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Factors Influencing the Enhancement of Marine Oil Spill Response Operations: Application of Interpretive Structural Modeling at Chabahar Port

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ABSTRACT

Marine oil pollution is a major environmental challenge that threatens marine ecosystems, coastal economies, and human health. As Iran's only ocean port, handling a high volume of ocean-going vessel traffic, Chabahar Port faces a significant risk of oil-related incidents. Despite existing research on the detection and cleanup of oil pollution, the literature lacks a study that comprehensively identifies the factors influencing the improvement of response operations and establishes a causal hierarchy among them. This study was conducted to identify and hierarchically classify these factors at Chabahar Port. This study is applied in terms of objective, descriptive-survey in terms of data collection, and quantitative in nature. The statistical population consisted of personnel from the Maritime Affairs Division of the Sistan and Baluchestan Ports and Maritime Administration, shipping companies, and the Department of Environment (N=35); 30 individuals participated via purposive non-random sampling. Through a systematic review of domestic and international literature, 22 influential factors were identified. Questionnaire reliability was assessed using Cronbach's alpha coefficient based on a pilot sample of 10 participants. Content validity was evaluated via the Delphi method over two rounds involving 20 experts (Kendall's coefficient = 0.92; Sig < 0.05). Finally, the factors were categorized using Interpretive Structural Modeling (ISM) and MICMAC analysis.

All 22 factors were validated through the Delphi process. The ISM results classified the factors into three causal levels; the third-level factors—comprising the identification of pollution sources, infrastructure development, and international standards—exhibited the highest driving power and the lowest dependence, identifying them as the system's primary drivers. Based on the MICMAC analysis, the factors were categorized into four groups: independent, dependent, linkage, and autonomous.

The results indicated that one factor fell into the independent group, three into the dependent group, and eighteen into the linkage group. It can be concluded that by identifying and prioritizing these influential factors, financial, human, and technical resources for combating marine oil pollution can be allocated more effectively, thereby preventing resource wastage or allocation errors. This prioritization of resources can serve as a basis for strategic planning by managers in this field.

1. Introduction

Oil spills into the marine environment are among the most significant environmental disasters, causing extensive adverse impacts on marine and coastal ecosystems. Such pollution can lead to the mortality of marine organisms, destruction of natural habitats, and loss of biodiversity. Oil spills reaching coastal areas can also cause coastal erosion, damage tourism resources, and reduce the economic productivity of

coastal regions. In this context, oil spill response operations encompass a range of physical, chemical, and biological methods aimed at mitigating the environmental impacts of oil. For example, physical methods such as booms and sorbents are used to contain and recover spilled oil, while chemical methods such as dispersants are employed to accelerate the dispersion and removal of oil from the water. In addition, biological techniques, including the use of oil-degrading bacteria, have attracted attention as a sustainable response strategy. Among the factors influencing the success of oil spill response operations are the physicochemical properties of the oil, marine environmental conditions, the type of affected shoreline, and the speed of response to the incident. These factors play a decisive role in determining the appropriate response method and its effectiveness. For instance, heavy and viscous oils generally require more complex cleanup methods because of their higher density and greater persistence [1, 2, 3].

Ineffective and improper implementation of marine oil spill response operations can result in serious environmental, economic, and human health consequences. Inadequate response measures may damage marine habitats and cause the mortality of marine species and aquatic birds. Furthermore, inappropriate long-term management of oil pollution can have persistent adverse effects on the environment, while restoration and recovery may require considerably more time and financial resources [4].

Another important concern is that improper response operations can adversely affect local industries that depend on marine resources. Oil pollution can negatively affect various economic sectors, including fisheries, coastal tourism, and maritime transportation, while ineffective response measures may further intensify these impacts. Moreover, oil pollution can pose risks to human health through direct contact with contaminants or through the consumption of contaminated seafood [5].

Improper oil spill response operations can also contribute to the degradation of biodiversity and the loss of various marine species. Therefore, the proper and effective implementation of response operations is essential for mitigating these risks and protecting the environment, the economy, and human health [6].

Various methods are used to clean up oil pollution from marine and coastal environments, including physical methods (booms and skimmers), chemical methods (dispersants), natural and synthetic sorbents, high-pressure hot-water washing, mechanical recovery, and bioremediation [7].

In Iran, the Law on the Protection of Seas and Navigable Rivers against Oil Pollution, enacted in 2010, stipulates that protective and preventive measures must be undertaken by the responsible institutions and operators of all vessels and oil-related facilities operating in the country's internal waters [8].

Oil recovery from the water surface is the stage that follows the containment of an oil spill during spill cleanup operations and is generally considered one of the most important stages of pollution removal. A key objective of containment is to increase the concentration of spilled oil, thereby increasing the thickness of the oil layer and facilitating its recovery. These two stages are usually performed simultaneously. Following the deployment of booms to contain the spill and ensure the effectiveness of the containment operation, personnel and equipment must be dispatched to the affected area immediately. When the spilled oil becomes widely dispersed across the water surface, its recovery becomes difficult and, in some cases, impossible [9].

Coastal refinery facilities, offshore oil platforms, tanker operations, tanker accidents, and the discharge of contaminated waters and rivers into the sea are among the major sources of marine oil pollution. Adverse environmental impacts, mortality of marine organisms, contamination of seafood and its resulting unsuitability for human consumption, and reduced flight capability of seabirds due to oil contamination of their feathers are among the consequences of the release of light and heavy crude-oil compounds into the marine environment. The cost of oil spill recovery depends on factors such as the type of petroleum hydrocarbons, the severity of the spill, the geographical and economic characteristics of the affected area, weather and sea conditions, and the recovery method employed, and may reach substantial levels. Although preventing oil spills is always the preferred strategy, an effective and timely response to an incident requires sufficient knowledge and awareness of the various oil spill recovery methods [10].

Chabahar Port is one of the most important and busiest ports in Iran. It is located in Sistan and Baluchestan Province in southeastern Iran, along the southern coast of the Gulf of Oman. As Iran's only oceanic port, Chabahar has two equipped terminals with an annual cargo-handling capacity of 8.5 million tons, allowing ocean-going vessels to berth at its facilities. Currently, more than 60% of the country's essential commodities are imported through this port, and it is the only Iranian port exempt from any sanctions. Accordingly, given its geographical location and economic, commercial, and tourism significance, Chabahar Port plays an important role in the economic and social development of both the region and the country [11].

Oil pollution in Chabahar Port may result from incidents such as oil leakage or spills from oil transportation vessels or illegal discharges into the sea. Such pollution can threaten the environment, the economy, and human health and directly affect the port as one of Iran's major economic and commercial ports. Therefore, the present study aims to identify and prioritize the factors affecting the improvement of oil spill response operations in the waters of Chabahar

Port. Accordingly, the study seeks to answer the following research questions:

a) What factors affect the improvement of marine oil spill response operations?
b) How should the factors affecting the improvement of marine oil spill response operations be prioritized?

2. Literature Review

2.1 Marine Oil Pollution and Oil Spill Response Operations

Pollution refers to the introduction or presence of harmful and undesirable substances in the environment that can adversely affect human health, animals, plants, and ecosystems. These pollutants originate from various sources, including industrial activities, transportation, agriculture, and other human activities, and can enter the air, water, and soil. Pollution may occur continuously or intermittently and can have direct and indirect consequences, including increased disease incidence, deterioration of air, water, and soil quality, reduced agricultural productivity, destruction of natural habitats, and exacerbation of climate change. Reducing pollution requires the adoption of cleaner technologies, effective implementation of environmental laws and regulations, increased public awareness, material recycling, efficient resource use, and promotion of sustainable lifestyles [12].

