atmospheric emissions from ships, measures such as using low-sulfur fuels, installing emission control devices and implementing energy conservation measures are needed.

In addition, the mining and processing of minerals has an impact on the environment. This includes issues such as land destruction, water pollution, and ecological damage. In ore transportation, the source of the ore and the production process need to be assessed to ensure compliance with environmental protection standards and sustainability principles.

In terms of the environment, the maritime mineral shipping industry needs to adopt sustainable measures to minimize reduce adverse environmental impacts. Mineral shipping requires attention to reduce the discharge of wastewater and pollutants in order to protect marine water quality. This can be achieved through the use of advanced wastewater treatment technologies, compliant waste disposal, and prevention of oil pollution, among other measures. In addition, ship emission standards and relevant international conventions can be developed and complied with to ensure that ship emissions meet environmental protection requirements. At the same time, mineral shipping requires attention to protect marine biodiversity. This can be achieved by avoiding damage to sensitive areas and species and taking measures to reduce the impact of ship collisions and discharges on marine life. In addition, relevant fisheries management regulations need to be observed to prevent the harvest and introduction of non-target species. By taking these factors into account and adopting appropriate measures, the mineral shipping industry can minimize adverse environmental impacts and achieve a balance between sustainable development and environmental protection.

5.6. Conclusions

The focus of this chapter is to establish an economic cost model for shipping deep sea minerals. With the developed economic model, economic feasibility study is conducted. Environmental impacts are also evaluated. The main conclusions include:

- The composition of shipping cost in deep-sea mining is greatly affected by the way of purchasing or renting MTVs. This study uses a time charter method that reduces CAPEX at the early stage but increases OPEX during operation, thus requiring reasonable chartering contracts to reduce CAPEX and fuel costs.
- The cost of fuel is mainly affected by the velocity of MTVs. Thus, an optimized maritime shipping route velocity is needed. The study provides analyzed different velocities for different numbers of PSVs, but a more advanced optimization model is needed for specific deep-sea mining project.
- The study suggests that leasing MTVs equipped with scrubbers is economically beneficial when fuel prices are high. Scrubbers can also effectively reduce fuel consumption and environmental impact by reducing sulfur emissions, particularly in high velocity and high fuel consumption scenarios.

In summary, as deep-sea mining technology continues to improve, commercial deep-sea mining will come to reality in near future. According to the research results of this report, from the perspective of initial investment costs, using a chartering method for MTV operations is more feasible, so considerations should be given to the ship chartering contracts signed in commercial activities. Secondly, fuel prices are also a way to reduce costs that can be achieved through commercial contract signing. Most importantly, when operating routes, setting economic velocity and specific arrival times at ports or PSVs can control the required number of MTVs and to minimize various cost indicators. Finally, although this report did not calculate environmental costs in detail, considering the current control of emissions from maritime navigation, leasing bulk carriers with scrubber is more environmentally valuable, and in the case of high oil prices and fast velocities, it can also bring lower total costs

6. Sustainability of port unloading

When deep sea minerals are transported to shore, they will be unloaded at bulk terminals. Bulk terminals are of considerable complexity with many large scale equipment and complex coordination of different equipment. This chapter will describe the general unloading process at a typical bulk terminal, as well as special unloading process of deep sea minerals due to its unique characteristics. Afterwards the sustainability of unloading deep sea minerals at bulk terminals will be investigated with development a set of criteria and indicators.

6.1. Introduction

Generally speaking, bulk terminals are designed for two major functions. One is to load and/or unload bulk ships as well as hinterland transport equipment (i.e. trains, trucks). The other function is temporary storage of bulk cargo in order to decouple differing in- and outgoing flow patterns [80].

6.1.1. Port operations

Figure 6-1 shows port nautical infrastructure and processes of port unloading. When a bulk ship arrives at a port, it is first anchored at anchorage. When a berth is available, port authority will allow the bulk ship to berth at a terminal. The berthing process will be assisted by tugs and pilots. When the birthing is finished, unloading process can be initiated. After unloading, the ship can departure from the terminal.

