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Environmental Risk Assessment Using FMEA and Entropy Based on TOPSIS Method: A Case Study Oil Wells Drilling

Negar Afzali-Behbahani[1,*], Mazdak Khodadadi-Karimvand[2], Afarin Ahmdi[1]

[1] Department of Natural Resources and Environment, Science and Research Branch, Islamic Azad University, Tehran, Iran; afzali.negar@yahoo.com; Afarin.ahmadi@gmail.com.

[2] Department of Industrial Engineering, Najafabad Branch, Islamic Azad University, Isfahan, Iran; mazdak.kh@gmail.com.

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Abstract

Drilling is among the major processes of exploration, description, and development of oil and gas reservoirs with a strategic significance in the oil industry. It has also always been a major challenge in the oil industry. Because of the importance of drilling in major upstream oil and gas industries, identifying related risks is also of great importance. Risk assessment systems are tools for identifying potential risks and assessing their levels, which have been widely used in various industries and disciplines in recent years. Accordingly, this study identified and assessed major environmental risks caused by onshore and offshore drilling operations and presented an approach to reduce their risk levels. Offshore and onshore risks were identified after identifying the drilling operation of oil wells. Indexes used in the FMEA method were selected to determine the most significant risks. The identified risks were then ranked by experts and entered the TOPSIS decision matrix as a useful technique to prioritize and select the most significant and most effective risks. Shannon's Entropy was used to weight identified indexes. Finally, 33 environmental risks resulting from oil well drilling operations in onshore and offshore ecosystems were identified. Corrective measures were presented for each environment to reduce the level of identified risks and their effect on the environment.

Keywords: Oil and gas well drilling, Environmental risk assessment, Failure mode and effects analysis, Technique for order of preference by similarity to ideal solution, Shannon entropy.

1 | Introduction

The drilling industry is considered one of the pillars and perhaps the central pillar of exploration and production of hydrocarbon reservoirs. Oil and gas production goals cannot be realized without planning for organizing and developing the drilling industry. The oil and gas exploitation industry play a vital, dynamic role in the global energy matrix worldwide [1]. The significance and extent of the drilling industry are clarified considering the fact that there are about 15 companies providing drilling services per drilling rig, further revealing the huge size of this industry in terms of technology and manpower [2]. Onshore and offshore drilling operations are performed worldwide to reach oil and gas reservoirs. Hence, there are global concerns about the environmental effects of drilling operation activities [3]. Various substances are used in the drilling industry, some of which are toxic and

Corresponding Author: afzali.negar@yahoo.com

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dangerous with detrimental effects on the ecosystem. Like any other industrial activity, wastes of the drilling operation are discarded to the environment at the end of the operation, having adverse effects on the environment in the long run in the absence of a plan for the treatment and elimination of such wastes [4]. Generally, oil and gas projects are associated with many uncertainties due to unique features, complexities, and uncertain environments [5].

Due to differences in the onshore and offshore environments, the effects of drilling operations differ in these two environments. Considering evident differences between the standards and regulations governing onshore and mobile offshore drilling units (regulations governing mobile offshore drilling rigs are stricter than onshore drilling units) [6], numerous studies have been conducted in this area. Ershadi et al. [7] conducted a study entitled "assessing environmental effects of drilling wastes" to evaluate the toxicity of drilling wastes and their effects on humans, plants, and ecosystems.

Risk assessment and environmental effect assessment methods are among the most efficient tools to evaluate and prioritize risks and hazards of oil and gas well drilling operations [8]. Environmental Impact Assessment (EIA) is a planning mechanism and a systematic approach for evaluating the environmental effects of a proposed project in its early stage [9].

Environmental risk assessment also determines risks and presents solutions to improve conditions and support decisions for selecting the best technology and measures to reduce risks [10]. Environmental risk assessment is a crucial environmental management tool to reduce risks of projects and achieve sustainable development, received much attention in planning and policymaking in most countries [11]. Risk assessment is the quantitative, qualitative analysis of risk potentials and the likelihood of possible risks and susceptibility of the surrounding environment [12].

There are multiple methods for environmental assessment, including Multiple Attribute Decision Making (MADM) methods. Decision-making considering multiple criteria, each with its special effect, is possible only using MADM models. Various indices proportional to the type of ranking are used in these methods. Technique for Order of Preference by Similarity to Ideal Solution (TOPSPS) is among the most useful MADM methods to solve real-world problems, first proposed by Huang and Yoon [24]. This technique has been employed in various areas. For instance, Jozi and Saffarian [14] assessed the environmental risk of the Abadan Gas Power Plant by the TOPSIS method in 2011.