Marine water pollution is one of the major challenges to environmental protection and the sustainability of marine ecosystems. It refers to the introduction of harmful substances and pollutants into oceans, seas, and coastal areas. These pollutants originate from various sources, including the discharge of municipal and industrial wastewater, agricultural runoff containing fertilizers and chemical pesticides, chemical industry activities, oil and gas operations, and marine accidents. In addition, the introduction of plastic waste and microplastics into the marine environment poses a serious threat to aquatic life and biodiversity. The continuation of these processes can lead to declines in biodiversity and aquatic resources, the accumulation of chemical pollutants, and increased environmental and health risks in marine and coastal areas. Addressing marine water pollution requires effective wastewater control and treatment, proper waste management, the application of clean and water-treatment technologies, and the promotion of environmentally responsible behaviors [13].

Marine pollution originating from petroleum sources is one of the most significant threats to the health of marine ecosystems and the environment. This type of pollution can result from oil discharges from vessels, oil leaks from tankers and oil and gas facilities, drilling accidents, and offshore oil platform activities. By forming a layer on the water surface, oil can disrupt oxygen exchange and essential biological processes in aquatic organisms and seabirds, potentially causing marine mortality, reduced growth and reproduction, disruption of food chains, and degradation of marine habitats. Other consequences include reductions in aquatic stocks and catches, deterioration of water quality, damage to coastal tourism, and economic losses. Human exposure to contaminated water or consumption of contaminated seafood may also pose health risks, including skin, respiratory, and gastrointestinal problems. Therefore, the prevention and control of oil pollution require the strengthening of environmental standards and regulations, continuous monitoring of petroleum sources, enhancement of preparedness for oil spill response, and the use of advanced technologies for the cleanup and treatment of contaminated waters [14].

Marine oil spill response is a complex, multi-stage process that requires planning, interorganizational coordination, and the application of appropriate technologies. First, the location of the spill and the extent and volume of contamination are determined using monitoring systems, aerial and marine surveillance, and other detection technologies. In the next stage, the most appropriate response strategy is selected based on the volume and type of oil, sea conditions, spill location, and the sensitivity of the affected area. Such strategies may include mechanical containment and recovery, the use of sorbents, or chemical treatment methods. Following the declaration of an emergency, coordination among maritime forces, environmental organizations, and other relevant agencies is undertaken to implement the response operation. The use of advanced equipment and technologies, including oil recovery and cleanup systems, specialized vessels, aircraft, unmanned aerial vehicles, and robots, can enhance the effectiveness of response operations. Finally, post-response monitoring and assessment are conducted to evaluate the extent of cleanup, identify residual pollution, and assess its environmental and social impacts. Overall, successful oil spill response depends on effective planning, coordination among responsible organizations, and the selection of technologies appropriate to the conditions of the incident [15, 16].

2.2 Chabahar Port

Chabahar Port, located in southeastern Iran along the coast of the Gulf of Oman, is one of the country's strategic ports and the only Iranian oceanic port with direct access to open waters. The port's geographical location facilitates access to international waters for the landlocked countries of Central Asia, Afghanistan, and parts of South Asia, making Chabahar one of the region's important gateways for transit and maritime trade. From an economic perspective, the port also plays an important role in the development of Iran's regional and international trade, particularly along trade routes connecting India, Afghanistan, and

Central Asia. The development of its infrastructure is considered one of the country's strategic objectives for strengthening Iran's position in international trade and transportation networks. In addition, existing capacities in the energy, petrochemical, and fisheries sectors further enhance the economic and developmental significance of Chabahar. The geographical location of Chabahar Port is illustrated in Figure 1.

Given the strategic location of Chabahar Port and the expansion of commercial, maritime, and industrial activities in the region, the likelihood of accidents and oil pollution incidents is also increasing. The movement of commercial vessels and tankers, the loading and unloading of oil cargoes, and the development of port and industrial infrastructure are among the factors that may increase the risk of oil spills and their associated environmental impacts. Therefore, identifying and prioritizing the factors affecting the improvement of oil spill response operations at this port is particularly important for protecting the marine ecosystem and ensuring the continuity of its economic and commercial activities. Strengthening the operational and managerial capacities for oil spill response can reduce the environmental and economic consequences of oil-related incidents while enhancing the resilience of Chabahar Port to environmental hazards. Moreover, improving the port's capabilities in managing and controlling oil pollution can contribute to strengthening the confidence of trading partners and regional countries and consolidating Chabahar's position as a safe and sustainable port within international transportation and trade networks.

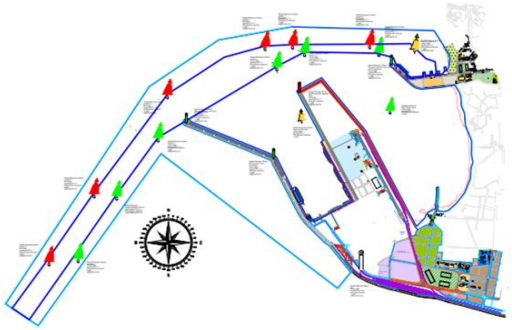


Figure 1. Geographical location of Chabahar Port

2.3 Review of Previous Research

Various studies have been conducted to investigate the role and impacts of marine pollution.

Sayareh et al. [17] examined the facilities and capabilities available for responding to oil and hazardous-material pollution at Chabahar Port and emphasized the need to enhance marine pollution response capacity. The data were collected through a questionnaire administered to employees of the Marine Pollution Response Department of the Ports and Maritime Organization at Chabahar Port. Golzadeh and Saadi [18] analyzed the capabilities and limitations of using booms and skimmers for oil spill response, identifying the strengths and weaknesses of these methods and proposing strategies to improve their application. The study employed library research, comparative analysis, and a case study of oil spill response operations in the Shavoor River, Khuzestan Province. Moghimi-Haji [19] introduced different types of skimmers and examined the role of this equipment in responding to oil pollution in water. The findings indicated that the selection of an appropriate skimmer should be based on environmental conditions and the type and volume of pollution.

Shirvani and Mousavi-Nejad [20] investigated the factors affecting the implementation of oil pollution conventions in the ports of Khuzestan Province. Based on the research literature and the opinions of 33 experts, the relevant factors were identified and their status at Imam Khomeini Port was evaluated. The results showed that the port had a favorable status in most sub-factors related to training and equipment. Esmailzadeh [21] examined the impacts of oil pollution on marine ecosystems and response strategies. The findings showed that petroleum compounds, depending on their characteristics, undergo evaporation, dissolution, or sedimentation in the marine environment, thereby damaging aquatic communities and marine ecosystems and ultimately causing economic losses. Furthermore, the expansion of petrochemical industries and maritime transportation has increased the need to control and mitigate the consequences of oil pollution.

Zolghi and Za'farouni [22] developed an emergency response plan for addressing oil pollution at loading and unloading terminals. The findings indicated that the ecological sensitivity, biodiversity, and extensive economic and oil-related activities in these areas increase the likelihood of environmental incidents and consequently necessitate the development and implementation of emergency response plans. Abbasgholizadeh Benam [23] examined international legal measures for addressing oil pollution in the high seas using a descriptive-analytical approach. The findings emphasized the need to strengthen legal and international measures to protect marine ecosystems and prevent the increasing consequences of oil pollution.

Azizi et al. [24] investigated strategies for reducing oil pollution in the marine environment of Chabahar. The findings showed that petroleum compounds are gradually degraded through physical, chemical, and biological processes, resulting in reduced toxicity. Nevertheless, oil wells, drilling rigs, and offshore platforms were identified as among the most important sources of petroleum pollutants entering marine waters. Krek et al. [25] investigated chronic oil pollution from ships and its contribution to background pollution in

the southeastern Baltic Sea. The results showed that the concentration of petroleum products exhibited seasonal variations and had declined since 2007. In addition, the annual amount of these substances released from ships was reported to be lower than their instantaneous concentration in the water column.