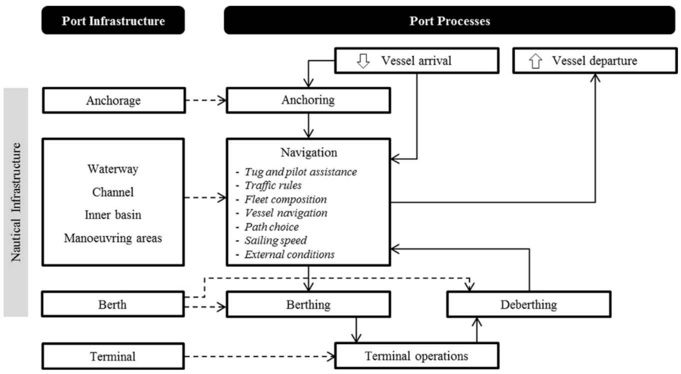

Fig 6.1. Diagram of port nautical infrastructure and processes [81]

A dry bulk terminal contains three main subsystems; the seaside, landside and stockyard. The seaside and landside are the connections with the bulk supply chain where dry bulk materials are imported to or exported from the terminal. At import terminals, dry bulk materials are supplied at the seaside and leave the terminal at the landside (Fig 6.2).

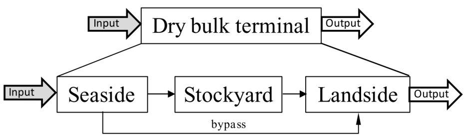

Fig 6.2. Illustration of an unloading (import) bulk terminal [82]

6.1.2. Seaside unloading equipment and technology

To unload a bulk ship, a variety of unloading equipment can be used at the seaside of terminals. A few examples of unloading equipment are introduced below.

A. Portal crane

A portal crane is equipped with rail travelling units, rotating upper structure, boom assembly, a grab and hoisting system [80]. The hoisting system is responsible for lowering and lifting the grab, as well as opening and closing the grab. When the unloading process is initiated, the driver will turn the rotating upper structure of the crane towards the bulk ship. When the boom is at the right location, the grab will be lowered to the cargo holder of the bulk ship. The grab will immerse into the bulk cargo. Afterwards the hoisting system will close the grab, lift the grab in the air. For the next step the driver will turn the rotating upper structure and let the grab locates on the top of a hopper. At this location the hoisting system will open the grab and let bulk materials fall into the hopper. Below the hopper usually a belt conveyor system is assigned, so that the bulk materials will be transported to stockpile area via belt conveyor systems.

Fig 6.3. Portal crane

B. Trolley type ship unloader

For trolley type ship unloader, a grab is connected to a trolley, which travels horizontally over a boom. The trolley travels between an outreaching location above a bulk ship and a location above a hopper. The unloading capacity of trolley type ship unloader is much higher than the portal cranes.

Fig 6.4. Trollye type ship unloader [83]

C. Bucket elevator

A bucket elevator uses a vertical bucket conveyor system to lift bulk materials from a bulk ship to a conveyor belt in the boom. At the end of the conveyor belt is a chute in the slewing center of the unloader. The bucket elevator has an L-shaped end that can reach the material lying under the hatch wings and in the corners of the cargo holders. Therefore the bucket elevator can unload bulk materials continuously with very high capacity. Another advantage of bucket elevators is that the transfer of bulk materials occurs in closed structures so the dust pollution to port area is much better than portal cranes or trolley type ship unloaders.

Fig 6.5. Bucket elevator [84]

D. Vertical screw conveyor unloader

A vertical screw conveyor unloader, as illustrated in the name, there is a vertical screw conveyor inside the boom. The vertical screw conveyor is capable to lift bulk materials from cargo holders to the top of the boom. Due to the limited efficiency of the vertical screw conveyor, the unloading capacity of this unloader is not high. But it is also considered as environment friendly because this unloader generates limited dust during operation.