Failure Mode and Effects Analysis (FMEA) is among the widely used risk assessment methods. FMEA systematically identifies the risk causes and their effects faced by a process or an ecosystem [15]. FMEA prevents the occurrence of events or environmental damages. Indexes used in the FMEA method can demonstrate the effectiveness and the significance of existing risks. Accordingly, FMEA indexes are used in this study.

This study identifies environmental risks caused by the drilling operation of oil wells and determines the most effective risks by weighting indexes according to the Entropy technique. The TOPSIS technique prioritizes identified risks, and appropriate corrective measures are proposed for the offshore and onshore ecosystems to reduce risk levels and the effect of risks on the environment.

1.1 | Study Area

Iran's oil fields include reservoirs, basins, and oil fields in Iran's onshore and offshore territory. Most fields explored (140 fields) are located in Zagros and Persian Gulf (Southwest of Iran). Some fields have also been explored or are exploring in the north of Central Iran, South Caspian, and Kope Dagh [16]. For this paper, an onshore drilling rig and an offshore drilling rig in the south (Persian Gulf) and southwest (Dehloran) of Iran were considered. The study area is shown in *Fig. 1*.

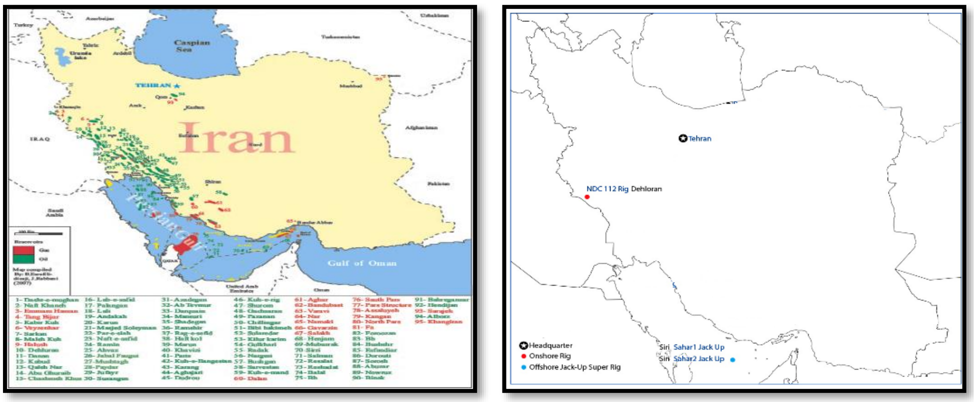

Fig. 1. Range of Iranian oil fields & scope of study [17].

1.2 | Operations and Systems

The best place for drilling an exploratory well is the point reaching the oil trap at the reservoir rock peak if a well is drilled at that point. Factors influencing this choice are the site location on the underground level lines, ease of leveling and preparing for installing the drilling rig, and road construction issues. After that, road construction and building operations begin. A pit called "Cellar" is drilled at the site of the well. A solid concrete foundation is constructed to install the drilling rig, capable of bearing the very heavyweight of the drilling rig [18]. After determining the well site and completing preparation steps, the rig components are transferred to the well site, connected by pins, and then installed by steel cables. This is the case for Jack-knife rigs as the most conventional drilling rigs. However, prefabricated portable mast rigs are transported to the drilling location by a truck and then installed by hydraulic arms [19]. The drilling operations and systems of oil wells include rotary drilling, casing, coring, mud circulation system, solid control, oil well cementing, acidizing, coiled tubing, fishing, logging, air or gas drilling, well control system, generators, and air compressors [20].

2 | Methods

This study assesses the risks of drilling onshore and offshore oil wells. To this end, some onshore and offshore drilling rigs in Iran were studied. The drilling operation of oil wells was evaluated by desk and field studies to identify oil well drilling operation risks. Thereafter, the environmental effects of different activities of onshore and offshore drilling operations were identified. FMEA indexes were ranked by experts to perform TOPSIS and prepare the decision matrix. The decision matrix was accordingly presented for the identified risks. FMEA is an appropriate approach to evaluate systems and design processes or services. This approach can discover paths including problems, errors, and risks leading to failures. FMEA is a preventive measure with a teamwork approach [21] to prevent possible errors [22]. TOPSIS is among the MADM methods [23] based on defining the positive and negative solutions for decision-making. Priorities in this method are determined based on proximity to the ideal positive solution and distance from the ideal negative solution [24]. Entropy is used for weighting indices in this study. Compared to subjective constant weighting methods such as Delphi, expert review, Analytic Hierarchy Process (AHP), and so on, the entropy method is more precise and objective, better explaining the results [25]. After completing the TOPSIS stages, identified risks are prioritized to identify the most significant ones. Schematically of the research stages is shown in *Fig. 2*.

