RISK AND POLLUTION PREVENTION FOCUSED ENVIRONMENTAL MANAGEMENT SYSTEM (RP2EMS): A CASE OF OFFSHORE OIL AND GAS OPERATIONS

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by

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ABSTRACT

Global offshore oil and gas (OOG) production is rapidly expanding to meet increasing energy demands. Since the offshore environment is sensitive, attention is increasingly devoted to environmental issues associated with OOG operations. An Environmental Management System (EMS) can be utilized to systematically manage all activities in OOG operations that give rise to environmental impacts. However, there is limited literature related to EMSs for OOG operations. This requires academics to examine common EMS frameworks and propose an EMS exclusively for OOG operations. This research was carried out to fill this gap.

Common EMS frameworks have the following limitations: (1) they are not very effective to convey and interpret sufficient information for decision-making; (2) there is no specified performance evaluation system to drive improvement; and (3) there is a burden of extensive documentation. Therefore, it is necessary to revise conventional EMS frameworks to overcome these limitations. The main aim of this study is to integrate Risk -Informed Decision-Making (RIDM) and Pollution Prevention (P2) paradigms within EMS, called **R**isk and **P**ollution **P**revention focused **E**nvironmental **M**anagement **S**ystem (RP2EMS). This framework also addresses the limitations of common EMS frameworks. Moreover, quantitative tools are developed to implement the proposed framework. The specific objectives of this research are: (1) development of an EMS framework; (2) development of a methodology to prioritize environmental issues; (3) development of a methodology for informed environmental decision-making; (4) development of a methodology for environmental performance evaluation; and (5) demonstration of developed methodologies through illustrative examples related to OOG operations.

As a preferred approach for environmental protection, P2 is integrated into the conventional EMS framework. The risk informed decision-making is coupled with P2 in this framework. This integration can reduce the effort and costs that are needed to develop waste management systems. As the first step, pollution prevention and control options are identified for important environmental issues. For each option, a risk assessment is carried out. Based on the calculated risks and related attributes, the better options are selected using a suitable decision-making method. Implementation of the selected options requires the proper assignment of responsibility and good communication during operations. The framework provides guidance and a procedure for the execution of environmental management emphasizing P2.

Identification and prioritization of the important environmental issues which are susceptible to causing significant negative impacts are necessary under the constraint of limited resources. This study proposes a hybrid approach using the fuzzy inference system (FIS) and fuzzy AHP for the prioritization of environmental issues in OOG operations. In this approach, a five-level hierarchy is developed. The highest level of the

hierarchy corresponds to the goal – prioritization of the significance of environmental issues, and the lowest level corresponds to environmental issues, whereas intermediate levels correspond to major concerns (environmental risks) and sub-parameters of risk. The FIS is applied at the lower levels of the hierarchy to infer the major risk parameters. Subsequently, the scores representing the extent of risk are calculated. Fuzzy AHP is used at the higher levels to synthesize the Significance Scores that will help to prioritize environmental issues.

To deal with the significant environmental issues, pollution prevention and other sustainable waste management options are investigated. The best options are selected using multi-criteria decision-making. This research proposes a game theoretical approach to solve multi-criteria conflict resolution problem under constrained and uncertain environments. Uncertainties in the quantification of imprecise data are expressed using rough numbers. A multi-criteria game is developed to model a decision problem in which three groups of decision-makers (i.e., operators, regulators and service engineers) are involved. There are three major categories of criteria: (1) costs, (2) environmental risks, and (3) technical feasibility. This game is solved using the generalized maximin solution concept. With the solution (i.e., optimal weights of the criteria), the rough numbers can be aggregated to an expected payoff for each alternative. Finally, the weights of the upper and lower limits of a rough number are employed to transform the expected payoff into a crisp score, based on which all alternatives are ranked to identify the best solution.

Environmental performance evaluation (EPE) is an essential part of EMS. A method is developed to identify and define specific environmental performance indicators on a case-by-case basis, which consists of five steps: (1) describing environmental requirements; (2) determining favorable outcomes corresponding to the requirements; (3) identifying required activities or issues to achieve the outcomes; (4) searching for proper measures of the activities or issues; and (5) generating a list of key indicators. Based on these steps, a quality function deployment (QFD) approach is developed to determine key indicators and evaluate environmental performance. To handle uncertainties in QFD, the decision makers' evaluations are quantified using rough numbers. The output of the proposed approach is environmental performance indices. Using these indices, decision makers can determine whether an improved performance has been achieved through an EMS.

This research provides an innovative EMS framework that integrates paradigms of P2 and risk-informed decision-making to systematically manage environmental issues in OOG operations. All the proposed approaches were validated through numerical examples.

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LIST OF ACRONYMS AND SYMBOLS

AHP	Analytic Hierarchy Process
BES	Best value
CFEMS	Compliance Focused Environmental Management System
DM	Decision Maker
EIA	Environmental Impact Assessment
EMAS	Eco-Management and Audit Scheme
EMS	Environmental Management System
EPE	Environmental Performance Evaluation
EPI	Environmental Performance Indicator
ES	Expected Score
FAHP	Fuzzy Analytic Hierarchy Process
FANP	Fuzzy Analytic Network Process
FCM	Fuzzy-c Means
FIS	Fuzzy Inference System
GHG	Green House Gases
GT	Game Theory
IEMS	Integrated Environmental Management System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MADM	Multiple Attribute Decision Making

NIS	Negative-Ideal Solution
NMVOC	Non-methane Volatile Organic Hydrocarbons
NV	Null Value
OOG	Offshore Oil and Gas
OBF	Oil-based Fluid
P2	Pollution Prevention
PDCA	Plan-Do-Check-Act
PIS	Positive-Ideal Solution
POEMS	Product Oriented Environmental Management System
QFD	Quality Function Deployment
RIDM	Risk-Informed Decision Making
RN	Rough Number
RP2EMS	Risk and Pollution Prevention Focused Environmental Management System
SBF	Synthetic-based Fluid
TEP	Total Expected Payoff
TFN	Triangular Fuzzy Number
US EPA	Environmental Protection Agency of the United States
VOC	Volatile Organic Hydrocarbons
WOR	Worst value
WBF	Water-based Fluid
M_g^j	m extent analysis value

S_i	Fuzzy synthetic extent
$\mu_A(x)$	Membership function
a	The lowest possible value in triangular fuzzy number
b	The most possible value in triangular fuzzy number
c	The largest possible value in triangular fuzzy number
T_D	Drastic operator
v_k	Centroid of cluster k
d^2	Square Euclidean distance
U	Degree of belongingness
U	Goal set
V	Degree of possibility
MinV	Minimum degree of possibility
μ	Mean
σ	Standard deviation
$\underline{apr}$	Lower approximation
$\overline{apr}$	Upper approximation
$\underline{\lim}$	Lower limit
$\overline{\lim}$	Upper limit
I_i	Importance
z_i	Non-dominated minimum payoff vector
I	Set of players

S	Set of all feasible payoffs
A	Set of alternatives
Ω	A weight defining how rough numbers are compared
W_i	Weight of *WHAT*s
IR_j	Importance rating
r	Correlation

LIST OF APPENDICES

Chapter 1

INTRODUCTION

This research was proposed to develop an innovative environmental management system (EMS) framework, which not only integrates the paradigms of pollution prevention (P2) and risk-informed decision-making (RIDM) but also overcomes the limitations of existing EMS frameworks. Quantitative tools are developed to effectively implement this EMS. They include models for prioritization of environmental issues, environmental decision-making and environmental performance evaluation related to offshore oil and gas (OOG) operations. This dissertation focuses on this new EMS framework and these developed models.

1.1 RESEARCH BACKGROUND

Energy plays a pivotal role in our daily lives. It is becoming increasing difficult to meet the demand for energy worldwide. In order to find additional supplies, oil and gas producers have been looking at more remote and difficult locations, such as offshore areas that contain large deposits of petroleum and natural gas. Both oil and gas account for 58% of the global commercial energy supply while 45% of this resource is produced offshore (Salter & Ford, 2000). World offshore oil production reached 1.26 billion tons in 2003, or about 34.1% of the world's total oil production. Meanwhile, world offshore gas production reached 685.6 billion cubic meters in 2003, or about 25.8% of total world gas production (Koottungal, 2004). By the end of 2007, these figures increased to 38.5% and 29.6%, respectively (Eni, 2009a, b).

1.1.1 INTRODUCTION TO OOG OPERATIONS

OOG development offers several benefits, including local employment through construction and servicing of the development sector, use of the product by local industry, alternative energy sources, and increased revenue to the region (Curran *et al.*, 2006). These benefits, however, may come at a cost to the natural environment. The rapid expansion of oil and gas production in offshore areas has stimulated increased attention to environmental issues associated with OOG operations. The life cycle of OOG operations (Figure 1.1) consists of four major stages: geological and geophysical survey, exploration, development and production, and decommissioning.

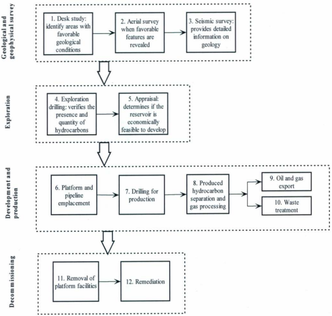


Figure 1.1 Life cycle of OOG operations

The geological and geophysical survey aims to identify major sedimentary basins and their geological structures. A seismic survey is the most common method used for this purpose. Using reflective properties of sound waves to various rock strata, the seismic survey provides information based on which geological structures can be determined. For example, a vessel tows an array of air-guns to release high pressure air every several seconds, which produces sound waves. These waves are focused on the seafloor, reflected by sub-sea features, and received by hydrophones.

Once a potential geological formation has been found, exploration activities are followed to confirm the hydrocarbon presence. Exploration wells are drilled for this purpose. If formation contains commercially viable quantities of hydrocarbon, well tests are conducted to help achieve the initial flow rate and reservoir pressure. If not, the field is decommissioned to a safe and stable condition. When successful drilling is finished, more wells are drilled for the appraisal of the size and extent of the field. Having established the size of the oil field, production wells are drilled. The number of wells required to be drilled for production is determined by the size of the oil field and its geological properties. In drilling activities, the major functions of a drilling rig are performed through hosting, circulating, and rotating systems. The drill pipe, with a drill bit mounted at its end, rotates to cut into rocks. Drilling fluids are circulated from tanks into the drill pipe and collar and then to the drill bit.

When crude oil and gas reach the surface, they are then directed to the central production facility for separation and other processes. Key operations in OOG production include: produced hydrocarbon separation, gas processing, oil and gas export, produced water treatment and injection, and seawater lifting for cooling duty and injection.