Fig 6.6. Vertical screw conveyor unloader [83]

6.2. Sustainability indicator system for port unloading

The unloading process of bulk materials at seaside of bulk terminals involves large scale equipment, significant consumption of energy, and dust generation. The sustainability of port unloading deep sea minerals will be investigated from five dimensions: environment, economic, social, safety and technology. The sustainability criteria and indicators are summarized in Table 6.1.

Table 6.1. Sustainability indicator system for deep sea minerals unloading at bulk terminals

Dimension	Criteria	Indicator	Unit
Environment	mitigation*	percentage of revenue invested in environmental causes	% of revenue/year
	Impact on environment*	emissions of GHG	Tonnes of GHG equivalent/year
		Dust generation	PM 2.5 at port area
		Extent of coastal and habitat positively/negatively impacted	Area of positively and negatively impacted habitat in hectares
		Technologies applied to reduce noise, air pollutions	No. and type of technologies No./year
		Support given to local entities working on the protection, conservation and management of local biodiversity and landscape	% of turnover dedicated to such support
		Poor water quality	Yes/no. if yes, specify
	Level of energy consumption*	Energy consumption	Tonnes of oil equivalent/year
		Energy demand met by renewable energy	% of total primary energy supply
	waste management*	Seafarers' waste generated and recycled	Tonnes of waste generated and recycled /year
		Wastewater generated and reused	Tonnes of wastewater generated and reused /year
		Ballast water recycled	Tonnes of ballast water recycled /year
		Technology available for solid waste, wastewater	Yes/no. if yes, specify

		and ballast water treatment	
		Hazardous waste management guidelines and measures to handle hazardous substances	Yes/no. if yes, specify
Economic	Economic benefits*	Total revenue generated by unloading work	Million $ /year
		Local public revenue generated through time	Million $ /year
	Economic viability	Gross value added*	Million $ /year
		Production of unloading process	Tonnes of minerals unloaded /year
		Specific investments in the unloading infrastructure and equipment	Million $ /year
		Turnover*	Million $ /year
	costs	Average personnel costs	x1000 $/year
		Maintenance costs	x1000 $/year
Social	employment	Direct and indirect jobs	No. of direct and indirect jobs x1000 persons/year
	Employment conditions	Average wage of employees*	$/year
		Presence and activeness of labour unions in the company*	Yes/no. if yes, specify
		Informal employment*	% informal employment of total employment
		Professional training	Hours of professional training /year
	Health management	Frequency of auditing by external health experts	No. of audits by external health experts /year

		Time of employees expose to hazardous substances	Hours of employees expose to hazardous substances during work
		Existence of policies and measures to combat occupational diseases and accidents	Yes/no. if yes, specify
Safety	Safety management	Accidents occurred during work	No. of accidents occurred during work /year
		Frequency of auditing by external safety experts	No. of audits by external safety experts /year
		Emergence plans and measures when accidents occur	Yes/no. if yes, specify
	Safety related hardware	Sufficient safety related hardware (helmet, shoes etc.) on site	No. of safety hardware per person
		Hazard detection system (camera, microphone, fire detector)	No. of hazard detection system per terminal
Technology	Equipment reliability	Time of unloading equipment malfunction	Hours of unloading equipment malfunction /year
		Maintenance time	Hours of maintenance for unloading equipment /year
	Technology advancement	Whether the unloading equipment and technical solutions are out of date	Yes/no. if yes, specify
	Energy efficiency	The efficiency of energy system used in unloading equipment	%

		Measures taken to increase energy efficiency	Yes/no. if yes, specify
	Use of shore power	Availability of shore power infrastructure at bulk terminal	Yes/no

Note: criteria and/or indicators marked with * are adopted from [85].

Some criteria and indicators in Table 6.1 are inspired by the report "Sustainability criteria for the blue economy" from European Commission. The criteria and indicators in EU report are more suitable for macro level, in another word for sectoral level. However, this study looks at sustainability assessment at the micro (operational) level. Some criteria and indicators are modified according to the application.