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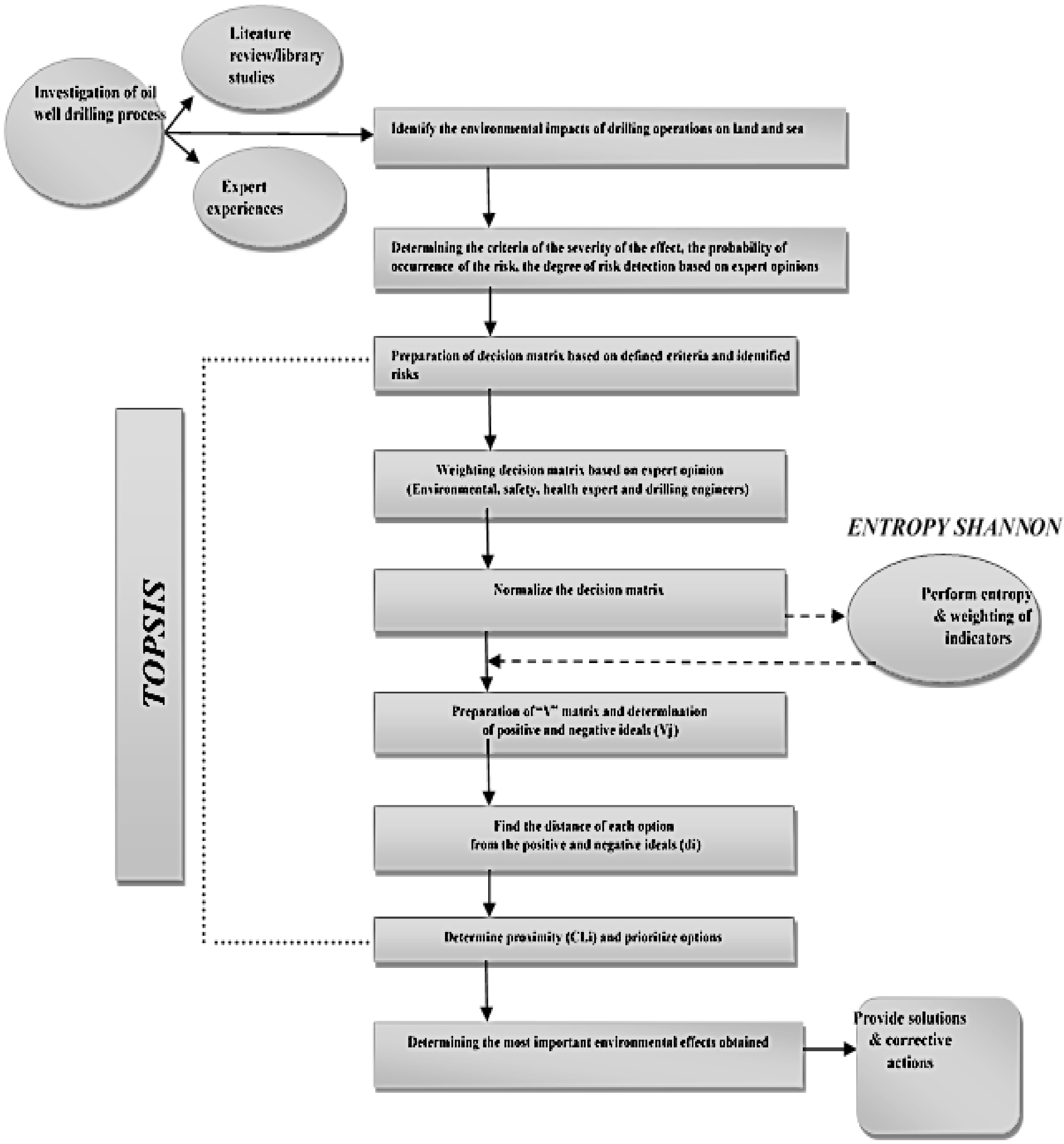

Fig. 2. Diagram of research steps.

2.1 | FMEA Indexes

FMEA indexes were used to determine the significance of identified risks. FMEA indexes include severity, occurrence, and detection. According to the FMEA tables, experts ranked and evaluated these indexes for each identified risk [26].

2.2 | TOPSIS Steps

The TOPSIS decision matrix was plotted, and related steps were performed after determining the values of indexes for all identified risks [27]. The matrix was first normalized by *Eq. (1)*.

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{1}^{m} x_{ij}^2}}. \quad (1)$$

To calculate the harmonic normal matrix (V), the weight of indexes was first calculated by the Shannon Entropy technique to obtain the matrix V.