Decommissioning of OOG installations includes the removal of platform facilities and equipment when the hydrocarbon field becomes depleted. Any necessary environmental remediation should also be conducted at this stage, such as preventing fluids from leaking and clearing the seafloor of any material and equipment.

1.1.2 ENVIRONMENTAL IMPACTS

Table 1.1 provides a summary of the environmental impacts that may be caused by OOG operations. Table 1.2 summarizes the types of wastes generated in OOG operations. The most intense and diverse environmental impacts are faced during the development and production stage. Generally, the environmental impacts of OOG operations can be divided into two broad categories – (1) chronic impacts caused by regular waste discharge or atmospheric emissions, and (2) acute impacts caused by large-scale accidental blowouts or spills.

Table 1.1 Environmental impacts and their sources (Patin, 1999)

Stage	Activities	Sources	Type and Nature of Impacts
Geological and geophysical survey	Aerial Survey	Aircraft	Noise caused by low-level flights, short-term impacts on human and marine livings
	Seismic survey	Seismic equipment	Acoustic source, short-term disturbance to marine organism and fish population
		Vessel operations	Atmospheric and aquatic emissions from vessels, short term
	Test drilling	Core and shallow drilling, deep drilling	Increase in turbidity, disturbance on bottom, discharge of drilling mud and cuttings
Exploration	Site selection and exploratory drilling	Operations	Emissions and discharges of pollutants, disturbance to fisheries, accidental blowouts
	Plugging the well and abandonment	Operations	Long-term impacts on benthic and pelagic habitats, biodiversity
Development and production	Platform emplacement, pipeline laying	Operations	Construction discharges, long term and chronic effects of discharges on benthic and pelagic biota
	Drilling for production and injection wells	Operations	Drilling fluids and cuttings discharge, produced water, accidental spillage, impacts on fisheries, physical disturbance
	Vessel traffic	Vessel operations	Operational emissions and discharges, impacts on marine birds, mammals and other organisms
Decommissioning	Platform/facility removal, plugging, use of explosive charges	Operations	Operational emissions and discharges, impacts on fisheries, marine organisms if explosive charges are used

Table 1.2 Wastes generated in OOG operations (Khan, 2006)

Seismic exploration	Drilling	Production	Decommissioning
• Sounds • Human generated wastes: sanitary wastes, kitchen and food wastes, laundry wastes, and sink and shower drainage, trash	• Drilling fluids • Drilling cuttings • Produced sands • Storage displacement water • Ballast water • Deck drainage • Well treatment fluids • Naturally occurring radioactive materials • Cooling water • Desalination brine • Water for testing fire control • Accidental discharges: oil spills, chemical spills, blowouts • Human generated wastes: sanitary wastes, kitchen and food wastes, laundry wastes, and sink and shower drainage, trash • Other industrial wastes: cardboard, empty containers, scrap metal, wood pallets, used chemicals and paint, sandblasting grit and paint, and cooling water	• Produced water • Treatment and completion fluids • Deck drainage • Produced sand • Ballast water • Well treatment fluids • Naturally occurring radioactive materials • Cooling water • Desalination brine • Water for testing fire control • Accidental discharge: oil spills, chemical spills, blowouts • Human generated wastes: sanitary wastes, kitchen and food wastes, laundry wastes, and sink and shower drainage, trash • Other industrial wastes: cardboard, empty containers, scrap metal, wood pallets, used chemicals and paint, sandblasting grit and paint, and cooling water	• Abandoned structures • Cut pieces of oil structures • Scrap materials

The following are descriptions of major waste streams in OOG operations:

(1) **Produced water** is water separated from oil or gas during OOG production. It may include formation water, injection water and solutions of chemicals used to separate oil-water mixtures. Produced water as a waste stream cannot be avoided during OOG production because it naturally occurs in sub-sea formations and comes together with extracted oil and gas. The volume of produced water may vary from site to site with the age of the site. Usually, the quantity of produced water grows while a reservoir is becoming depleted. Produced water is the most significant waste stream generated in OOG operations in both the volume and quantity of pollutants. The volume and toxicity of produced water is a function of many factors, e.g., formation age and completion/treatment chemicals. Much of the produced water is quite similar to seawater.

(2) **Drilling wastes** are one of the most substantial discharges during OOG operations. These wastes are composed of drilling fluids and cuttings. Drilling wastes may cause a number of physical changes to the local marine environment near drilling rigs. The discharge of wastes will alter the local habitat by burying the original sea floor, smothering the local benthic community, and providing a new substrate for colonization (Neff, 1987). Biological impacts of drilling wastes are determined by their toxicity and dispersal properties; in addition, these impacts are generally thought to be limited to within several kilometers of drilling rigs (Davies *et al*., 1984). However, other researchers have suggested impacts of

up to 10 km (Kenchington, 1997) and in broad areas around drilling rigs (Olsgard & Gray 1995).

(3) **Flaring emission** is emission from the combustion of waste gases in an open flame. It occurs during well testing, waste gas disposal and emergencies. Flaring is a necessary practice in OOG operations because it can prevent damage and convert toxic gas to less hazardous emissions. Gas flaring may take place during various operations of OOG production. During processing, waste emissions, including hydrogen sulfide rich gases, are flared. Waste gases produced during well testing are also flared. Generally, flaring emission is usually found at wells, dehydrators, compressors and gathering pipelines. The efficiency of flaring determines the components of the emission. The flaring efficiency is a measure of the effectiveness of how flares convert all carbons into CO_2. Ideally, high efficiency flares only produce water and carbon dioxide, whereas low efficiency flares may produce CO along with CO_2. However, when waste fuel enters the flares, many other by-products such as particulate matter, PAH, VOCs, NO_x may also be present in the flaring emissions.

(4) **Venting emissions** in OOG operations refer to any fugitive emissions due to the venting of unused associated gas. The primary concern of venting emissions is methane (CH_4) and non-methane volatile organic hydrocarbons (NMVOC). CH_4, being a Green House Gas (GHG) has an impact equal to 21 times of the effect of

CO_2.

(5) **Oil & gas spills** have a long history in the OOG industry; however, spill frequency and volumes have been declining over the years because of improvements in operations, technology, and regulations despite an increase in hydrocarbon production and transportation in offshore areas (Anderson & LaBelle, 2000). Oil & gas spills usually occur due to equipment failure, operational mistakes or even natural disasters in drilling, transportation and storage. Two main spill scenarios of drilling operations are intense and prolonged hydrocarbon gushing, which usually occurs in exploratory drilling and routine episodes of hydrocarbon spills and blowouts. Spills during transportation are usually caused by collisions, fires, explosions, and structural failures. Spills in storage occur in both above and underwater tanks. The environmental impacts of oil & gas spills can be generally categorized as acute and chronic impacts. Acute impacts usually occur at the first stage of the spill and usually cause intoxication, death, physio-biochemical disturbances or behavior responses in fish and marine mammals. Marine organisms living at the sea surface, in inter-tidal zones, and in other coastal habitats such as seabirds, juvenile salmon, and larvae are expected to be affected most severely (GESAMP, 1993). The chronic impacts of spills usually refer to the disturbance of reproduction of marine organisms, their population changes or community structure changes. In general, the environmental impacts are caused by various factors, such as the size of spill, location, timing, type of

species and life-stage sensitivity.

(6) **Deck drainage** is the waste stream generated from natural precipitation, deck washing, tank and facility cleaning. Deck drainage may contain various contaminants, including detergents and dispersants used for washing, emulsified oil and some other chemicals. The volume of deck drainage is proportional to the size of the platform and its discharge rate is dependent on the frequency of wash-down operation and natural precipitation.

(7) **Storage displacement water** is water from oil storage cells used for displacing crude oil during transfer to other containers, and its amount is directly proportional to the size of the storage tank. The discharge rate complies with the production rate of crude oil. On average, the oil content in the storage displacement water is 300 mg/L (Environment Canada, 1990), which depends on the solubility of crude oil and its emulsifying characteristics.

1.1.3 ENVIRONMENTAL REGULATIONS

The increasing awareness of environmental issues has driven the establishment of stringent regulations. The current OOG environmental regulatory framework is a result of both international laws and national or provincial legislations, but the national legislation is the main component of the framework. Figure 1.2 gives a general structure of the environmental regulatory framework.

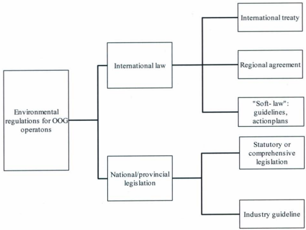


Figure 1.2 OOG environmental regulatory framework

MAJOR INTERNATIONAL TREATIES

The MARPOL73/78 Convention, *United Nations Law of the Sea (UNLOS) 1982*, *Convention of Prevention of Marine Pollution by Dumping of Wastes and other Matter* (1972) are the three main international conventions associated with environmental protection in the marine environment that deal with oil, noxious liquid substances, harmful substances in packaged form, sewage and garbage from ships and dumping activities. The provisions of these international treaties are very general and do little for operational obligations. Furthermore, all of these treaties regulate pollution from ships or dumping and exclude jurisdiction over pollution discharges caused by offshore exploration and production.

REGIONAL AGREEMENTS

Considering the difficulties in reaching stringent legislations at a global level and properties of trans-boundary marine pollution, the most plausible and acceptable solution to regulating all operational pollution discharges from OOG operations is to address this issue at a regional level (Sergei & Jay, 1996).

UNEP Regional Seas Programme, *1992 Helsinki Convention* in the Baltic Sea, *1992 OSPAR Convention* in the Northeast Atlantic, *Kuwait Regional Convention for Cooperation in the Protection of Marine Environment* (1978) in the Persian/Arabian Gulf, and *Barcelona Convention for Protection against Pollution* in the Mediterranean Sea (1976) are five major regional agreements. In general, the regional agreements deal with all operational pollution discharges from OOG operations in a more focused manner because they are more easily implemented in comparison to international treaties. Regional agreements offer opportunities for custom-built regimes (a regime that is administrated by nations in one region) and more stringent legislative standards (Seigei & Jay, 1996).

SOFT LAWS

"Soft laws" refer to the declaration, action plans and guidelines. The United Nations Environment Programme (UNEP), International Maritime Organization (IMO), Regional Association of Oil and Natural Gas Companies in Latin America and the Caribbean (ARPEL), International Association of Oil and Gas Producers (OGP formally known as E & P Forum), and the World's Bank are major promulgators of environmental guidelines for OOG operations. These environmental guidelines provide more specific information about environmental management, pollution prevention and control technologies, and environmental reporting in the OOG industry. Table 1.3 summarizes the major environmental guidelines currently used in the OOG industry.