Yang et al. [26] examined offshore oil pollution, including its sources, consequences, and prevention and response methods from physical, chemical, and biological perspectives. The study emphasized the increasing severity of oil pollution associated with the growth of maritime transportation.

Han et al. [27] assessed the consequences of the Penglai 19-3 oil spill accident by modeling oil transport using hydrodynamic and monitoring data. The results indicated a rapid decline in the abundance of shellfish in areas exposed to the pollution.

Jafarzadeh et al. [28] conducted a systematic review and meta-analysis of oil spill detection methods based on synthetic aperture radar (SAR) imagery. The study examined the effects of data characteristics, sensors, frequency bands, polarization, and imaging conditions on oil spill detection.

Yang et al. [29] conducted a systematic review of decision-support tools for oil spill response, examining the advantages and limitations of existing and emerging approaches and emphasizing the requirements for oil spill response in cold and polar regions.

Wang et al. [6] proposed a method based on synthetic aperture radar (SAR) imagery and a deep convolutional neural network for oil spill detection. Through model optimization and post-prediction processing, the proposed approach improved detection accuracy.

Asif et al. [1] investigated the environmental consequences and challenges associated with oil spills in coastal areas. The results showed that fluorometric sensors are capable of detecting oil on different substrates, including snow and ice. The study also indicated that physical, chemical, and biological response methods each have specific advantages and limitations depending on coastal conditions.

Zhang et al. [14] confirmed the potential of optical polarization remote sensing for oil spill detection and examined the challenges associated with polarization modeling and feature extraction.

Nguyen et al. [30] modeled an oil spill in the East China Sea and demonstrated that integrating data with high temporal and spatial resolution and incorporating wind-drift effects can improve prediction accuracy. A one-month simulation also showed that the oil slick primarily moved northeastward under the influence of ocean currents.

Gong et al. [31] proposed a semi-supervised method for detecting oil fluorescence induced by ultraviolet radiation. By utilizing unlabeled data, the method improved classification accuracy and the generalizability of the model.

Iouzzi et al. [32] modeled the behavior and fate of an oil spill in the Amzorn River estuary. The findings emphasized the necessity of rapid response to reduce environmental consequences and cleanup costs, as well as its importance in developing emergency response plans.

Arslan et al. [33] proposed a method based on principal component analysis and satellite remote-sensing data for oil spill detection and monitoring. The results showed that integrating multisource imagery and data can improve the accuracy of oil spill detection.

Kuang et al. [34] investigated the interactions among wind, waves, and currents in determining oil spill behavior in the Yangtze River estuary. The results showed that hydrodynamic conditions, particularly storms, have significant effects on the transport, dispersion, sedimentation, and spatial extent of oil slicks.

Wu et al. [12] proposed a method based on induced fluorescence and a random sample consensus algorithm for rapid oil pollution detection. The method demonstrated high accuracy and the capability to identify oil concentrations ranging from 0 to 1000 mg/L.

Nguyen et al. [10] used integrated modeling to identify high-risk areas for oil spills in the coastal waters of Taiwan based on the frequency of oil slicks reaching the shoreline and the presence of sensitive resources. The findings can be applied to response planning and the improvement of shipping regulations.

Akhmedov et al. [5] developed a comprehensive model for oil spill detection and segmentation in marine environments. After 100 training epochs, the model achieved an accuracy of more than 97% and demonstrated suitable capabilities for real-time oil spill detection.

3. Methodology

3.1 Factor Extraction

The research philosophy of this study is interpretivism, grounded in the interpretive paradigm and a subjectivist approach. Accordingly, reality is not perceived as an objective entity independent of individuals, but rather as something shaped through social interactions. The research approach is inductive, meaning that by examining data and specific evidence and establishing relationships among them, general inferences are drawn. In terms of objective, the present study is applied research, as it aims to identify and prioritize the factors influencing the enhancement of oil spill response operations at sea. Regarding data collection methods, this research is descriptive-survey in nature, and in terms of data type, it is quantitative, employing quantitative methods for prioritizing the factors. Furthermore, the study is cross-sectional in terms of time frame, with data collected at a specific

point in time through observation and questionnaires [35].

The statistical population of the study comprised 35 personnel from the Maritime Deputy of the Ports and Maritime Administration of Sistan and Baluchestan Province (Chabahar Port), shipping companies, and the Department of Environment. Sampling was conducted using a non-random purposive (judgmental) method, and individuals with at least five years of work experience at Chabahar Port and a bachelor's degree in fields related to pollution were included in the study. The sample size was determined as 30 participants based on Morgan's table. Data were collected through both library and field methods. Library research was employed to review theoretical foundations, background literature, and identify factors affecting the improvement of oil spill response operations, while the field method, utilizing a questionnaire, was applied for prioritizing the identified factors.

To identify the factors influencing the enhancement of oil spill response operations at sea, an extensive search was conducted using relevant keywords in domestic databases including Magiran, Civilica, IranDoc, the Academic Center for Education, Culture and Research (ACECR) studies center, and Noor Database, as well as international databases such as MDPI, Elsevier, and Sage. In the initial stage, 68 articles were identified, of which 35 were excluded after reviewing titles and abstracts. Ultimately, 22 relevant articles were selected for factor extraction.

For the selection of studies to be included in the meta-analysis, only those studies were considered that addressed variables related to oil spill response operations at sea and utilized quantitative and statistical data derived from field studies or statistical results of previous research. Figure 2 illustrates the search, screening, and selection process of the reviewed studies.

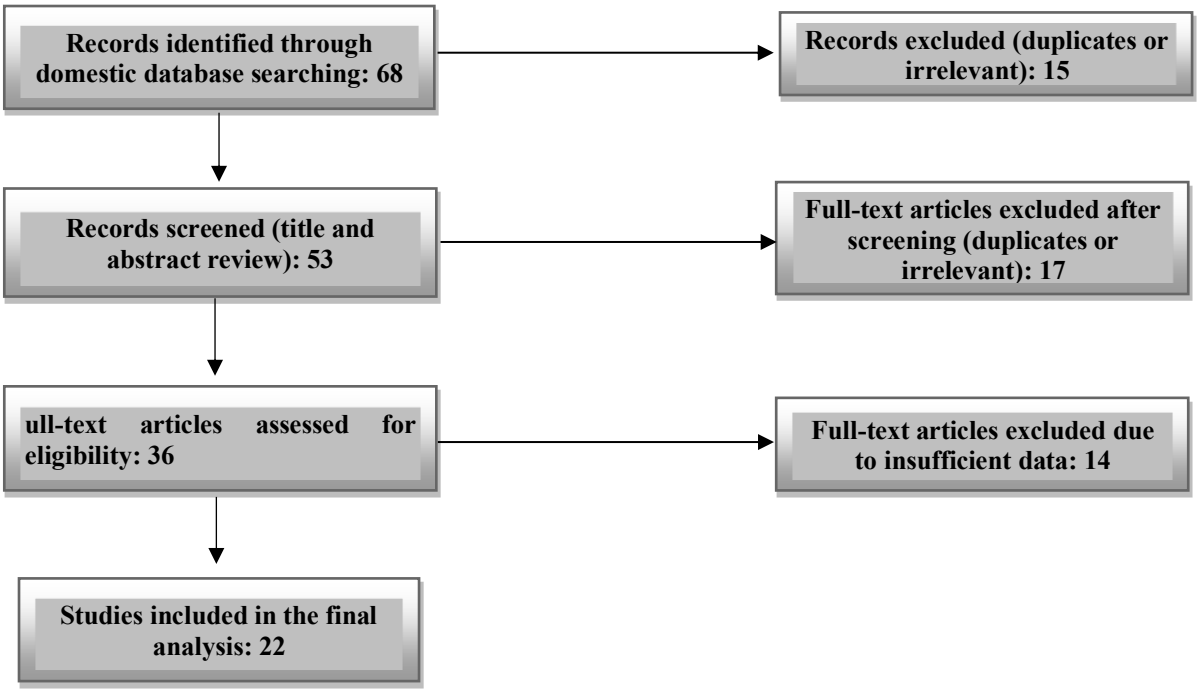


Figure 2: Process of searching, screening, and selecting studies

As illustrated in Figure 2, the literature review process resulted in the identification of 22 factors contributing to the improvement of oil spill response operations at sea. These factors, along with their respective references, are presented in Table 1.