2.3 | Shannon Entropy

As mentioned earlier, the Shannon Entropy by *Eq. (2)* and *Eq. (3)* was used for weighting indexes.

$$E_j = -k.\sum_{i=1}^{m} P_{ij}.Ln(P_{ij}). \quad (2)$$

$$P_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}}. \quad (3)$$

After calculating the Entropy of each index, the dispersion of values for the index j was calculated from *Eq. (4)*. The weight of indexes was calculated from *Eq. (5)*.

$$dj = 1 - Ej. \quad (4)$$

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}. \quad (5)$$

After determining the weight of indexes, the harmonic matrix V was obtained by multiplying each entry of the norm matrix by the weight of indexes. After determining positive and negative ideals, the distance of each alternative from the positive and negative ideals (di+, di-) was calculated from *Eq. (6)* and *Eq. (7)*, respectively.

$$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{ij}^-)^2}. \quad (6)$$

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{ij}^+)^2}. \quad (7)$$

The proximity of each alternative to the ideals and the rank and priority of risks (CLi) were calculated from *Eq. (8)*.

$$CL_i^* = \frac{d_i^-}{d_i^- + d_i^+}. \quad (8)$$

3 | Results

3.1 | Identifying Environmental Pollutants

According to the literature on drilling oil wells, the process was analyzed, and sections causing environmental effects were identified as activities and pollutants. Wastes are among the major sources of pollution in the drilling industry. High volumes of drilling cuttings with impact and pollution potentials are considered among major wastes of the drilling operation [28]. Some of these wastes are natural drilling byproducts such as drilling cuttings, and some are drilling materials such as drilling fluids and additives. In general, wastes produced during the drilling operation result from drilling rig activities or the circulation system. Major wastes of oil well drilling include drilling mud, drilling cuttings, produced waters, and chemicals.

Drilling cuts and disposal materials have received much attention from the beginning of drilling operations, and numerous studies have been conducted to reduce toxicity and biodegrade drilling muds. Discharging drilling cuttings adversely affect ecosystems, especially the marine ecosystem, seriously threatening to restore and resettle marine species after discharging drilling wastes, particularly in tropical and subtropical climates. Heavy metals are among the major challenges of offshore drilling operations arising from drilling mud or cuttings, causing bioaccumulation in living organisms. Bioaccumulation of metals is also dependent on their availability so that the availability of a particle decreases by absorption to other particles or forming complexes with water molecules.

The environmental effects of hydrocarbons are totally different under various conditions. Moreover, aromatic and linear-chain paraffinic hydrocarbons show high and low toxicity, respectively. The toxicity of hydrocarbons increases from Alkanes to Alkenes, Cyclo-Paraffins, aromatics, and poly aromatic hydrocarbons. Toxic hydrocarbons are low boiling point aromatics, especially benzene, toluene, Ethyl benzene, and xylene.

3.2 | Identifying Environmental Aspects

Environmental aspects identified in onshore and offshore environments affect humans, aquatics, and benthos (including Echinodermata, crustaceans, fish, aquatic mammals, etc.), aquatic and terrestrial plants, soil quality, and air quality. The major problem with offshore and onshore drilling operations is oil spills and the leakage of oil derivatives to the environment (such as crude oil, hydrocarbons, salts, heavy metals, etc.). Some activities in the oil industry produce parts of pollutants (such as access road construction, fixing locations and kiosks, waste incineration, etc.).

The leakage (spill) of oil and its derivatives reduces biodiversity. It causes damages and scars on the skin and eyes of mammals, mutation in reptile infants, lack of spawning in turtles, extinction of turtle infants due to the similarity of oil spill emulsion and jellyfish larva, oil bioaccumulation in living organisms, musculoskeletal system development disorder in animals, hypothermia and death of mammals/birds, loss of aquatic plants due to algal bloom, acute and chronic effects for humans, etc. A total of 33 risks were identified for onshore and offshore drilling operations. The environments affected by these operations were then determined. The identified risks were ranked by the FMEA indexes using brainstorming and expert opinions. To this end, environmental, drilling, and HSE experts declared their opinions regarding identified risks and valuated the severity, occurrence, and detection of each index (considering the large number of risks, part of matrices and tables are presented in *Tables 1* to *4*).

Table 1. An example of the risks identified in the decision matrix.