In addition, the sustainability dimensions of safety and technology are included in the index system above. The study team consider that for sustainability assessment at operational level like port unloading, safety and technology cannot be neglected.

6.3. Conclusions

This chapter overviews the sustainability of unloading deep sea minerals at bulk terminals. Main unloading equipment and associated unloading processes are presented. A set of sustainability dimensions, criteria and indicators for port unloading are developed.

7. Conclusions and recommendations

7.1. Conclusions

This project studied the sustainability of maritime transport for deep-sea mining by developing a Maritime Transport Sustainability Framework. Literature review, peer interviews, surveys are conducted during the research. A list of conclusions can be drawn based on the outcomes of the research:

- Literature study on deep-sea mining value chain has shown that rare attention has been paid to maritime transport of deep sea minerals. Knowledge gap on sustainable maritime transport of deep sea minerals has to be filled before commercial deep-sea mining starts.
- Maritime Transport Sustainability Framework is proved to be an effective operational approach for sustainability assessment in maritime sector. In the developed Framework, value chain analysis is applied to provide a horizontal narrative by categorizing maritime transport activities into four processes. Five sustainability dimensions, namely environment, economic, social, safety and technology are proposed in the Framework. A variety of sustainability criteria and indicators are developed for the four processes of maritime transport.
- From the analysis of 6,368 accidents of bulk carrier from 1995 to 2022, it is found that mechanical damage/failure, wrecked/stranded and collision are the most common reasons for bulk vessels accidents. Medium-sized bulk vessels are most seen accidents, with the Supramax type accounting for 23.27%.
- An economic model has been developed for the economic analysis of maritime transport of deep sea minerals. It was found that there exists optimum choice of voyage speed for minerals transport vessels when it services multiple production support vessels. It was found that for bulk vessels using VLFO may experience lower operation cost than the option to use HSFO 380cst when fuel price becomes.

7.2. Recommendations

A set of recommendations has been developed from the research steps of the study. These recommendations are aimed at policymakers, investors, economic operators, and researchers who wishes to apply the Maritime Transport Sustainability Framework.

- The collection and availability of data should be improved to enhance the applicability of Maritime Transport Sustainability Framework. In maritime transport sector, many data are either not publicly available or not collected at all. This restricts the transparency and sharing of sustainability information, and consequently hinders sustainability transformation of the sector.
- The identification of key sustainability dimensions, criteria and indicators should be based on custom challenges and situations. Though it is widely accepted that sustainability can be assessed from environment, economic, and social dimensions, more dimensions may be needed especially for sustainability assessment at local levels.
- Maritime Transport Sustainability Framework should be implemented over long period of time and associated with a monitoring system. Some criteria and indicators developed in this study only provide a basic qualitative parameters which should be monitored in long term.

- Maritime Transport Sustainability Framework needs to be periodically updated to maintain the up-to-date status of its criteria and indicators. The Framework provides a broad yet detailed understanding of issues in sustainability in maritime transport of deep sea minerals. However, as it is a rather new research field, criteria and indicators may change quickly with the development of technologies, transport solutions and business models. Therefore, the Framework should be checked for the updated value chain analysis of maritime transport for deep-sea mining.

In addition, two research directions for future are recommended by the study team. One is further study on liquefaction issues of deep sea minerals during shipping is needed. The deep sea minerals mined from oceans are fully saturated. The water content in deep sea minerals may lead to liquification, which may cause severe accidents of bulk carriers. Secondly, knowledge gap exists in the health issues of workers who will have close contact with deep sea minerals. a recent study shows that deep sea minerals could be radioactive and can cause damage to human health [86]. The health of ship crew and port equipment operators for maritime transport of deep sea minerals should be studied in future. With such study, recommendations and regulations on handling and transport of deep sea minerals can be formulated to protect the health of workers involved in maritime transport industry.