Table 1.3 Major guidelines associated with environmental issues in OOG operations

Organization	Guidelines	Environmental management	Pollution prevention/ control technologies
UNEP/E&P forum	Environmental Management in Oil and Gas Exploration and Production (1997)	X	
UNEP	Offshore Mining and Drilling (1982)		X
UNEP	The Oil Sector Report (1999)		X
IMO	Guidelines for the Removal of Offshore Installations	X	
IMO	Guidelines for the transport and handling of limited amounts of hazardous and noxious liquid substances in bulk on offshore supply vessels		X
OGP (E&P Forum)	Guidelines for waste management with a special focus on areas of limited infrastructure (2008)	X	
OGP (E&P Forum)	Guidelines for the Development and Application of Health, Safety and Environmental Management Systems (1994)	X	
OGP (E&P Forum)	Exploration and Production Waste Management Guidelines (1993)		X
OGP (E&P Forum)	E&P Forum Guidelines for the Planning of Downhole Injection Programmes for Oil-Based Fluids Wastes and Associated Cuttings from Offshore Wells		X
OGP (E&P Forum)	Technologies for handling produced water in offshore environment (1996)		X
OGP (E&P Forum)	Guidelines for produced water injection (2000)		X
The World Bank	Environmental, Health, and Safety Guidelines for Offshore Oil and Gas Development (2007)	X	X
ARPEL	A Guideline for the Disposal and Treatment of Produced Water (2005)		X
ARPEL	A Guideline for the Treatment and Disposal of Exploration and Production Drilling Wastes (2005)		X

NATIONAL AND PROVINCIAL LEGISLATIONS

Existing legislations at the national and provincial levels can be categorized into two modes: the statutory mode and comprehensive legislative mode. The statutory mode means environmental aspects of OOG operations are regulated through multiple statutes. In the comprehensive legislative mode, framework legislation, particularly for OOG environmental issues, is adopted. Table 1.4 summarizes major national regulations for environmental issues of OOG operations.

Provincial legislations are usually administrated by local agency. For example, in Newfoundland offshore area, Canada-Newfoundland and Labrador Offshore Petroleum Board is the local regulatory agency. Regulations at this level are more prescriptive.

Table 1.4 National legislations regarding environmental issues in OOG operations

Nation	Legislative mode	Major national environmental legislations	Major regulatory body	Major industry association
UK	Statutory	• The Offshore Installations Regulations 2002 • Offshore Petroleum Production and Pipe-line Regulations 1999 • Prevention of Oil Pollution Act 1971 • Draft Offshore Chemicals Regulations 2002 • Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001 • Environmental Protection Act 1990 • Waste Management Licensing Regulations 1994	• Department of Trade and Industry(DTI) • Environment Agency • Department for Transport Local Government and the Regions	• UK Offshore Operators Association (UKOOA) • International Association of Drilling Contractors (IADC) • Offshore Contractors Association (OCA)
US	Statutory	• The National Environmental Policy Act (NEPA) • The Outer Continental Shelf (OCS) Lands Act • The Coastal Zone Management Act • Clean Water Act • The Oil Pollution Act • Clean Air Act • The Coastal Zone Management Act • Resource Conservation and Recovery Act	• U.S. Minerals Management Service (MMS) • U.S. Environmental Protection Agency (EPA) • U.S. Fish and Wildlife Service (FWS) • U.S. Coast Guard (USCG) • National Oceanic and Atmospheric Administration(NOAA)	• The American Petroleum Institute (API) • National Ocean Industries Association (NOIA) • Independent Petroleum Association of America (IPAA) • The Offshore Operator's Committee (Gulf of Mexico)
UAE	Statutory	• Federal Law No. (24) of 1999 for the Protection and Development of the Environment	• UAE Federal Environmental Agency • UAE Coast guard • Abu Dhabi Environmental Research and Wildlife Development Agency (ERWDA)	• Abu Dhabi National Oil Company (ADNOC)
Malaysia	Statutory	• Environmental Quality (Industrial effluents and sewage) regulations • Environmental Quality (Clean Air) Regulations • Merchant Shipping (Oil Pollution) Act • Environmental Quality (Scheduled Waste) Regulations	• Department of Environment • PETRONAS and Ministry of Domestic Trade and Consumer Affairs • The Marine Department • Ministry of Transport Malaysia	• Federation of Malaysian • Manufacturers Malaysian Gas Association
China	Comprehensive legislative	• Regulations on the Administration of Environmental Protection in the Exploration and Development of Offshore Petroleum 1983	• Ministry of Environmental Protection	• China Petroleum Enterprise Association
Canada	Statutory	• Canadian Environmental Protection Act • Newfoundland Offshore Area Petroleum Drilling Regulation • Newfoundland Offshore Area Petroleum Production and Conservation Regulations	• Environment Canada • Canada-Newfoundland • Offshore Petroleum Board • The Canada-Nova Scotia Offshore Petroleum Board	• Canadian Association of Petroleum Producers

1.1.4 ENVIRONMENTAL MANAGEMENT FOR OOG OPERATIONS

In order to achieve regulatory compliance and even beyond-compliance, OOG operators require more effective and efficient environmental management. Moreover, the functions of environmental management have been transited from responsibility for assuring regulatory compliance to maximizing the reduction of environmental burdens. This transition is initiated by the recognition of environmental issues as part of the cost of operating a business. OOG operators are currently developing ways to enhance their environmental management process (e.g., Curran *et al.*, 2006; Salem *et al.*, 2009). It has always been the focus of environmental managers and regulators in the OOG industry to adopt a systematic approach (e.g., EMS) to reduce environmental burdens and improve the environmental performance of OOG operations. EMS is a systematic approach to environmental management, which requires a holistic view of the natural environment and consists of numerous complex subsystems (Petak, 1981). The International Organization for Standardization (ISO) defines EMS as the part of overall management system which includes organizational structure, planning activities, responsibilities, practices, procedures, processes and resources for developing, implementing, achieving, reviewing and maintaining the organization's environmental policy. Regulators have an interest in efficient regulatory mechanisms and there is an expectation that the EMS could facilitate this (Ammenberg & Sundin, 2005). Therefore, OOG operators should aim to develop EMSs which is properly designed and can be effectively implemented for improvement of the environmental performance. Although implementation of an EMS is still voluntary in the OOG industry, an increasing number of OOG operators are actively practicing it to manage environmental issues, reduce their operational costs, and improve their public image. This trend encourages researchers to examine common EMS frameworks and propose new frameworks which could help improve environmental management in OOG operations. This research aims to fill this gap.

1.2 SCOPE AND OBJECTIVES

The main objectives of this research are:

(1) To explore a systematic approach for effective environmental management in OOG operations; and

(2) To design and construct quantitative tools for successful implementation of this systematic approach.

To accomplish the above objectives, the following tasks were planned:

(1) Developing a new EMS framework- **R**isk and **P**ollution **P**revention focused **E**nvironmental **M**anagement **S**ystem (RP2EMS), which integrates paradigms of pollution prevention (P2) and risk-informed decision-making;

(2) Developing the methodology for the prioritization of environmental issues;

(3) Developing the methodology for environmental decision-making; and

(4) Developing the methodology for environmental performance evaluation.

The following are some topics related to OOG environmental issues which were not included in this research:

(1) The methodology for ecological risk assessment of wastes in OOG operations;

(2) The methodology for human health risk assessment of wastes in OOG operations; and

(3) The methodology for emergency planning in an EMS.

1.3 ORGANIZATION OF THE THESIS

This thesis is organized into seven chapters. The organization of this research is provided in Figure 1.3. Chapter 1 provides an introduction to the research problem and gives the scope and objectives of the proposed research. Chapter 2 reviews EMS frameworks and significant paradigms in current environmental management. Chapter 2 provides the theoretical background of the proposed EMS framework - RP2EMS. Chapter 3 presents the developed RP2EMS framework. Chapters 4 to 6 present the developed quantitative tools with illustrative examples. These three chapters are written as three journal articles either published or under review for possible publication. Chapter 4 develops a hybrid approach for the prioritization of environmental issues in OOG operations using a fuzzy inference system and fuzzy analytic hierarchy process. Chapter 5 develops a rough-set based game theoretic approach for environmental decision-making in OOG operations. Chapter 6 develops a rough-set based quality function deployment approach for environmental performance evaluation for OOG operations. Chapter 7 provides the major conclusions of this research. Recommendations for future work are also included in this chapter.

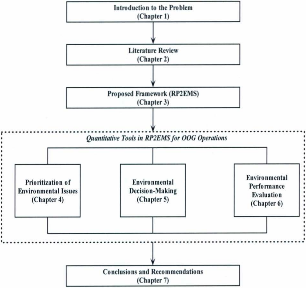


Figure 1.3 Organization of the thesis

Chapter 2

LITERATURE REVIEW

An Environmental Management System (EMS) can be considered as a structured framework for managing significant environmental impacts in an organization. This chapter reviews common EMS frameworks and identifies their limitations. Moreover, paradigms of pollution prevention and risk informed decision-making are also introduced in this chapter.

2.1 COMMON ENVIRONMENTAL MANAGEMENT SYSTEM FRAMEWORKS

With Total Quality Management (TQM) being a forerunner of the EMS (Christie & Rolfe, 1995; Aboulnaga, 1998), almost all EMS follows a Plan-Do-Check-Act cycle (as shown by Figure 2.1).

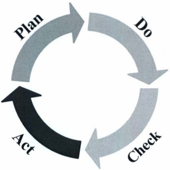


Figure 2.1 Plan-Do-Check-Act cycle

Plan: senior management commitment, environmental impacts, policies and objectives

Since senior management have a vital role to play at any time of change within their organization, it is important to secure the senior management commitment for an EMS. Furthermore, a stakeholder review should be conducted to collect information about the expectations of an organization as well as thoughts on strategic issues regarding environmental management.

Environmental impacts should be identified to provide a foundation to address exactly what issues are going to be managed. The starting point is to establish the organization's scope of an EMS and to focus management effort on those aspects that are classified as being significant. Then, relevant legislations need to be identified.

Environmental policy identifies the main environmental issues for the organization and acts as a signpost for the actions that will be taken to manage and improve the organization's environmental protection program. Sheldon & Yoxon (2006) summarized five key areas to be addressed when designing an environmental policy: attitude, accuracy, awareness, resource and action. The objectives of an EMS can be general in nature and may change from year to year; however, they must indicate an overreaching goal with respect to environmental impacts reduction.