Table 1: Factors Identified from the Review of Research Literature

Row	Factors	Research Method	Source
1	Identification and tracking of oil pollution sources	Quantitative	[25]
2	Establishment of pollution prevention systems	Quantitative	[30]
3	Application of novel technologies for pollution detection and tracking	Qualitative	[6]
4	Development of educational programs for oil pollution reduction	Qualitative	[32]
5	Establishment of rapid response teams for oil incident management	Qualitative	[34]
6	Application of artificial intelligence for pollution prevention	Quantitative	[26]
7	Collaboration with relevant international organizations	Qualitative	[27]

Row	Factors	Research Method	Source
8	Development of sustainable development plans for pollution reduction	Qualitative	[29]
9	Development of infrastructure related to oil incidents	Qualitative	[12]
10	Establishment of communication and coordination systems among various organizations	Qualitative	[1]
11	Establishment of international standards for oil spill response	Qualitative	[31]
12	Comprehensive training and awareness-raising on oil spill response	Qualitative	[33]
13	Risk assessment and management related to oil incidents	Qualitative	[35]
14	Development of green and environmentally friendly technologies	Qualitative	[10]
15	Establishment of strict regulations and legislation for pollution prevention	Qualitative	[5]
16	Establishment of cooperative networks among various centers	Qualitative	[28]
17	Development of maintenance and upgrading plans for oil spill response equipment	Qualitative	[14]
18	Establishment of regional and international monitoring and evaluation systems	Qualitative	[14]
19	Promotion of environmental protection culture and reduction of oil consumption	Qualitative	[36]
20	Development of emergency plans and necessary logistics for oil incident response	Qualitative	[37]
21	Establishment of comprehensive and reliable databases on oil pollution	Qualitative	[9]
22	Development of international collaborations to address oil pollution impacts	Qualitative	[38]

3.2 Data Analysis

To evaluate the validity and reliability of the identified factors, a researcher-developed questionnaire was designed based on a five-point Likert scale. The questionnaire was administered to 10 managers and experts affiliated with the Ports and Maritime Administration of Sistan and Baluchestan Province, shipping companies, and the environmental organization of Chabahar Port. Convergent validity was measured using the Average Variance Extracted (AVE), while reliability was assessed through Cronbach's alpha and Composite Reliability (CR). Following the Fornell–Larcker (1981) criterion, AVE values above 0.5 were considered indicative of acceptable convergent validity, and CR values above 0.7 were deemed to reflect satisfactory internal consistency. The detailed results of these analyses are summarized in Table 2.

Table 2: Validity and Reliability Indices for the Identified Factors

Row	Factors	AVE	Composite Reliability (CR)	Cronbach's Alpha
1	Identification and tracking of oil pollution sources	0.788	0.633	0.769
2	Establishment of pollution prevention systems	0.502	0.861	0.788
3	Application of novel technologies for pollution detection and tracking	0.577	0.846	0.867
4	Development of educational programs for oil pollution reduction	0.691	0.793	0.808
5	Establishment of rapid response teams for oil incident management	0.788	0.749	0.768
6	Application of artificial intelligence for pollution prevention	0.629	0.809	0.815
7	Collaboration with relevant international organizations	0.576	0.881	0.739
8	Development of sustainable development plans for pollution reduction	0.732	0.798	0.700
9	Development of infrastructure related to oil incidents	0.625	0.833	0.834
10	Establishment of communication and coordination systems among various organizations	0.639	0.800	0.800
11	Establishment of international standards for oil spill response	0.799	0.834	0.702
12	Comprehensive training and awareness-raising on oil spill response	0.766	0.800	0.801
13	Risk assessment and management related to oil incidents	0.729	0.788	0.866
14	Development of green and environmentally friendly technologies	0.711	0.798	0.799
15	Establishment of strict regulations and legislation for pollution prevention	0.764	0.845	0.734
16	Establishment of cooperative networks among various centers	0.664	0.769	0.900
17	Development of maintenance and upgrading plans for oil spill response equipment	0.766	0.786	0.855
18	Establishment of regional and international monitoring and evaluation systems	0.785	0.888	0.749
19	Promotion of environmental protection culture and reduction of oil consumption	0.834	0.867	0.795
20	Development of emergency plans and necessary logistics for oil incident response	0.761	0.882	0.732
21	Establishment of comprehensive and reliable databases on oil pollution	0.715	0.887	0.861
22	Development of international collaborations to address oil pollution impacts	0.666	0.916	0.899

The results demonstrated that all identified factors exhibited satisfactory validity and reliability. To further validate the factors, a two-round Delphi technique was conducted involving 20 experts, using a five-point Likert scale. In the second round, no factors were excluded, as all maintained an average score of 4 or above. Additionally, Kendall's W coefficient was calculated to assess the consensus among experts across the two rounds. The significance level ($p < 0.05$) confirmed a statistically meaningful agreement, with a 92% correlation observed between the first and second rounds, thereby validating all 22 factors.

For the prioritization of the identified factors, both the Analytical Hierarchy Process (AHP) and Interpretive Structural Modeling (ISM) are viable methods. However, ISM was selected for this study due to its superior capability in uncovering the interrelationships and multi-directional influences among factors, ultimately presenting them within a hierarchical framework. Consequently, ISM is better suited for complex contexts where factors exert reciprocal effects on one another.

4. Findings and Results

The prioritization of the extracted factors was carried out using Interpretive Structural Modeling (ISM). This interactive methodology facilitates the identification and systematic structuring of complex interrelationships among variables, relying on expert input. By evaluating the driving power and dependence of each factor, ISM organizes them into a hierarchical multi-level model, making it a robust tool for tackling complex problems [39]. The step-by-step procedure of ISM encompasses factor identification, establishment of contextual relationships, construction of the Structural Self-Interaction Matrix (SSIM), derivation and analysis of the reachability matrix, level partitioning, development of a directed graph with the elimination of transitive relationships, formulation of the interpretive structural model, and final validation and refinement [40]. The demographic profile of the expert panel, including average age, years of experience, and academic qualifications related to the subject matter, is summarized in Table 3.

Table 3: Demographic Characteristics of the Expert Panel

Group	Number	Mean Age (years)	Mean Work Experience (years)	Education
Personnel of the Ports and Maritime Administration of Sistan and Baluchestan Province (Chabahar Port)	30	38.33	8.33	Bachelor's: 14 Master's: 14 PhD: 2

The examination of the mean age of the expert panel revealed that the personnel of the Maritime Deputy of the Ports and Maritime Administration of Sistan and Baluchestan Province (Chabahar Port) had a mean age of 38.33 years and a mean work experience of 8.33 years. Among the participants in the present study, 14 held a bachelor's degree, 14 held a master's degree, and 2 held a doctoral degree.

The first research question pertains to the identification of factors influencing the enhancement of oil spill response operations at sea. To address this question, in the initial stage, factors relevant to the subject were identified and listed as the intended criteria, the results of which are presented in Table 1. In the second stage, the contextual relationships among the factors—meaning the conceptual connections between the components of the system—were examined using the Delphi method and Kendall's W test. The results indicated a significance level of less than 0.05 and a Kendall's coefficient of 0.92, signifying statistical significance and a high level of agreement among the variables.