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Appendix - Ⅰ

Appendix I Scoring Sheet for sustainability indicator system for ship-to-ship mooring

Dear Experts:

First of all, we would like to thank the experts for taking time out of their busy schedules to give an initial score to our indicators, i.e., relative importance. This is the indicator evaluation system about the safety of mooring system which is very important in deep-sea mining system, where Table A presents the who two-ship mooring safety factor indicator system , and Table B is the definition and description of the scale which will be given in the calculation of hierarchical analysis in order to quantify the judgment, and it introduces the definition and description of the scale which gives the different importance degree values, and the importance degree of each indicator can be expressed in numerical values. Table C shows the importance of five indicators to the general objective (i.e. mooring safety); Table D shows the importance of nine indicators to human indicators; Table E shows the importance of six indicators to environmental indicators; Table F shows the importance of five indicators to ship equipment indicators; Table G shows the importance of seven indicators to MTV operability; Table H shows the importance of two indicators to accidental indicators . Please rate Tables C, D, E, F, G, H according to the scale of Table B. Since the tables correspond to the symmetric matrix, you only need to fill in the blank half of the table. Thank you!

Specialist Name:

Working Site:

Table A. Sustainability indicator system for ship-to-ship mooring

objective	Layer 1	Layer2
Sustainability mooring analysis	Human Indicators	Communication Skills
		Mooring operation quality
		Design and construction quality
		Maintenance quality
		Duty Arrangement
		Operating procedures
		Nautical expertise
		Crew Physical Condition
		Crew Mental condition
	Economic Indicators	Infrastructure Investment
		Operational Efficiency
		Labor Costs
		Maintenance and Upkeep
		Risk Management and Insurance
		Market Demand and Competition
	DP system indicators	DP Sensor System
		DP Propulsion System
		Ship electrical system
		DP system responsiveness
		DP system design and configuration
		Mooring ropes
		Buffer cushions
		Vessel equipment mechanical failure
	Maneuverability of MTV	Ship Age
		Ship Type
		Bow height
		Fullness of the bow
		Hull center of gravity position
		Displacement
		Mooring distance
		Mooring speed
	Accidental indicators	Natural Disasters
		Equipment failure

Table B. Scale of indicator weight

Scale	Definition and Description
1	Two elements are equally important for an attribute
3	When two elements are compared, the former element is slightly more important than the latter element
4	When two elements are compared, the former element is significantly more important than the latter element
7	Two elements are compared in which the former element is much more important than the latter element
9	Comparing two elements, the former element is extremely important than the latter element
2，4，6，8	The former element is more important than the latter element between the calibrated criteria
$1/a_{ij}$	Inverse comparison of two elements

Table C. Human indicators

	Human Indicators	Economic Indicators	DP system indicators	Maneuverability of MTV	Accidental indicators
Human Indicators					
Economic Indicators					
DP system indicators					
Maneuverability of MTV					
Accidental indicators					

Table D. Human indicators

	Communication Skills	Mooring operation quality	Design and construction quality	Quality of maintenance and upkeep	Duty Arrangement	Operating procedures	Nautical expertise	Crew Physical Condition	Crew Mental Fitness
Communication Skills									
Mooring operation quality									
Design and construction quality									
Quality of maintenance and upkeep									
Duty Arrangement									
Operating procedures									
Nautical expertise									
Crew Physical Condition									
Crew Mental Fitness									

Table E. Economic indicators

	Infrastructure Investment	Operational Efficiency	Labor Costs	Maintenance and Upkeep	Risk Management and Insurance	Market Demand and Competition
Infrastructure Investment						
Operational Efficiency						
Labor Costs						
Maintenance and Upkeep						
Risk Management and Insurance						
Market Demand and Competition						

Table F. DP system indicators

	Sensor Systems	Thruster Systems	Power system	System responsiveness	System design and configuration
Sensor Systems					
Thruster Systems					
Power system					
System responsiveness					
System design and configuration					

Table G. Maneuverability of MTV indicators

	Ship Age	Ship Type	Bow height	Fullness of the bow	Hull center of gravity position	Displacement	Mooring distance	Mooring speed
Ship Age								
Ship Type								
Bow height								
Fullness of the bow								
Hull center of gravity position								
Displacement								
Mooring distance								
Mooring speed								