Do: operations and documentation

Operations should then be conducted to avoid or reduce environmental impacts. Roles, responsibilities, processes, resources and schedules should be prioritized at this step. Documentation, the bulk of most EMSs, should include environmental policy, regulations to which operations are subject, action plans for operations, and records of monitoring and outcome measurements.

Check: management review and performance evaluation

The purpose of the management review is to achieve continuous improvement of an EMS in meeting the organization's objectives. This review can be conducted through interviews with employees to determine their awareness for the implementation of an EMS. Performance of the EMS should also be evaluated. Not only should the overall performance of an EMS, but also its individual parts, be audited. Performance evaluation can be conducted through both internal and external audits.

Act: operation adjustment, training and communication

When deviations from environmental policy and objectives are identified, corrective actions should be conducted to adjust the current operation. Communication and training are conducted to improve the awareness of environmental issues across all levels of the organization.

Training, providing more specific instructions on personal operational and monitoring activities, aims to ensure that every employee is well-prepared for his or her job/tasks and the related environmental impacts.

The significant role of communication in an EMS is to inform all employees of the environmental policy as well as their individual responsibility in implementing an EMS.

2.1.1 ISO 14000 BASED EMS

The most well-accepted EMS framework is based on ISO 14001 (ISO, 1996), which is seen as an effective tool to implement an organization's environmental strategies (Lawrence*et al.*, 2002) (Figure 2.2). This international standard framework is based on the above PDCA cycle. It starts from an organization's commitment to an environmental policy. Then, the organization should establish an environmental management program to develop, implement, review and maintain the environmental policy.

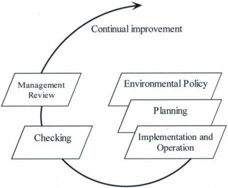


Figure 2.2 ISO 14000 based EMS framework (ISO, 2004)

Two important documents for the ISO 14001 based EMS are ISO 14001 and ISO 14004. ISO 14001 specifies requirements for an EMS to enable an organization to develop and implement a policy and objectives which take into account the legal requirements and other requirements to which the organization subscribes, and information about significant environmental aspects. ISO 14004 (General guidelines on principles, systems and supporting techniques) is the document that should be read first to learn the general approach to an EMS and find many suggestions on how to design and implement such an EMS.

2.1.2 THE ECO-MANAGEMENT AND AUDIT SCHEME (EMAS)

In Europe, most companies usually adopt the EMS framework defined by the Eco-Management and Audit Scheme (EMAS). The EMAS framework is quite similar to the ISO framework in components. The current legislation of EMAS is working to adopt the ISO framework as its basis (Matthew, 2001). The general framework of the EMAS is shown in Figure 2.3. Table 2.1 shows the differences between the EMAS and the ISO 14001 based EMS.

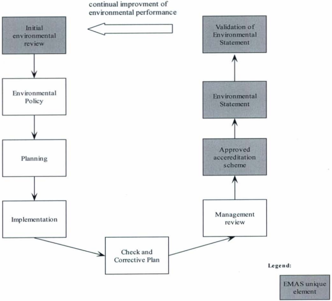


Figure 2.3 The EMAS framework (European Commission, 2008)

Table 2.1 Differences between the EMAS and the ISO 14001 based EMS (European Commission, 2008)

Aspects \ EMS Name	EMAS	ISO14001 based EMS
Legal status	Under legal bases: Regulation of the European Parliament and the Council under Public Law	Under no legal bases
Organization	The entity to be registered shall not exceed the boundaries of the Member State, and it is intended to go towards entities and sites	Does not go towards entities or sites
Environmental policy	Includes commitment to continual improvement of environmental performance of an organization	Does not include commitment to continual improvement of environmental performance, but performance of the management system
Initial environmental review	Obligatory preliminary review, when is the first time that the organization sets its environmental status	Initial review is recommended, but not required
Environmental aspects	Identification and evaluation of environmental aspects, establishment of criteria for assessing the significance of the environmental aspects	Requires only a procedure that is able to identify environmental aspects
Legal compliance	Obligatory to demonstrate it. Required full legal compliance. There is a compliance-audit	Only commitment to comply with applicable legal requirements. There is a non-compliance audit
External communication	Open dialogue with the public. Public Environmental Statement	Not open dialogue with the public. Only is required to respond to relevant communications from external interested parts.
Continual improvement	Annual improvement required	Requires periodical improvement without a defined frequency
Management review	Is wider and requires an evaluation of environmental performance of an organization, based on a performance-audit	Requires environmental performance in the management, but not through a performance-audit
Contractors and suppliers	Influence over contractors and suppliers is required	Relevant procedures are communicated to contractors and suppliers
Employees involvement	Active involvement of employees and their representatives	No
Internal environmental auditing	Includes: system-audit, a performance-audit (evaluation of environmental performance), an environmental compliance audit (determination of legal compliance)	Includes only a system audit against the requirements of the standard
Audits	Check for improvement of environmental performance. Frequency required: 3 year cycle during which all areas are verified at least once	Check environmental system performance. No frequency required
External verification	Accredited environmental verifiers	No
Authorities are informed	Obligation by validation of environmental statement	No obligation

2.1.3 THE COMPLIANCE FOCUSED EMS

Among studies conducted by the U.S. EPA to identify causes of observed non-compliance of organizations' environmental issues, a significant number of cases show that non-compliance arises from inadequately designed EMS frameworks. The National Enforcement Investigations Center (NEIC) of the U.S. EPA has developed the Compliance Focused EMS (CFEMS) to supplement, but not to replace the ISO 14001 based EMS (Sisk, 2005). This CFEMS comprises the following twelve elements:

(1) Environmental policy;

(2) Organization, personnel and oversight of an EMS;

(3) Accountability and responsibility;

(4) Environmental requirements;

(5) Assessment, prevention, and control;

(6) Environmental incidents and non-compliance investigations;

(7) Environmental training, awareness, and competence;

(8) Environmental planning and organizational decision-making;

(9) Maintenance for records and documentation;

(10) Environmental protection program;

(11) Continuing program evaluation and improvement;

(12) Public involvement/community outreach.

The framework of the CFEMS (Figure 2.4) is essentially the same as the ISO 14001 based EMS. However, additional requirements are included to ensure that compliance is attained to the largest extent. First of all, compliance with laws, regulations, and permits becomes the primary goal of the CFEMS. Furthermore, a process is required to be developed to implement and maintain ongoing internal compliance monitoring. Procedures to investigate and promptly correct non-compliance are required to be established; moreover, internal and external reporting of non-compliance is also standardized within an organization. Finally, a program for periodic audits of facility compliance with environmental requirements by independent auditors is also required.

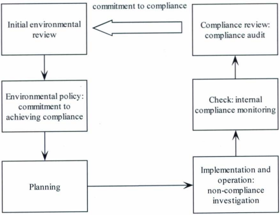


Figure 2.4 The CFEMS framework

2.2 LIMITATIONS OF COMMON EMS FRAMEWORKS

(1) Not effective to convey and interpret sufficient information for decision-making

A management system can be viewed as a tool to simplify the decision-making process and improve its efficiency (Esquer-Peralta, 2007). Petak (1981) advocated that decision making is a critical factor affecting managerial performance and system effectiveness. Therefore, an EMS should be able to help in informed decision making, i.e., to identify cost-effective and environmental friendly options.

However, common EMS frameworks are not very effective to convey sufficient and useful information for decision-making. EMS frameworks only define activities that help to prevent deviation from predetermined objectives. EMS frameworks also put too much emphasis on identifying and monitoring environmental impacts, and pay little regard to the organization and interpretation of related information for decision making.

(2) No specified environmental performance evaluation system to estimate improvement

Performance measurement provides the critical information needed to evaluate an organization's current operations and implement adjustments to make improvements. Nevertheless, common EMS frameworks promote either a prescriptive or conformance based approach instead of a performance based approach, and, therefore, no specified performance measurement and evaluation systems are found in common EMS frameworks.

A prescriptive approach provides clear instructions to organizations and standardizes organizational activities by documenting and controlling the processes. Although prescriptive approach may help in administrating processes, it does not drive changes for performance improvement. The common EMS frameworks also incorporate a conformance based approach that assures the conformance of certain standards or regulations. However, conformance based approach does not drive further performance improvement when conformance is reached. This is the fundamental flaw in these frameworks.

(3) Burden of extensive documentation

Another major limitation of EMS frameworks is the burden of extensive documentation. These documentations define the activities or steps to be followed to fulfill the requirements and personnel responsibility across the organization in an EMS. Proper management of these documents is a challenge and involves a massive cost. The cost of documentation may discourage small and medium-sized organizations from attaining EMS certification (Carraro & Leveque, 1999).

2.3 ENVIRONMENTAL MANGEMENT PARADIGMS

2.3.1 POLLUTION PREVENTION (P2)

Pollution Prevention (P2) is defined as "The use of processes, practices, materials or energy that avoid or minimize the creation of pollutants and wastes without creating or shifting new risks to communities, workers, consumers or the environment" (Wolnik & Fisher, 2005). P2 is a preferred paradigm for environmental protection in many industries, because it has numerous economic benefits (Zarker & Kerr, 2008). P2 emphasizes source reduction measures for all wastes generated at production areas for protection of the environment. P2 approaches are considered as the most preferred options in the environmental protection hierarchy as shown in Figure 2.5. Because P2 is a re-thinking of the source of pollution for optimizing or redesigning the process to reduce or eliminate the production of pollutants, no or less control or mitigation activities will be needed. P2 recognizes waste as inefficient in the system, and relies on the source reduction.

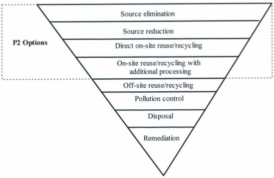


Figure 2.5 Environmental protection hierarchy

Traditional pollution control options usually involve the use of complex treatment technologies and large amounts of manpower, which increases compliance costs (Hossain, 2009). On the contrary, P2 addresses environmental impacts more effectively through the following six common practices: (1) product or process design, (2) equipment modification and process changes, (3) raw material substitution, (4) improving operating efficiency, (5) on-site reuse and recycling, and (6) inventory management.

Over last two decades, the U.S. EPA has taken steps towards environmental management emphasizing P2 and promoting beyond-compliance performance (Zarker & Kerr, 2008). P2 can serve as a vehicle to improve the efficiency of environmental management because it will lead to benefits such as a reduction in the amount of labor and equipment required for waste treatment, reductions in waste treatment and production costs, improvement in business efficiency and profitability, reduction of regulatory non-compliance costs, reduction of risk to workers and to the community, and improvement of the organization's public image. Finally, P2 can be used to help promote the continual improvement of environmental management through ongoing identification, evaluation, and implementation of P2 opportunities.