The second research question addresses the prioritization of factors influencing the enhancement of oil spill response operations at sea. In the first stage of Interpretive Structural Modeling (ISM), the Structural Self-Interaction Matrix (SSIM) was developed, the results of which are presented in Table 4. At this stage, the 22 identified factors were placed in the rows and columns of the matrix, and experts determined the pairwise relationships among the factors based on their specialized knowledge and experience. To define the type of relationships, the symbols V, A, X, and O were used to indicate the influence of factor i on j, the influence of factor j on i, mutual influence, and no relationship, respectively, which were coded as 1, -1, 2, and 0, respectively. The identified factors and their corresponding codes are presented as follows: Identification and tracking of oil pollution sources (A), Establishment of pollution prevention systems (B), Application of novel technologies for pollution detection and tracking (C), Development of educational programs for oil pollution reduction (D), Establishment of rapid response teams for oil incident management (E), Application of artificial intelligence for pollution prevention (F), Collaboration with relevant international organizations (G), Development of sustainable development plans for pollution reduction (H), Development of infrastructure related to oil incidents (I), Establishment of communication and coordination systems among various organizations (J), Establishment of international standards for oil spill response (K), Comprehensive training and awareness-raising on oil spill response (L), Risk assessment and

management related to oil incidents (M), Development of green and environmentally friendly technologies (N), Establishment of strict regulations and legislation for pollution prevention (O), Establishment of cooperative networks among various centers (P), Development of maintenance and upgrading plans for oil spill response equipment (Q), Establishment of regional and international monitoring and evaluation systems (R), Promotion of environmental protection culture and reduction of oil consumption (S), Development of emergency plans and necessary logistics for oil incident response (T), Establishment of comprehensive and reliable databases on oil pollution (U), and Development of international collaborations to address oil pollution impacts (V).

Table 4: Structural Self-Interaction Matrix (SSIM) for the Identified Factors

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
A		1	2	2	-1	2	-1	2	2	0	1	1	1	1	1	1	1	1	-1	-1	1	1
B	-1		-1	2	-1	-1	-1	1	2	0	0	-1	1	1	1	1	1	1	1	1	2	2
C	2	1		2	-1	2	0	2	2	0	1	1	1	1	1	1	1	1	1	1	2	2
D	2	2	2		-1	-1	-1	2	2	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	1
E	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	-1	2	2	-1
F	2	1	2	1	-1		-1	-1	2	1	2	2	2	2	2	2	2	2	0	1	1	1
G	1	1	0	1	-1	1		1	1	1	2	2	2	2	1	2	1	2	-1	-1	-1	2
H	2	-1	2	2	-1	1	-1		2	0	1	1	1	1	1	1	1	1	-1	1	1	1
I	2	2	2	2	-1	2	-1	2		0	1	1	1	1	1	1	1	1	0	0	1	-1
J	0	0	0	1	-1	-1	-1	0	0		1	1	-1	1	1	1	1	1	1	1	0	1
K	-1	0	-1	1	-1	2	2	-1	-1	-1		2	1	2	2	2	0	-1	1	-1	2	2
L	-1	1	-1	1	-1	2	2	-1	-1	-1	2		2	1	1	1	1	-1	1	-1	2	2
M	-1	-1	-1	-1	-1	2	2	-1	-1	1	-1	2		1	1	1	-1	0	1	-1	-1	-1
N	-1	-1	-1	-1	-1	2	2	-1	-1	-1	2	-1	-1		0	0	-1	-1	1	-1	2	2
O	-1	-1	-1	-1	-1	2	-1	-1	-1	-1	2	-1	-1	0		0	-1	-1	1	-1	2	2
P	-1	-1	-1	-1	-1	2	2	-1	-1	-1	2	-1	-1	0	0		-1	-1	-1	-1	2	2
Q	-1	-1	-1	-1	-1	2	-1	-1	-1	-1	2	-1	-1	0	0	0		0	0	1	1	1
R	-1	-1	-1	-1	-1	2	2	-1	-1	-1	2	-1	-1	0	0	0	0		0	2	2	2
S	1	1	1	1	1	1	1	-1	2	2	-1	1	1	1	1	1	1	-1		2	2	2
T	2	2	2	2	2	2	2	0	1	1	1	2	2	2	2	2	2	0	1		1	2
U	2	2	2	1	2	1	2	-1	-1	-1	2	2	2	2	1	2	1	1	1	-1		0
V	1	1	1	1	1	1	1	-1	1	1	1	1	1	1	1	1	1	1	0	0	2	

Once the initial reachability matrix was established, the final reachability matrix was derived through the application of the transitivity rule. This rule posits that if variable i is linked to variable j, and variable j is linked to variable k, then variable i is also linked to variable k. In this phase, the indirect (secondary) relationships among the variables were systematically examined, leading to the development of the final reachability matrix, which is presented in Table 5. This matrix provides valuable insights into the driving power and dependence of each variable. Specifically, driving power is defined as the total number of variables that a particular variable can influence, while dependence is defined as the total number of variables that influence that particular variable.

Table 5: Final Reachability Matrix with Driving Power and Dependence

Factor	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	Driving Power
A	1	0	1	0	1	1	0	0	1	0	1	1	1	0	1	1	1	0	1	0	1	0	**13**
B	1	1	1	1	1	0	1	1	1	1	0	1	1	1	0	0	0	1	0	0	0	1	**14**
C	1	0	1	1	0	1	0	0	0	0	1	1	1	0	1	1	0	1	1	1	1	1	**14**
D	1	0	0	1	1	0	1	1	0	1	1	1	1	1	0	0	0	1	0	1	0	1	**13**
E	1	0	0	1	1	0	0	1	1	1	1	0	0	0	1	1	0	0	1	1	1	1	**13**
F	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	0	1	0	0	0	0	1	**9**
G	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1	1	1	1	0	**14**
H	1	1	1	1	0	0	0	1	1	1	1	1	0	1	1	1	0	1	1	0	0	1	**15**
I	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	1	0	0	1	1	1	1	**16**
J	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	0	1	0	1	0	**14**
K	1	0	0	0	1	1	1	1	0	1	1	1	1	1	1	0	1	1	0	0	0	1	**14**
L	1	0	0	0	0	0	0	1	1	1	1	1	0	1	0	1	0	1	1	1	0	0	**11**
M	0	0	0	1	1	1	1	0	1	1	0	1	1	1	0	1	1	0	1	0	1	0	**13**
N	1	1	1	1	1	0	0	1	1	1	1	0	0	1	1	0	0	0	0	1	1	1	**14**
O	1	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	0	0	**13**
P	0	0	1	1	0	0	1	1	1	0	0	1	1	0	0	1	0	0	1	0	1	0	**10**
Q	1	1	1	0	1	0	0	0	1	1	1	0	0	1	1	1	1	0	0	1	1	1	**14**
R	1	1	1	0	0	1	1	1	0	1	1	1	1	0	0	1	1	1	1	1	0	0	**15**
S	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	0	1	0	1	0	1	1	**15**
T	0	0	1	1	1	1	0	1	1	1	1	1	1	0	1	0	0	1	1	1	1	0	**15**

Factor	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	Driving Power
U	0	0	0	0	0	1	1	1	1	1	0	1	0	1	0	0	0	0	0	0	1	1	**9**
V	0	1	1	1	1	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	0	1	**16**
Dependence	**16**	**9**	**12**	**13**	**13**	**12**	**13**	**17**	**16**	**15**	**16**	**15**	**12**	**15**	**13**	**12**	**11**	**11**	**15**	**12**	**13**	**13**	

In order to establish the hierarchical structure of the final ISM model, the final reachability matrix was subjected to level partitioning. This procedure was carried out using three key sets for each factor: the reachability set (comprising the factor itself and all other factors it influences), the antecedent set (comprising the factor itself and all other factors that influence it), and the intersection of these two sets. The level of each factor was determined by identifying those factors for which the reachability set and the intersection set were identical. Such factors were assigned to the highest level of the hierarchy and were then removed from subsequent partitioning iterations. This iterative process was repeated until the levels of all 22 factors were determined. The outcomes of this level partitioning are summarized in Table 6.