Indexes / Risks	C1 Severity	C2 Probability	C3 Detection
A1: Decreased biodiversity of organisms due to bioaccumulation of hydrocarbons	8	6	2
A2: Decreased biodiversity of living organisms due to bio-shock	8	6	2
A3: Hypothermia and bird death due to exposure to oil pollutaants	10	7	3
A4: Harm to birds by swallowing petroleum products while grooming and arranging their feathers	8	7	3
A5: Hypothermia and death of furry marine mammals due to contact with oil pollutants	10	6	3

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Table 2 presents weights calculated for the FMEA indexes.

Table 2. Results of calculated weights of indicators.

	C1	C2	C3
Ej	0.16	0.21	0.24
dj	0.84	0.79	0.76
Wj	0.351	0.33	0.317

After determining the weights, the weighted matrix V was obtained by multiplying the norm matrix entries by the weight of indexes (see *Table 3*).

Table 3. Part of the weighted "V" matrix.

X	Severity	Likelihood	Detection
Weight	0.351703407	0.330661323	0.317635271
A1	0.165840957	0.161456083	0.074175894
A2	0.165840957	0.161456083	0.074175894
A3	0.207301196	0.18836543	0.111263841
A4	0.165840957	0.18836543	0.111263841
A5	0.207301196	0.161456083	0.111263841

After calculating positive and negative ideals and distance from the ideals, the identified risks were ranked (see *Table 4*).

Table 4. Part of the final results and final ranking.

V	Severity	Likelihood	Detection	S*	S-	C*	Rank
A1	0.05832683	0.053387282	0.02356088	0.123020576	0.03293069	0.211160134	20
A2	0.05832683	0.053387282	0.02356088	0.123020576	0.03293069	0.211160134	20
A3	0.072908537	0.062285162	0.03534132	0.126472352	0.03644422	0.223698668	18
A4	0.05832683	0.062285162	0.03534132	0.118666003	0.039253119	0.248564702	16
A5	0.072908537	0.053387282	0.03534132	0.122335671	0.039568902	0.244396446	17

4 | Conclusion

According to the results, 33 risks were identified based on the FMEA indexes and then ranked by the weighting and ranking techniques based on the TOPSIS and Entropy methods. All risks related to transportation (marine and land), fixing locations, constructing access roads are completely possible due to their nature, fully destructing the vegetation and habitats of animals, changing their habitat, and contaminating soil. Accordingly, all risks were prioritized as major ones. In general, ecological effects are among the major considerations for all discharges from exploration and production activities in the oil and gas industry [29] so that a basic task in all environmental assessments and a basic principle in management policies to discharge into the sea is to define and determine the region exposed to the risk [30].

Furthermore, activities such as the leakage of pollutants to the coastal region and its destruction and loss of the coastal landscape, the leakage of industrial wastes to the aquatic environment causing problems for aquatics and benthos, problems arising from ballast water for aquatics and benthos due to non-native invasive species were ranked as major risks. The lowest rank was assigned to activities such as waste incineration and air pollution so that this risk could be fully eliminated by control measures such as waste separation and recycling. Other identified risks were ranked as moderate risks. According to Ershadi et al. [7], the leakage of petroleum derivatives to the marine environments significantly affects seabed organisms, especially in places where drilling cuttings are deposited on the seabed.

Based on the results, benthos is also exposed to oil spill risks. Considering the drilling operation of oil wells, corrective and control measures were presented according to expert opinions to reduce the level of risk, particularly high-priority risks. Industrial wastes of the drilling operations are among the major sources of water and soil pollution in the drilling industry, and their risk level can be reduced to an acceptable extent by controlling and corrective measures.

The leakage of oil and industrial wastes in onshore and offshore environments may cause several problems such as the loss of aquatics and benthos, changing the habitat of animals, soil contamination, entering toxins into the food chain of marine organisms, the loss of planktons, and destruction of coasts. Thus, drilling waste management is a proper method to make an interaction between drilling and the environment and reduce the adverse effects of drilling activities in the environment. Such management can be applied by different methods such as preventing pollution or minimizing wastes at the production source and recycling and reusing wastes. Drilling waste management technologies can be classified into waste volume reduction, recycling and reusing, and disposing [31].

The severity and, in some cases, the range of effect are used in the conventional environmental risk assessment methods as the only quantitative criterion, and other criteria (if exist) play a qualitative-quantitative role [32].

Using the MADM methods in this study, three measurable indexes were used to rank the major risks, and the significance of environmental effects was determined by a set of selected indexes. The application of multiple-attribute techniques should be considered an intrinsic principle in environmental assessment studies. Determining the significance of environmental effects is among the major multi-criteria problems which should be considered in environmental assessment studies to determine the most significant and effective risks and take appropriate corrective measures to reduce their impact. Hence, other decision-making methods such as various weighting methods are recommended to be used in environmental assessment studies.

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