2.3.2 RISK INFORMED DECISION-MAKING (RIDM)

The Sustainable Development Agenda (1990) has motivated the development of environmental management decision-making tools, among which RIDM is one novel development (Pollard *et al.*, 2008). The U.S. Nuclear Regulatory Commission (NRC) defines RIDM as an approach to decision-making in which insights from probabilistic risk analyses are considered with other engineering insights. RIDM is mostly applied in areas such as establishing maintenance programs, optimizing inspection policies and justifying plant modifications, and revising technical specifications (Christou & Mattarelli, 2000; Simola & Pulkkinen, 2004). Figure 2.6 shows a general RIDM process.

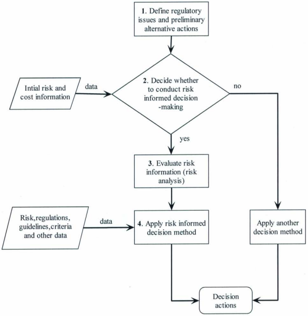


Figure 2.6 The RIDM process (NRC, 2004)

Risk informed decision approaches may be seen as utility or right-based decision methods (Ersdal & Aven, 2008). Multi-attribute analysis and cost-benefit analysis are examples of utility based methods. The right-based methods (e.g., constrained risk and zero risk) use risk acceptance criteria, which implies an acceptable risk level. The calculated risks are compared to this level. The risks are usually related to human health and the ecological environment.

RIDM has been employed in recent years for the management of environmental issues such as the redevelopment of Brownfield sites, restoration of chemically affected soil and groundwater, and decision-making related to wetlands and surface waters impacted by pollutants (Arulanantham & Feldman, 2003). RIDM has been the subject of great interest in environmental management because it is able to encode and incorporate the uncertainties of environmental risks inherent along with other useful information. Moreover, RIDM allows environmental management to address the uncertainties associated with the process and identify areas that may be over/under designed. Therefore, the RIDM paradigm has the potential to be used as a tool in properly managing environmental risks and improving overall environmental management within an organization.

Chapter 3

PROPOSED FRAMEWORK

This chapter presents a novel EMS framework. It integrates paradigms of pollution prevention and risk informed decision-making and addresses the limitations of common EMS frameworks. Furthermore, the uniqueness of the proposed framework is highlighted through a comparison with other EMS frameworks in the literature.

3.1 RISK AND POLLUTION PREVENTION FOCUSED ENVIRONMENTAL MANAGEMENT SYSTEM (RP2EMS)

3.1.1 THE RATIONALE

Traditionally, Pollution Control and Mitigation is used as a preferred approach in an EMS. The proposed EMS framework (Figure 3.1) integrates the concept of pollution prevention (P2) due to the following reasons:

(1) P2 is a widely accepted and a preferred approach for environmental protection (all pollution control options can only be viewed as temporary solutions);

(2) P2 can harness environmental management in two ways:

    (a) Environmental management is implemented from a more holistic perspective;

    (b) Less effort and investment are needed to develop/operate waste treatment systems when wastes are eliminated or minimized at their sources, which reduces the costs of environmental management;

(3) P2 can be the key for effective EMS because the majority of environmental aspects are unregulated and it can help to identify problems as well as opportunities (Chu, 2003);

(4) P2 can be easily integrated with EMS because it is also based on a similar cycle of continuous improvement.

The implementation of P2 needs systematic planning, integrated practice, evaluation and corrective actions that are similar to an EMS framework; therefore, the most effective way is to integrate P2 concepts into the EMS's continuous cycle of planning, implementing and operating, evaluating, and improving environmental performance. With this integration, P2 alternatives would be routinely considered at the start through to the end of an environmental management process and will help minimize environmental impacts within the organization. P2 is proposed to be implemented through the risk informed decision-making (RIDM) paradigm for the following reasons:

(1) RIDM provides a mechanism of quantifying environmental impacts and evaluating various solutions by reporting associated risks;

(2) A consensus on the concept of sustainable development (Clayton & Radcliff, 1996) highlights the importance of managing risk.

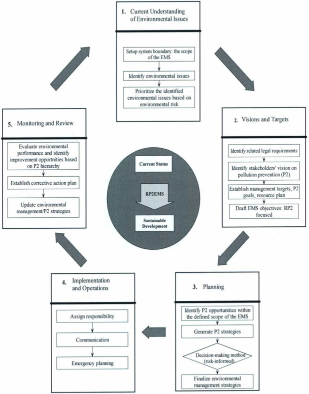


Figure 3.1 The framework of RP2EMS

3.1.2 PROPOSED FRAMEWORK

As shown in Figure 3.1, the starting point is defining the system boundary of the EMS. Will it consider all of the four stages of OOG operations (i.e., geological and geophysical survey, exploration, development and production, and decommissioning) or only a specific stage? This decision influences the subsequent identification of environmental issues and P2 options. Having prioritized the environmental issues, all applicable legal requirements need to be identified. This is important, as regulatory compliance is the bottom line that an EMS aims to achieve. The visions, values, and goals of stakeholders and other decision makers constitute the basis for establishing pollution prevention and control strategies, lists of attributes that will be evaluated in decision-making, and a procedure for how to perform decision-making processes. The next step is to identify P2 opportunities applicable to the identified significant environmental issues and generate a list of alternative pollution protection options.

A risk informed decision-making method is used to select the suitable alternatives. Implementation of the selected alternatives requires the proper assignment of responsibility and good communications during operations. Moreover, emergency planning is also required to help to achieve short and long term responses and recovery during an unexpected emergency event. Finally, the environmental performance of the current operation is evaluated. Based on the results of environmental performance evaluation, decision makers need to identify opportunities for improvements and update their current environmental management strategies.

The framework provides guidance and a procedure for the execution of environmental management focusing on P2. The aim is to achieve a certain level of consistency in environmental management involving uncertainties and confidence in reaching more desirable outcomes. Quantitative tools were developed and discussed in Chapters 4 to 6 for the following major steps:

(1) Prioritization of environmental issues: to develop the environmental policy of an environmental management system (EMS), it is always a challenge for decision makers to identify the significant environmental issue through prioritization. The challenge results from lack of information and uncertainty in the decision making process. Integrating fuzzy inference system (FIS) with fuzzy AHP, the proposed approach enables the decision makers to account for the impacts of uncertainty in determining the overall priority. Additionally, by implementing FIS at the lower levels of the analytic hierarchy, the computation is simplified, the problem of consistency is resolved and adding or deleting criteria in the hierarchy becomes easy to operate in the algorithm, thus, the limitations of conventional fuzzy AHP methods are eliminated. Finally, this approach generates a crisp numerical score, based on which prioritization of the environmental issues can easily be accomplished.

(2) Environmental decision-making: an innovative approach is developed to support decision-making in environmental management of OOG operations. Game theory is introduced to model decision-making by different groups of players with conflicting preferences on decision objectives/criteria. Additionally, uncertain

qualitative and quantitative data are transformed into rough numbers using rough set theory. In this way, the subjective selection of membership functions and α-cut in fuzzy set-based games are avoided. The multi-criteria game is solved using the generalized maximin solution concept. Aggregating those rough numbers with the optimal weight of each criterion (i.e., solution of the game), a total expected payoff (in rough number form) is obtained for each alternative. Finally, weights of the upper and lower limits are introduced to turn the expected payoff into a crisp score. By comparing these scores, the best alternative can be identified.

(3) Environmental performance evaluation: adopting QFD to implement a novel scheme to identify the specific indicators on a case-by-case basis, the proposed approach provides a transparent process for EPE. It is also the first time that QFD coupled with rough sets has been explored for EPE. Moreover, by implementing rough set theory, the approach enables decision makers to account for the impacts of incomplete and vague information in the evaluation process. Finally, this approach generates crisp indices, based on which environmental performances can easily be compared and potential improvements could be proposed.

3.2 ISO 14000 BASED EMS

ISO 14001 based EMS is the most widely accepted and applied system. Figure 3.2 shows the differences between the RP2EMS and ISO 14001 based EMS.

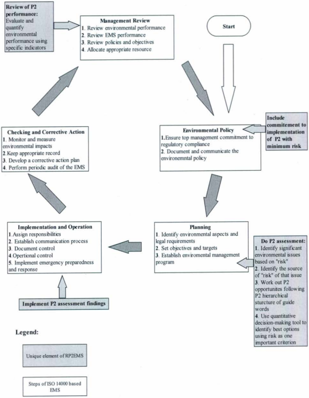


Figure 3.2 Comparison between the RP2EMS and ISO 14001 based EMS

3.3 OTHER EMS FRAMEWORKS

In the following section, three recently proposed EMSs, which also involve P2 concepts, are reviewed in comparison to RP2EMS.

LIFE CYCLE ASSESSMENT (LCA) INTEGRATED EMS

LCA is gaining popularity as a method that assists the quantification of environmental impacts and evaluation of the optimization alternatives throughout the life cycle of a process, product or activity in an EMS (Azapagic, 1999). Since life cycle thinking is critical to enable the identification of opportunities that exist to minimize environmental impacts at every stage of production, the integration of LCA and EMS can internalize environmental issues throughout the life cycle of production into corporate thinking at all levels (Sangle, 2005). Khan *et al*. (2002) proposed a methodology (Figure 3.3) for effective EMS based on LCA that characterizes, quantifies and interprets environmental impacts so that it can help to identify problems and opportunities in reaching environmental improvement and also evaluate implemented or proposed options for process change/modification, raw material changes, etc. Lewandowska *et al*. (2011) summarized major limitations of this system:

(1) Time consumption;

(2) Impossible to assess environmental aspects with qualitative character; and

(3) A risk that LCA may not capture all environmental impacts well.

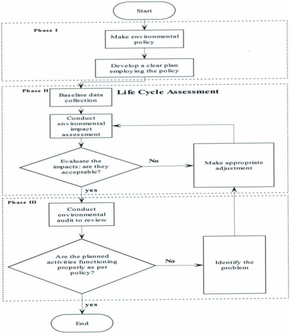


Figure 3.3 A systematic procedure to develop LCA integrated EMS (Khan *et al.*, 2002)

PRODUCT ORIENTED EMS (POEMS)

POEMS focuses on the continuous improvement of a product's eco-efficiency (ecological and economic) along its life cycle through systematic integration of eco-design in the organization's strategies and practices (Rocha & Brezel, 1999). POEMS is a logical extension of current, often primarily named facility-oriented EMS (Rene *et al.*, 1999). Ammerberg & Sundin (2005) advocated that POEMS resulted from the integration of concept design for the environment (DfE) and the EMS. DfE employs design approaches to reduce overall environmental impacts of a product, process, or practice. A POEMS has two parts:

(1) Integration of environmental aspects into the product development process; and

(2) Integration of the product development process into the management system of an organization.