Table 6. Level Partitioning of the Identified Factors

Row	Factors	Reachability Set	Antecedent Set	Intersection Set	Driving Power	Dependence	Level
1	Identification and tracking of oil pollution sources	{1, 3, 5, 6, 9, 11, 12, 13, 15, 16, 17, 22}	{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 17, 18}	{1, 3, 5, 6, 9, 11, 12, 15, 17}	109	113	I
2	Establishment of pollution prevention systems	{1, 2, 3, 4, 5, 7, 8, 9, 10, 12, 13, 14, 20}	{2, 7, 8, 9, 14, 20}	{2, 7, 8, 9, 14, 20}	74	66	II
3	Application of novel technologies for pollution detection and tracking	{1, 3, 4, 6, 11, 12, 13, 15, 16, 21}	{1, 2, 3, 7, 8, 9, 14, 16, 17, 18}	{1, 3, 16, 18}	43	49	III
4	Development of educational programs for oil pollution reduction	{1, 4, 5, 7, 8, 10, 11, 12, 13, 14, 18}	{2, 3, 4, 5, 8, 9, 10, 13, 14, 20}	{4, 5, 8, 10, 13, 14}	68	68	II
5	Establishment of rapid response teams for oil incident management	{1, 4, 5, 8, 9, 10, 11, 15, 16, 20}	{1, 2, 4, 5, 7, 9, 11, 13, 14, 15, 17}	{4, 5, 9, 11, 15}	69	73	II
6	Application of artificial intelligence for pollution prevention	{1, 6, 7, 8, 9, 14, 15, 22}	{1, 3, 6, 9, 10, 11, 13, 15, 20}	{1, 6, 9, 15}	44	48	III
7	Collaboration with relevant international organizations	{1, 2, 3, 5, 7, 9, 11, 13, 15, 17, 22}	{2, 4, 6, 7, 9, 11, 13, 15, 16, 18}	{2, 7, 9, 11, 13, 15, 18}	62	54	II
8	Development of sustainable development plans for pollution reduction	{1, 2, 3, 4, 8, 9, 10, 11, 12, 14, 15, 16, 22}	{2, 4, 5, 6, 8, 9, 10, 11, 12, 14, 15, 16, 18}	{2, 4, 8, 9, 10, 11, 12, 14, 15, 16, 18}	126	123	I
9	Development of infrastructure related to oil incidents	{1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 14, 16, 18}	{1, 2, 5, 6, 7, 8, 9, 10, 12, 13, 14, 16, 17}	{1, 2, 5, 7, 8, 9, 14, 16}	110	112	I
10	Establishment of communication and coordination systems among various organizations	{1, 4, 6, 8, 9, 10, 11, 12, 13, 14, 16, 17}	{2, 4, 5, 8, 10, 11, 12, 13, 14, 17, 18}	{4, 8, 10, 11, 12, 13, 14, 17}	70	79	II
11	Establishment of international standards for oil spill response	{1, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 17}	{1, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14, 17, 18}	{1, 5, 7, 8, 10, 11, 12, 14, 17}	101	106	I
12	Comprehensive training and awareness-raising on oil spill response	{1, 8, 9, 10, 11, 12, 14, 16, 18}	{1, 2, 3, 4, 8, 10, 11, 12, 13, 16, 18}	{1, 8, 10, 11, 12, 16, 18}	79	87	II
13	Risk assessment and management related to oil incidents	{4, 5, 6, 7, 8, 10, 11, 13, 14, 15, 17, 22}	{1, 2, 3, 4, 7, 10, 11, 13, 15, 16, 18}	{4, 7, 10, 11, 13, 15, 18}	64	63	II
14	Development of green and environmentally friendly technologies	{1, 2, 3, 4, 5, 8, 9, 10, 11, 14, 15}	{2, 4, 6, 8, 9, 10, 11, 12, 13, 14, 15, 17}	{2, 4, 8, 9, 10, 11, 14, 15}	96	92	II
15	Establishment of strict regulations and legislation for pollution prevention	{1, 5, 6, 7, 8, 13, 14, 15, 16, 17, 18}	{1, 3, 5, 6, 7, 8, 11, 14, 15, 17}	{1, 5, 6, 7, 8, 14, 15, 17}	63	67	II
16	Establishment of cooperative networks among various centers	{3, 4, 7, 8, 9, 12, 13, 16}	{1, 3, 5, 8, 9, 10, 12, 13, 15, 16, 17, 18}	{3, 8, 9, 12, 13, 16}	55	59	II
17	Development of maintenance and upgrading plans for oil spill response equipment	{1, 2, 3, 5, 9, 10, 11, 14, 15, 16, 17}	{1, 6, 7, 10, 11, 13, 15, 17, 18}	{1, 10, 11, 15, 17}	34	38	III
18	Establishment of regional and international monitoring and evaluation systems	{1, 2, 3, 5, 9, 10, 11, 14, 15, 16, 17}	{1, 6, 7, 10, 11, 13, 15, 17, 18}	{1, 10, 11, 15, 17}	81	78	II

Row	Factors	Reachability Set	Antecedent Set	Intersection Set	Driving Power	Dependence	Level
19	Promotion of environmental protection culture and reduction of oil consumption	{1, 3, 5, 9, 12, 13, 15, 20, 22}	{1, 5, 9, 13, 20}	{1, 5, 9, 13, 20}	80	60	II
20	Development of emergency plans and necessary logistics for oil incident response	{4, 8, 11, 13, 16, 19, 20, 22}	{1, 5, 6, 9, 12, 16, 20}	{16, 20}	75	65	II
21	Establishment of comprehensive and reliable databases on oil pollution	{2, 5, 7, 10, 14, 15, 18, 20, 21, 22}	{3, 5, 20, 21}	{5, 20, 21}	82	72	I
22	Development of international collaborations to address oil pollution impacts	{1, 4, 7, 9, 10, 11, 15, 17, 19, 20, 22}	{1, 3, 5, 9, 11, 16, 18, 20, 21}	{1, 11, 20}	80	69	III

Based on the level partitioning outcomes and the final reachability matrix, a hierarchical structural model was developed to illustrate the relationships and positioning of the factors affecting the improvement of oil spill response operations at sea. This hierarchical structure categorizes the 22 identified factors into distinct levels, reflecting their relative influence and dependence within the system. The final level assignment and the specific position of each factor within the hierarchy are summarized in Table 7.

Table 7: Hierarchical Structure and Level Assignment of the Identified Factors

Level	Factors Influencing the Enhancement of Oil Spill Response Operations at Sea
Level I	Identification and tracking of oil pollution sources
	Development of sustainable development plans for pollution reduction
	Development of infrastructure related to oil incidents
	Establishment of international standards for oil spill response
	Establishment of comprehensive and reliable databases on oil pollution
Level II	Establishment of pollution prevention systems
	Development of educational programs for oil pollution reduction
	Establishment of rapid response teams for oil incident management
	Collaboration with relevant international organizations
	Establishment of communication and coordination systems among various organizations
	Comprehensive training and awareness-raising on oil spill response
	Risk assessment and management related to oil incidents
	Development of green and environmentally friendly technologies
	Establishment of strict regulations and legislation for pollution prevention
	Establishment of cooperative networks among various centers
	Promotion of environmental protection culture and reduction of oil consumption
	Development of emergency plans and necessary logistics for oil incident response
	Establishment of regional and international monitoring and evaluation systems
Level III	Application of novel technologies for pollution detection and tracking
	Application of artificial intelligence for pollution prevention
	Development of maintenance and upgrading plans for oil spill response equipment
	Development of international collaborations to address oil pollution impacts

In this phase, the MICMAC (Matrix of Cross-Impact Multiplications Applied to a Classification) technique was utilized. This analytical approach is designed to evaluate the driving power and dependence of variables, thereby facilitating the identification of critical factors within a complex system. The primary purpose of the MICMAC analysis is to assess the influence and dependency of each factor and to map their positions within the overall research framework. After computing the driving power and dependence scores for all 22 factors, they were plotted on the MICMAC matrix and categorized into four distinct clusters based on predefined threshold values. These thresholds are typically determined by calculating the average number of factors and adding one unit to that average.