Table H. Accidental indicators

	Natural Disasters	Equipment failure
Natural Disasters		
Equipment failure		

Appendix Ⅱ

Appendix II Scoring sheet for sustainability assessment of ship-to-ship minerals transfer

Dear Experts:
First of all, we would like to thank the experts for taking time out of their busy schedules to give an initial scoring of our indicators, i.e. relative importance. Table A presents the whole Sustainability Evaluation of Ore Transfer System; Table B is the relative importance scoring table for the secondary indicators; Tables C, D and E are the relative importance scoring tables for each tertiary indicator. Please complete the scoring of Tables B, C, D and E, because the tables correspond to the symmetric matrix, so you only need to fill in the blank half. Thank you!

Specialist Name:

Working Site:

Table A. Sustainability indicator system for ship-to-ship minerals transfer

objective Indicator (A)	Secondary indicators (B)	Tertiary indicators (C)
Sustainability indicators for mineral transfer units (A)	Environmental Indicators(B1)	Noise(C1)
		Water pollution(C2)
		Carbon Emission(C3)
		Resource consumption(C4)
		Waste generation(C5)
		Marine pollution area (C6)
		Dust control (C7)
		Renewable Energy Utilization (C8)
		Energy saving technology and equipment (C9)
		Water consumption per unit of transshipment (C10)
	Economic indicators(B2)	Annual transfer volume (C11)
		Energy consumption per unit transfer volume (C12)
		Equipment procurement cost (C13)
		Operation and maintenance cost (C14)
		Economic efficiency (C15)
		Uncertainty (C16)
		Equipment replacement rate (C17)
		Environmental investment (C18)
	Technical indicators (B3)	Transit accident rate (C19)

		Equipment reliability (C20)
		Sustainability (C21)
		Technical Feasibility(C22)
		Technical operability(C23)
		Technical Maturity(C24)
		Technological Innovation (C25)
		Contingency Management (C26)

Table B. Scales of indicators weight

	Environmental Indicators	Economic Indicators	Technical indicators
Environmental Indicators			
Economic Indicators			
Technical indicators			

Table C. Environment indicators

	Noise(C1)	Water pollution(C2)	Carbon Emission(C3)	Resource consumption(C4)	Waste generation(C5)	Marine pollution area (C6)	Dust control (C7)	Renewable Energy Utilization (C8)	Energy saving technology and equipment (C9)	Water consumption per unit of transshipment (C10)
Noise(C1)										
Water pollution(C2)										
Carbon Emission(C3)										
Resource consumption(C4)										
Waste generation(C5)										
Marine pollution area (C6)										
Dust control (C7)										
Renewable Energy Utilization (C8)										
Energy saving technology and equipment (C9)										
Water consumption per unit of transshipment (C10)										

Table D Economic indicators

	Annual transfer volume (C11)	Energy consumption per unit transfer volume (C12)	Equipment procurement cost (C13)	Operation and maintenance cost (C14)	Economic efficiency (C15)	Uncertainty (C16)	Equipment replacement rate (C17)	Environmental investment (C18)
Annual transfer volume (C11)								
Energy consumption per unit transfer volume (C12)								
Equipment procurement cost (C13)								
Operation and maintenance cost (C14)								
Economic efficiency (C15)								
Uncertainty (C16)								
Equipment replacement rate (C17)								
Environmental investment (C18)								

Table E. Technic indicators

	Transit accident rate (C19)	Equipment reliability (C20)	Sustainability (C21)	Technical Feasibility(C22)	Technical operability(C23)	Technical Maturity(C24)	Technological Innovation (C25)	Contingency Management (C26)
Transit accident rate (C19)								
Equipment reliability (C20)								
Sustainability (C21)								
Technical Feasibility(C22)								
Technical operability(C23)								
Technical Maturity(C24)								
Technological Innovation (C25)								
Contingency Management (C26)								

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