Product-specific environmental review or product profiling is one significant step in POEMS. One challenge in POEMS is to investigate potential improvements based on product profiling information and develop procedures for the DfE activities. The DfE activities should be performed at the operational level based on the defined procedures and use as much product profiling information as possible. Lastly, in order to provide a solid base for reaching continuous improvement, revisions of existing procedures and products are conducted to identify improvement opportunities.

POEMS can reveal the environmental impacts caused by the organization's operations and aims to reduce these impacts. However, it may be out of control of one organization because co-operations between organizations (e.g., producers and actors) are needed at each stage of product life cycle (Rene *et al.*, 1999).

INTEGRATED EMS (IEMS)

The U.S. EPA released IEMS through its DfE Program. The DfE approach to developing an IEMS has six main steps (U.S. EPA, 2000):

(1) Identify and compare alternatives to evaluate trade-offs and information gaps;

(2) Use the DfE's Substitute Tree to evaluate alternatives (Figure 3.4);

(3) Use the Pollution Prevention Hierarchy to evaluate and rank approaches (Figure 3.5);

(4) Integrate environmental consideration into day-to-day decision making that includes cost and performance to provide environmental solutions to promote competitiveness;

(5) Recognize the need for a commitment for continuous improvement; and

(6) Work in partnership with stakeholders; engage participation and support of employees and open communication.

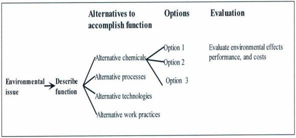


Figure 3.4 Substitute tree (U.S. EPA, 2000)

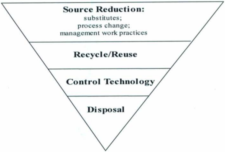


Figure 3.5 Pollution prevention hierarchy (U.S. EPA, 2000)

IEMS emphasizes environmental and human health risk reduction, pollution prevention, and proper resource management through technical methods that integrate cleaner technologies with management methods. Chu (2003) summarizes two goals of IEMS:

(1) To ensure that an EMS drives continuous environmental improvement; and

(2) To make the EMS easier for operators.

Table 3.1 shows the differences between proposed and existing EMS frameworks to highlight the novelty of the RP2EMS.

Table 3.1 Comparing EMS frameworks

Aspects / EMS Name	P2 is included or not?	"Risk reduction" is emphasized or not?	Conformance based or performance based?	Performance evaluation system?	Decision support system?
RP2EMS	yes based on risk informed P2	yes	performance based	yes	yes risk informed decision support system
LCA integrated EMS	yes P2 is treated as another environmental protection option other than pollution control	no	conformance based	yes	no
POEMS	yes P2 is treated as another environmental protection option other than pollution control	no	conformance based	no	no
IEMS	yes P2 hierarchy is used to evaluate and rank environmental protection options	yes	conformance based	yes but only environmental performance criteria are suggested to be developed	no

Chapter 4

PRIORITIZATION OF ENVIRONMENTAL ISSUES USING FUZZY INFERENCE SYSTEM AND FUZZY ANALYTIC HIERARCHY PROCESS

PREFACE

This work has been published: Yang, M., Khan, F., Sadiq, R. (2011). Prioritization of environmental issues in offshore oil and gas operations: A hybrid approach using fuzzy inference system and fuzzy analytic hierarchy process. *Process Safety and Environmental Protection*, 89 (1), 22-34.

The first author (Ming Yang) formulated the research problem, constructed the approach, executed the case study, and developed the first draft of the manuscript. The co-authors (Drs. Faisal Khan and Rehan Sadiq) supervised the work, critically reviewed the developed approach and suggested revisions of the manuscript.

4.1 INTRODUCTION

An EMS can be utilized to systematically manage all activities in OOG operations that cause environmental impacts. A key component of an effective EMS is the environmental policy, i.e., a short written statement by the operators setting out their intent and commitments to deal with environmental issues. Identification of the significant environmental issues that cause the major negative impacts is necessary when insufficient resources exist to implement an EMS. The environmental policy should provide clear guidance to ensure that the available resources are directed towards the significant issues that must immediately be addressed by the EMS. Prioritization will help by sorting out this issue. The process of the prioritization involves preferences and attitudes towards multiple criteria/attributes. This process is usually subjected to a scarcity of information and uncertainties due to human interpretation. Therefore, prioritization of environmental issues in OOG operations is a complicated problem that necessitates the application of a robust decision support technique. This chapter aims to propose a novel approach for the prioritization of environmental issues based on environmental risk.

4.2 MULTI-ATTRIBUTE DECISION-MAKING (MADM) TECHNIQUES FOR PRIORITIZATION

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), outranking method, and analytic hierarchy process (AHP) are the three most frequently used multi-attribute decision-making (MADM) techniques for prioritization (Bozbura *et al.*, 2007). TOPSIS was developed by Hwang & Yoon (1981) to achieve the rankings of the alternatives based on the shortest distance from the positive-ideal solution (PIS) and the farthest distance from the negative-ideal solution (NIS). The outranking method determines which alternatives are preferred to the others by systematically comparing each criterion instead of building complex utility functions (Brans *et al.*, 1984). AHP, developed by Saaty (1980) based on mathematics and psychology, is the most popular method for decision-making. AHP helps to turn a complex problem under study into a hierarchical structure consisting of a goal and subordinate features. The procedure for using the AHP is given as follows:

(1) Use a hierarchy to model the decision problem that consists of the decision goal, available options, and criteria for assessing these options;

(2) Obtain priorities of the elements of the hierarchy by pair-wise comparisons of the elements at each level of the hierarchy by means of a nominal scale;

(3) Synthesize these priorities to obtain priority for the hierarchy;

(4) Check the consistency;

(5) Finalize the decision based on the results from this process.

Saaty (1996) also developed a more general form of AHP - analytic network process (ANP) to release the mutual dependencies and feedback effect of the criteria. The ANP can be used as an effective approach in situations where the interactions among the elements of a system form a network structure (Saaty, 1996).

Once objective information is available, the probability theory is used to deal with randomness in conducting decision analysis. However, most of the decision analyses in the real world are performed with subjective or uncertain information. The uncertainty results from the qualitative definition of linguistic expressions. To solve this problem, Bellman and Zadeh (1970) made the first attempt at establishing a conceptual framework based on the fuzzy set theory. With the assistance of experts' knowledge, fuzzy logic that is a multi-valued logic derived from fuzzy set theory is applied to deal with vagueness in human perceptions and thoughts (Beskese *et al.*, 2004). Fuzzy logic (Zadeh, 1965) is an extension of Boolean logic and is now commonly used for complex computer-aided decision-making. In classical (Boolean) logic, whether the element belongs to the set or not is clearly defined using 0 or 1. While in the case of fuzzy logic, whether the elements belong to the set is not definite. In order to express this mathematically, any value within the interval [0, 1] can be used to represent the degree of belongingness (membership) of each element to the set. This concept can be simply represented by the following expression:

$$\mu_A : X \rightarrow [0,1]$$

If the membership $\mu_A(x)$ is close to 1, it refers to a greater degree of belongingness of the element x to the set A. If the degree is close to 0, the degree of belongingness of x to A is small.

The fuzzy version of AHP is preferred in the prioritization of environmental issues in OOG operations due to the following two reasons. First, when pair-wise comparison is used, no measurement scale for each criterion/attribute needs to be explicitly defined (Spires, 1991), which eases prioritization for decision makers. Second, Klir & Yuan (1995) identified three types of uncertainties: (1) vagueness (lack of sharp distinction), (2) non-specificity (two or more alternatives are unspecified), and (3) discord (disagreement in selecting alternatives). Fuzzy logic theory is one of the best techniques to quantitatively deal with vagueness type uncertainty that dominates in the process of prioritization. A typical example was given by Tesfamariam & Sadiq (2006) to use fuzzy AHP in risk-based environmental decision making. Nevertheless, the studies by Buyukozkan *et al.* (2004) and Wang & Chen (2008) on different fuzzy AHP methods indicated four limitations:

(1) The computational requirement is tremendous, especially at the lowest level of hierarchy where numbers of alternatives are compared in a pair-wise manner based on each sub-criterion or attribute;

(2) Sometimes they only allow triangular fuzzy numbers to be used;

(3) Adding or deleting criteria or attributes in the analytic hierarchy is not easy to operate in the algorithm;

(4) The number of the pair-wise comparisons increases with the number of criteria. When the comparison ratios are given by fuzzy numbers, inconsistent ratios are more likely to be expected in real world cases.

In order to eliminate the above limitations, a hybrid approach for prioritization using the fuzzy inference system (FIS) and fuzzy analytic hierarchy process (FAHP) is proposed in this chapter. In the literature, FIS has never been implemented in conjunction with fuzzy AHP to structure a methodology for prioritization.

4.3 FUZZY ANALYTIC HIERARCHY PROCESS (FAHP)

Since decision makers are not explicit in their preference during comparisons; therefore, it is generally very common to find expert judgments using interval values. FAHP was originally proposed by Van Laarhoven & Pedrycz (1983). Some environmental applications of FAHP have recently been reported to prioritize the factors in cleaner production implementation (Tseng *et al.*, 2009) and to assess the eco-vulnerability (Li *et al.*, 2009). Recent years have also seen the application of the fuzzy analytic network process (FANP) in the environmental decision-support (Promentilla *et al.*, 2008; Liu & Lia, 2009). Table 4.1 summarizes five frequently used FAHP methods that have significant differences in their theoretical structures.