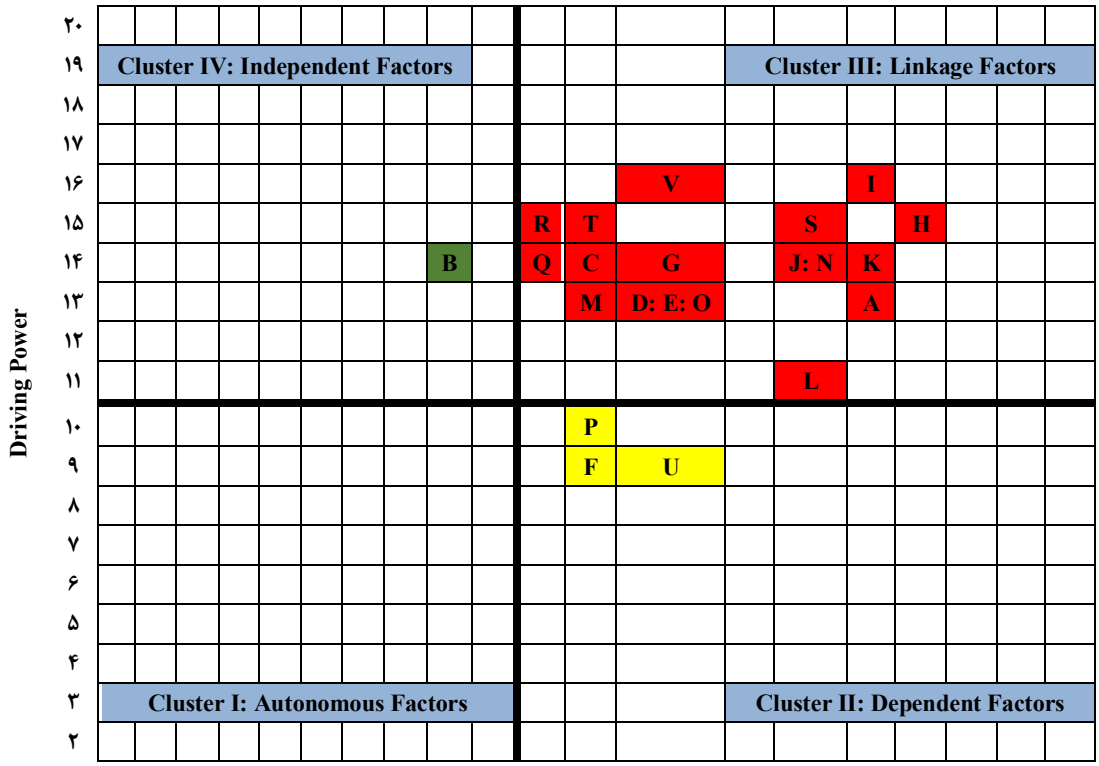
The first cluster, autonomous variables, comprises factors with low driving power and low dependence, indicating their limited interaction with other elements of the system. The second cluster, dependent variables, consists of factors with low driving power but high dependence, meaning they are strongly influenced by other factors. The third cluster, linkage variables, includes factors characterized by both high driving

power and high dependence; these variables are highly sensitive and can both affect and be affected by other factors. The fourth cluster, independent variables, encompasses factors with high driving power and low dependence. These are considered key driving factors that exert significant influence over the rest of the system.

The detailed driving power and dependence values for each factor, along with their respective cluster classifications, are presented in Table 8. Additionally, the MICMAC matrix plot, which visually illustrates the distribution of the factors across the four clusters, is depicted in Figure 3.

Table 8: Driving Power and Dependence of the Identified Factors (MICMAC Analysis)

Row	Factor	Dependence	Driving Power
A	Identification and tracking of oil pollution sources	16	13
B	Establishment of pollution prevention systems	9	14
C	Application of novel technologies for pollution detection and tracking	12	14
D	Development of educational programs for oil pollution reduction	13	13
E	Establishment of rapid response teams for oil incident management	13	13
F	Application of artificial intelligence for pollution prevention	12	9
G	Collaboration with relevant international organizations	13	14
H	Development of sustainable development plans for pollution reduction	17	15
I	Development of infrastructure related to oil incidents	16	16
J	Establishment of communication and coordination systems among various organizations	15	14
K	Establishment of international standards for oil spill response	16	14
L	Comprehensive training and awareness-raising on oil spill response	15	11
M	Risk assessment and management related to oil incidents	12	13
N	Development of green and environmentally friendly technologies	15	14
O	Establishment of strict regulations and legislation for pollution prevention	13	13
P	Establishment of cooperative networks among various centers	12	10
Q	Development of maintenance and upgrading plans for oil spill response equipment	11	14
R	Establishment of regional and international monitoring and evaluation systems	11	15
S	Promotion of environmental protection culture and reduction of oil consumption	15	15
T	Development of emergency plans and necessary logistics for oil incident response	12	15
U	Establishment of comprehensive and reliable databases on oil pollution	13	9
V	Development of international collaborations to address oil pollution impacts	13	16



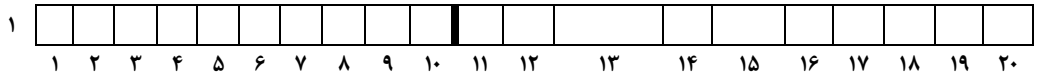


Figure 3. MICMAC diagram of factors influencing the enhancement of oil spill response operations at sea

5. Discussion and Conclusion

Based on the research findings, a total of 22 factors influencing the enhancement of oil spill response operations at sea, with a focus on Chabahar Port, were identified. These factors include: "identification and tracking of oil pollution sources," "establishment of pollution prevention systems," "application of novel technologies for pollution detection and tracking," "development of educational programs for oil pollution reduction," "establishment of rapid response teams for oil incident management," "application of artificial intelligence for pollution prevention," "collaboration with relevant international organizations," "development of sustainable development plans for pollution reduction," "development of infrastructure related to oil incidents," "establishment of communication and coordination systems among various organizations," "establishment of international standards for oil spill response," "comprehensive training and awareness-raising on oil spill response," "risk assessment and management related to oil incidents," "development of green and environmentally friendly technologies," "establishment of strict regulations and legislation for pollution prevention," "establishment of cooperative networks among various centers," "development of maintenance and upgrading plans for oil spill response equipment," "establishment of regional and international monitoring and evaluation systems," "promotion of environmental protection culture and reduction of oil consumption," "development of emergency plans and necessary logistics for oil incident response," "establishment of comprehensive and reliable databases on oil pollution," and "development of international collaborations to address oil pollution impacts."

The elaboration of these factors reveals that the **identification and tracking of oil pollution sources** through satellite trackers, marine sensors, and unmanned aerial vehicles (UAVs) plays a critical role in the rapid detection of spills and the precise determination of their location. These measures not only reduce response time but also prevent the spread of pollution to other areas, and the data obtained can be utilized to improve future prevention strategies. Furthermore, **pollution prevention systems**—through measures such as installing safety equipment on vessels and oil facilities, employing leak prevention technologies, developing safety protocols, and implementing regular maintenance and repair programs—reduce the likelihood of incidents. From this perspective, effective prevention can reduce the costs and consequences associated with post-incident pollution response.