Table 4.1 Summary of FAHP methods in the literature (Bozbura *et al*., 2007)

Methods	Main characteristics	Advantages (A) and disadvantages (D)
Cheng *et al.* (1996)	• Uses entropy concepts to do weights' aggregation • Builds fuzzy standards • Represents performance scores by membership functions	(A) The computational requirement is not very tremendous (D) Entropy is used when probability distribution is known (D) The method is based on both probability and possibility measures
Chang (1996)	• Uses synthetical degree values • Composite total sequencing	(A) The computational requirement is not very tremendous (A) It follows the steps of crisp AHP and does not involve additional operations (D) It allows only triangular fuzzy numbers to be used though they are easy to apply
Boender, de Grann & Lootsma (1989)	• Modfies Van Laarhoven and Pedrycz's method • Presents a more robust approach to the normalization of the local priorities	(A) The thoughts of multiple decision-makers can be modeled (D) The computational requirement is tremendous
Buckley (1985)	• Extends Saaty's priority method with trapezoidal fuzzy numbers • Uses the geometric mean method to derive fuzzy weights and performance scores	(A) It is easy to extend to the fuzzy case (A) It guarantees a unique solution to the reciprocal comparison matrix (D) The computational requirement is tremendous
Van Laarhoven & Pedrycz (1983)	• Directly extends Saaty's priority method with triangular fuzzy numbers • Uses Lootsma's logarithmic least square method to derive fuzzy weights and performance scores	(A) The thoughts of multiple decision-makers can be modeled in the reciprocal matrix (D) There is not always a solution to the linear equations (D) The computational requirement is tremendous (D) It allows only triangular fuzzy numbers to be used

The above summary indicates that Chang's extent analysis method (Chang, 1996) is relatively easier to implement and therefore is used in our approach. Chang's method uses triangular fuzzy numbers (TFNs) rather than trapezoidal or Gaussian fuzzy numbers. Figure 4.1 shows these three commonly used fuzzy numbers. In the proposed approach, TFNs are also used due to the following reasons:

(1) TFNs are intuitively easy to apply and calculate and also prove to be effective in the decision analyses (Kahraman *et al*., 2004; Chang *et al*., 2007);

(2) When interval-valued assessments are employed, decision makers usually provide narrower intervals than their actual perceptions may authorize in order to avoid providing imprecise information. TFNs can effectively solve this problem by enabling decision makers to provide a supporting set of fuzzy numbers as the interval that certainly contains the unknown ratio of the relative importance (Ramik & Korviny, 2010);

(3) TFNs provide the potential for representing and reconciling conflicts in group decision making because "a" (the lowest possible value), "c" (the largest possible value), and "b" (the most possible value) can be interpreted as the minimum, maximum and the geometric mean of the decision makers' judgments (Ramik & Korviny, 2010).

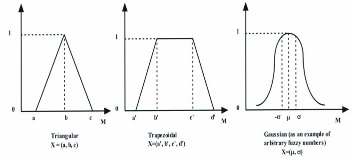


Figure 4.1 Representations of triangular, trapezoidal, and arbitrary fuzzy numbers

The outlines of the Chang's method are provided as follows:

Let $X = \{x_1, x_2, ... x_n\}$ be an object set and $U = \{u_1, u_2, ... u_m\}$ be a goal set. Each object is taken to do an extent analysis for each goal (g_i). Then, for each object, *m* extent analysis values can be achieved:

$M_{g_i}^1, M_{g_i}^2 ... M_{g_i}^m$, ($i$ = 1, 2,..., n) where all $M_{g_i}^j$ (j = 1,2,...,m) are triangular fuzzy numbers that have three parameters (i.e., **a**- the lowest possible value, **b**- the most possible value, and **c**- the largest possible value). Figure 4.2 presents the steps of this method.

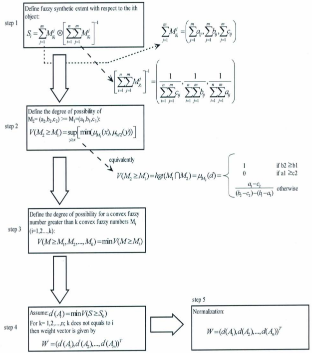


Figure 4.2 Steps of Chang's extent analysis method

4.4 FUZZY INFERENCE SYSTEM (FIS)

The FIS is also known as a fuzzy rule-based system or fuzzy expert system. An FIS is a way of formalizing the reasoning process of human language using fuzzy logic. The operational mechanism of an FIS is that the system formulates suitable rules, and based upon the rules, inference is made using fuzzy IF-THEN rules and fuzzy reasoning. A standard FIS consists of four blocks that include a fuzzification interface, a knowledge-base to define rules and fuzzy sets, a decision-making unit, and a defuzzification interface. Below is a summary of each block:

(1) *Fuzzification interface* transforms crisp inputs into degrees of belongingness to predefined linguistic expressions (constants) based on membership functions;

(2) *Knowledge-base* contains a rule base defining a number of fuzzy IF-THEN rules and a database defining fuzzy sets used in the fuzzy rules;

(3) *Decision-making unit* performs the interface operations of the rules using fuzzy reasoning, the steps of which are presented in Figure 4.3, and the most widely used t-norm operators in fuzzy set theory are listed in Table 4.2;

(4) *Defuzzification interface* transforms the results from fuzzy values into crisp values.

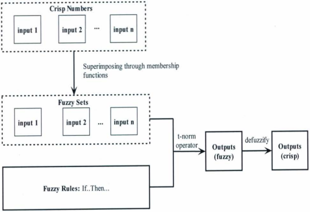


Figure 4.3 Steps involved in fuzzy reasoning

Table 4.2 Commonly used t-norm operations in fuzzy set theory (Novak & Pedrycz, 1988)

Min operator	min (a, b)
Product operator	a*b
Bounded operator	max (0, a+b-1)
Drastic operator	$T_D = \begin{cases} a, if \quad b=1 \\ b, if \quad a=1 \\ 0, otherwise \end{cases}$

There are two major fuzzy inference methods: Mamdani and Sugeno inference method. The main difference between these two methods is that Mamdani uses fuzzy sets as the rule consequent, while Sugeno employs linear functions of input variables as the rule consequent (Sivanandam *et al*., 2007).

In the literature, FIS has been implemented for fault detection (White & Lakany, 2008; Nan *et al*., 2008), supporting customers' requirements (Juang *et al*., 2007), modeling streamflow (Katambara & Ndiritu, 2009), assessing water quality (Ocampo-Duque *et al*., 2006), and other areas. Very few papers have been found in which FIS is proposed for risk assessment. Elsayed (2009) developed an FIS to infer risk from two input variables (i.e., consequence and likelihood). In the proposed approach, FIS is implemented to infer consequence and likelihood, respectively, instead of risk.

4.5 THE PROPOSED METHODOLOGY

4.5.1 ANALYTIC HIERARCHY FOR THE PRIORITIZATION OF OOG ENVIRONMENTAL ISSUES

There are varieties of environmental issues triggering various environmental risks/impacts in OOG operations (Table 4.3). "Significance" is the most frequently used word to describe risks/impacts and also provides a basis for regulatory and policy decisions (Shepard, 2005). Therefore, the prioritization of environmental issues can be equivalently performed in the prioritization of the significance of those issues in terms of environmental risks. To measure environmental risk, consequence and likelihood are two important parameters of which there are sub-parameters such as severity, geographical scale, duration, likelihood with respect to exposure, and toxicity or mechanism assessment. Thus, a five-level analytic hierarchy (Figure 4.4) has been designed to serve the goal of prioritization of the significance.

Table 4.3 Environmental issues in OOG operations (adapted from Patin, 1999)

Offshore Operations	Environmental issues	Potential Environmental Risks/Impacts
Seismic survey	High energy wave	Severe biological damage to larvae and fry adult fish
Electro survey	Artificial electrical fields	May cause death of fish and other marine organisms
Drilling for exploration and production	Drilling fluids and cuttings discharge	Increase turbidity, long term ecological impacts on marine living things due to hydrocarbon pollution
	Produced water discharge	Small scale hydrocarbon pollution, long term
	Well treatment fluids discharge	Severe biological damage to larvae and fry adult fish
	Air emission	Local, regional or global climate change
Platform operation	Deck drainage discharge	Small scale hydrocarbon pollution, not very severe
	Storage displacement water discharge	Small scale hydrocarbon pollution, not very severe
	Sewage and living waste discharge	Little disturbance to the surrounding marine environment
	Air emission	Local, regional or global climate change
Transportation	Noise	Little disturbance because it takes place in isolated offshore areas
	Air emission	Local, regional or global climate change
	Accidental oil spill	Severe acute ecological damage to marine living things, locally or regionally
Installation and decommissioning	Air emission	Local, regional or global climate change
	Accidental oil spill	Severe acute ecological damage to marine living things, locally or regionally

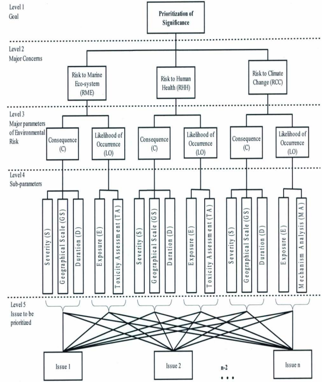


Figure 4.4 A hierarchy used for the prioritization of OOG environmental issues

4.5.2 THE HYBRID APPROACH

A panorama of the hybrid approach is given in Figure 4.5. Pair-wise comparisons need to be operated at each level/hierarchy in fuzzy AHP methods. This requires extensive computations, most of which are done at the lowest level where comparisons are made in between each alternative on each sub-criterion/attribute. For example, in the conventional approach, if there are 10 issues (at level 5) to be prioritized in the above hierarchy, for each of the 15 sub-criteria/attributes (at level 4), 100 (10×10) comparisons are required. After these comparisons have been completed, 1500 (15×10) sets of fuzzy triangular numbers need to be processed for weights' vectors. Thus, FIS is proposed to be implemented at the lower levels of the hierarchy to simplify the computation and can easily be coded in Matlab. Moreover, the number of pair-wise comparisons is significantly reduced in this approach, which also resolves the problem of consistency of the conventional FAHP methods. As another advantage of combining FIS with fuzzy AHP, adding or deleting sub-criteria or attributes becomes easy to operate. What needs to be done is just writing new rules instead of rewriting an algorithm in the traditional approach. This advantage allows decision-makers to adjust the system based on the current situation without any difficulty. Lastly, this combination does not degrade the ability of the system to handle imprecise and vague information in the process of prioritization.