Moreover, **the application of novel technologies for pollution detection and tracking**, including satellite systems, advanced radars, and biosensors, enables rapid pollution detection and provides accurate information regarding its extent and severity. These technologies can enhance the speed and accuracy of detection, thereby facilitating quicker response and reducing environmental consequences. Alongside technology, **human resource training** is also a key factor in improving oil spill response operations. Conducting specialized courses for port personnel, ship crews, and rapid response teams, along with the use of realistic scenario simulations and practical training, enhances the preparedness of human resources for prevention, detection, and response. In this regard, **rapid response teams**, equipped with appropriate resources and specialized training, must remain continuously operational and carry out containment and cleanup operations based on pre-established plans. The coordination of these teams with other relevant organizations is also essential for effective crisis management.

On the other hand, **artificial intelligence**—with its capacity to analyze large volumes of data from monitoring systems—can be used to predict the likelihood of spills, provide early warnings, identify risk patterns, and recommend preventive measures. Additionally, this technology can enhance the efficiency of pollution response operations by assisting in the selection of appropriate and faster cleanup methods. **Collaboration with international organizations** is also important, as it facilitates access to knowledge, resources, and advanced technologies, enables the exchange of experiences, supports the implementation of global standards, and enhances coordination in pollution response operations.

In the domain of sustainable development, reducing dependence on fossil fuels and utilizing renewable energy sources can help mitigate environmental risks. Implementing projects such as solar and wind energy in port facilities, alongside reducing environmental impacts, can contribute to the sustainable development of port activities at Chabahar Port. Furthermore, the **development of infrastructure related to oil incidents**—including the establishment of pollution response equipment depots, operational bases, and maintenance and repair facilities—enhances regional preparedness for incidents. Such infrastructure should be designed to ensure rapid access to equipment and resources during critical situations.

The establishment of communication and coordination systems among various organizations, through the creation of crisis control centers, early

warning systems, and clearly defined information-sharing protocols, can accelerate response efforts and mitigate the consequences of incidents. Additionally, **the formulation and implementation of international standards for oil spill response**, particularly concerning safety requirements for vessels and oil facilities, enhance coordination and reduce the risks associated with incidents. Alongside these measures, **public education and awareness-raising**, especially in coastal areas, can strengthen the culture of marine environmental protection by increasing awareness of the consequences of oil pollution and prevention methods.

Furthermore, **risk assessment and management related to oil incidents**—through the identification of vulnerabilities, prediction of potential scenarios, and development of preventive and rapid response plans—play a significant role in reducing the consequences of incidents. The use of **green and environmentally friendly technologies**, such as oil-absorbing biomaterials and bioremediation technologies, can increase the efficiency of the cleanup process while minimizing the adverse effects of response operations. On the other hand, the **establishment of strict regulations and legislation** for vessels, oil facilities, and oil-related activities, along with the enforcement of safety standards and appropriate enforcement mechanisms, can serve as a deterrent to pollution incidents.

The establishment of cooperative networks among research centers, environmental organizations, and port authorities facilitates the exchange of knowledge, resources, and experiences, thereby fostering the development of innovative solutions. Additionally, **regular maintenance and upgrading of pollution response equipment**—such as skimmers and containment booms—are essential for maintaining operational readiness and ensuring the proper functioning of equipment during crises. **Regional and international monitoring and evaluation systems**, utilizing sensor networks, monitoring stations, and data analysis systems, enable continuous monitoring of pollution status and provide up-to-date information to decision-makers.

In this context, **promoting a culture of environmental protection and reducing oil consumption** through education, awareness campaigns, and encouragement to adopt alternative energy sources can be effective in reducing dependence on oil and preventing pollution. **Emergency response plans and necessary logistics for oil incident response** should pre-specify the financial, human, and equipment resources required for rapid response, containment, and cleanup. Furthermore, **the establishment of comprehensive and reliable databases** containing information on pollution sources, response equipment, cleanup methods, and past operational outcomes can improve future decision-making and planning while facilitating information exchange at regional and international levels. Finally, **the development of international collaborations** through knowledge sharing, resource and experience exchange, joint projects, international exercises, and the development of new technologies can enhance the capacity to address the consequences of oil pollution.

The results of the level partitioning using the ISM method revealed that the factors "identification and tracking of oil pollution sources," "development of infrastructure related to oil incidents," "establishment of international standards for oil spill response," "development of sustainable development plans for pollution reduction," and "establishment of comprehensive and reliable databases on oil pollution" are positioned at Level I. These factors exhibit the highest degree of dependence and are located at the end of the system's influence chain. In other words, these factors are primarily outcomes of the performance of lower-level factors and are considered outputs of the system; therefore, their direct management without considering the influential factors at lower levels will have limited effectiveness.

At Level II, the factors "promotion of environmental protection culture and reduction of oil consumption," "development of emergency plans and necessary logistics for oil incident response," "risk assessment and management related to oil incidents," "development of green and environmentally friendly technologies," "establishment of strict regulations and legislation for pollution prevention," "establishment of cooperative networks among various centers," and "establishment of regional and international monitoring and evaluation systems" were positioned. These factors serve as intermediaries between the root factors and the dependent factors, meaning they are both influenced by lower-level factors and exert influence on higher-level factors. Therefore, improving these factors can affect the overall performance of the system and is of significant importance in planning and management.

Finally, the factors "establishment of cooperative networks among various centers," "establishment of regional and international monitoring and evaluation systems," "application of artificial intelligence for pollution prevention," "development of maintenance and upgrading plans for oil spill response equipment," and "development of international collaborations to address oil pollution impacts" were placed at Level III. These factors, as root factors, possess the highest driving power and the lowest dependence within the system's structure. Consequently, changes and improvements in these factors can influence other levels of the system. From this perspective, attention to these factors in decision-making and planning processes should be given higher priority. Proper management of root factors can pave the way for improving higher-level factors and ultimately

enhancing the overall performance of oil spill response operations.

Based on the research findings, the use of novel technologies for **identifying and tracking oil pollution** sources is recommended. In this regard, the utilization of Geographic Information Systems (GIS), satellite imagery, underwater sensors, and automated monitoring systems can be effective in accurately identifying pollution sources, tracking oil spill trajectories, and determining affected areas. Additionally, the installation of leak detection sensors on pipelines, tanks, and oil docks, along with the enforcement of periodic inspections of equipment and infrastructure, can reduce the probability of incidents. These systems, by issuing automated early warnings, can facilitate rapid response.

Furthermore, the use of **UAVs equipped with infrared and spectral sensors** for detecting oil spills in marine and remote areas is recommended. These devices can provide the necessary information for pollution identification and operational decision-making within a short period. In addition, the use of underwater robots for pipeline inspection, subsurface monitoring, and data collection from contaminated areas can enhance the accuracy of monitoring and detection operations.

In summary, this study provides a comprehensive framework for understanding the multidimensional factors affecting oil spill response operations at sea. The findings underscore the critical role of root factors—particularly technological innovation, international collaboration, and artificial intelligence—in driving systemic improvements. For policymakers and port authorities, prioritizing these leverage points can lead to more resilient and effective response systems. Future research should focus on empirical testing of the proposed model, comparative studies across different ports, and the integration of real-time data analytics to enhance predictive capabilities.

Despite the findings of this research, the present study faced certain limitations. First, due to time constraints, the model obtained was not tested. Additionally, due to time limitations, the relationships among the identified factors were not independently examined and tested. Finally, the spatial scope of the research was limited to Chabahar Port; therefore, the generalization of the results and findings to other marine areas and ports should be undertaken with caution, taking into account the degree of similarity in organizational, operational, and environmental conditions.

6. References

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