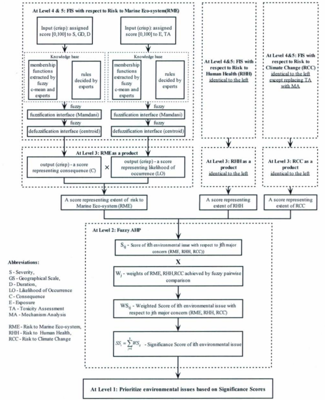


Figure 4.5 The hybrid approach for the prioritization of environmental issues

More explanations on specific operations in this approach are provided as follows:

(1) At Level 5 and 4 in the hierarchy (Figure 4.4)

To infer "consequence" and "likelihood of occurrence", two independent FISs are developed. They have the same structure but different input and output variables (Table 4.4). There are various methods that can be applied to generate membership functions that include intuition, inference, rank ordering, fuzzy clustering, neural network, genetic algorithms, and inductive reasoning (Sivanandam *et al.*, 2007). To generate membership functions of the input variables, fuzzy c-means is proposed because of its simplicity and robustness, while membership functions of the output variables could be defined by a group of experts. Fuzzy c-means is one of the fuzzy clustering methods which determine not only which cluster an object belongs to but also to what degree this object belongs to the cluster. This method aims to minimize the weighted within-class sum of squared Euclidean distance. Specifically, it minimizes an objective function that represents the distance from any given data point to a cluster center weighted by that data point's membership grade. This can be expressed using the following equation:

$$J(U, v_1, \ldots, v_k) = \sum_{i=1}^{n} \sum_{k=1}^{K} (u_{ik})^m d^2(x_i, v_k) \qquad \textbf{(4.1)}$$

where $v_k = (v_{ka})$, $k = 1, 2 \ldots, K$, $a = 1, 2 \ldots, p$ denotes the values of the centroid of a cluster k, $x_i = (x_{ia})$, $i = 1, 2, \ldots, n$; $a = 1, 2 \ldots, p$ is the ith objective with respect to p variables, and $d^2(x_i, v_k)$ is the square Euclidean distance between x_i and v_k. The m denotes the degree of fuzziness of the clustering chosen from $[1, \infty]$. In order to obtain the solution U and v_k that minimizes equation 1, a Picard iteration of the following expressions is conducted:

$$u_{ik} = \frac{1}{\sum_{i=1}^{K} \{d(x_i, v_k) / d(x_i, v_i)\}^{\frac{2}{m-1}}} ; \quad (4.2)$$

$$v_k = \frac{\sum_{i=1}^{n} (u_{ik})^m x_i}{\sum_{i=1}^{n} (u_{ik})^m} \quad (4.3)$$

It is easy to use [center, U] = fcm (data, cluster_n) to compute the centers and degree of belongingness (U) to these centers in Matlab. If a Gaussian shape is assumed and recognized to be appropriate for membership functions of all input variables, then the identified centers can be directly used as the "means" of those Gaussian membership functions. The standard deviations of the datasets consisting of scores representing experts' ideas (as values of x-axis) and degree of belongingness (as values of y-axis) can be used as the standard deviations of those Gaussian shape membership functions. The required datasets can be achieved by distributing questionnaires (e.g., see Appendix I) to a number of experts for their judgments expressed using an integer score in the range [0,100]. Take "Severity" as an example, each of the 20 experts is assumed to assign 5 integers $\in$ [0, 100] (where 0 represents the "least significant" and 100 represents the "most significant") to the 5 categories of waste streams. Thus, a dataset consisting of 100 (5×20) integers can be achieved for generating the membership function of "Severity".

Table 4.4 Input and output variables of FIS to infer parameters of risk

FIS for	Variable Type	Variable Name	Fuzzy Sets (linguistic constants)
Consequence	Input	Severity	Low, moderate, high
		Geographical Scale	Local, regional, global
		Duration	Short, moderate, long
	Output	Consequence	Very slight, slight, medium, serious, very serious
Likelihood of Occurrence	Input	Exposure	Uncommon, common, frequent
		Toxicity Assessment or Mechanism Assessment	Uncommon, common, frequent
	Output	Likelihood of Occurrence	Very low, low, medium, high, very high

Having defined the membership functions, fuzzy rules can be developed by environmental and operational experts in the OOG industry and management teams.

In this study, since there is no linear relationship existing between input and output variables, the Mamdani fuzzy method is used. The soft computational operators employed by the Mamdani method are listed as follows:

- **And** Operator: 'min' (i.e., conjunctive logic)
- **Or** Operator: 'max' (i.e., disjunctive logic)
- **Implication** Method: 'min' (i.e., conjunctive logic)
- **Aggregation** Method: 'max' (i.e., disjunctive logic)
- **Defuzzfication** Method: 'centroid'

The mechanism of the Mamdani inference method is as follows: (1) first the inputs are fuzzified to get their membership values. If there is more than one input in the rule, a fuzzy operator (t-norm operator) should be applied to achieve a single membership value (2) then implication method (min) is applied to reach each rule's conclusion (3) the fuzzy aggregation method is used to combine the conclusion of each rule into a single fuzzy set (4) finally, the deffuzzification method is applied to transform the conclusions into crisp numbers.

For illustrative purposes, considering one environmental issue (e.g., drilling wastes discharge) is to be processed using the above defined two FISs to infer the consequence and likelihood of occurrence with respect to RME, RHH, RCC (defined at level 2 in Figure 4.4), first experts need to develop input row matrixes, as shown in Table 4.5.

Table 4.5 An example of an input row matrix of one environmental issue

Matrix for RME					Matrix for RHH					Matrix for RCC				
C			LO		C			LO		C			LO	
S	GS	D	E	TA	S	GS	D	E	TA	S	GS	D	E	MA
60	30	70	90	60	30	20	20	30	10	0	0	0	0	0

After defining the membership functions and rules, by running the two FISs independently, crisp numbers representing the extent of consequence and likelihood of occurrence, respectively, can be obtained:

For RME - 60.5 and 67.2, For RHH - 34.0 and 35.0, For RCC - 25.9 and 35.0

(2) At Level 3 in the hierarchy

As commonly defined in the literature, risk can be calculated as a product of consequence and likelihood of occurrence. Scores representing the extent of these two parameters are the outputs of the two FISs discussed above. Following the previous example, scores representing the extent of RME, RHH, and RCC induced by the issue are calculated:

$60.5 \times 67.2 = 4066$, $34.0 \times 35.0 = 1190$, $25.9 \times 35.0 = 907$

(3) At Levels 2 and 1 in the hierarchy

Varieties of fuzzy scales are found in the literature (Erensal *et al.*, 2006; Leung & Cao, 2000) to convert the linguistic scale into a fuzzy scale. The triangular fuzzy conversion scale used in the proposed approach is given in Table 4.6. Questionnaires (see Appendix II) are needed to get the evaluations. An example of converted results of pair-wise comparisons is given in Table 4.7.

Table 4.6 Triangular fuzzy conversion scale (Bozhura & Beskese, 2007)

Linguistic Scale	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	(1,1,1)	(1,1,1)
Equally important	(1/2,1,3/2)	(2/3,1,2)
Weakly more important	(1,3/2,2)	(1/2,2/3,1)
Strongly more important	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strongly more important	(2,5/2,3)	(1/3,2/5,1/2)
Absolutely more important	(5/2,3,7/2)	(2/7,1/3,2/5)

Table 4.7 An example of converted results of pair-wise comparisons

	RME	RHH	RCC
RME	(1, 1, 1)	(1, 3/2, 2)	(1/2, 1, 3/2)
RHH	(1/2, 2/3, 1)	(1, 1, 1)	(1, 3/2, 2)
RCC	(2/3, 1, 2)	(1/2, 2/3, 1)	(1, 1, 1)

The weights' vector of RME, RHH, and RCC can be obtained using Chang's extent analysis method. For example, based on the numbers given in Table 4.7, the values of fuzzy synthetic extent, with respect to RME, RHH, and RCC, were calculated as follows:

$$S_{RME} = (5/2, 7/2, 9/2) \otimes (2/25, 3/28, 6/43) = (0.200, 0.375, 0.628)$$

$$S_{RHH} = (5/2, 19/6, 4) \otimes (2/25, 3/28, 6/43) = (0.200, 0.339, 0.558)$$

$$S_{RCC} = (13/6, 8/3, 4) \otimes (2/25, 3/28, 6/43) = (0.173, 0.286, 0.558)$$

The degrees of possibility were calculated as follows:

$V(S_{RME} \geq S_{RHH}) = 1.000$ $\quad$ $V(S_{RME} \leq S_{RHH}) = 0.909$

$V(S_{RME} \geq S_{RCC}) = 1.000$ $\quad$ $V(S_{RME} \leq S_{RCC}) = 0.800$

$V(S_{RHH} \geq S_{RCC}) = 1.000$ $\quad$ $V(S_{RHH} \leq S_{RCC}) = 0.870$

The minimum of the degrees of possibility was obtained:

$MinV(S_{RME} \geq S_i) = 1.000$

$MinV(S_{RHH} \geq S_i) = 0.909$

$MinV(S_{RCC} \geq S_i) = 0.800$

The weights' vector was worked out based on the above values:

$W = (d\ (RME), d\ (RHH), d\ (RCC))^T = (0.369, 0.336, 0.295)$

Finally, for the issue of drilling wastes discharge, the Significance Score (SS_i) can be synthesized using the calculated scores representing the extent of risks and their weights:

$0.369 \times 4066 + 0.336 \times 1190 + 0.295 \times 907 = 2168$

Similarly, for each environmental issue, such a score can be obtained. The issue with the highest score is the most significant one that needs to be highlighted in the environmental policy of an EMS.

4.6 A CASE STUDY

Considering an offshore operator is planning to develop an EMS aiming to achieve better environmental performance, decision makers need to prioritize 11 environmental issues (given below) to sort out the significant one to be immediately addressed by an EMS:

(1) Produced water discharge - the largest waste stream in volume but causes limited environmental impact;

(2) Drilling waste discharge - may cause physical changes and biological impacts on the marine environment and organisms near the rigs;

(3) Deck drainage discharge - may contain various contaminants including detergents and dispersants used for washing, emulsified oil and some other chemicals;

(4) Storage displacement water discharge - is polluted by crude oil;

(5) Flaring emissions - produces green house gases (GHG) that account for climate change and also pollutes the air that OOG operators may breathe;

(6) Waste gas emissions - may be composed of methane (CH_4), non-methane volatile organic hydrocarbons (NMVOC), and volatile organic hydrocarbons (VOC); may be toxic to humans;

(7) Chemical use and exposure - such as biocides that may be toxic to marine organisms and humans;

(8) Oil spill (drilling accidents) - intense and prolonged hydrocarbon gushing; may cause acute impacts such as intoxication, death, physio-biochemical disturbances or behavioral responses in fish and marine mammals, and chronic impacts such as the disturbance of reproduction of marine organisms, population changes or community structure changes;

(9) Oil spill (transportation accidents) - caused by collisions, fires, explosions, and structure failures; the same impacts as described in the above issue;

(10) Physical disturbance (seismic survey) - seismic disturbance may destroy fish bladders, larvae and disrupt traditional migration paths of fish and marine mammals;

(11) Decommissioning and rehabilitation - might affect the local fish population; in some cases, explosives are applied to remove whole platforms, which may cause injury or even death to fish or marine mammals.

The proposed approach was coded and implemented following the steps given in Figure 4.6. The input matrixes mentioned at step 3 for inferring the consequence and likelihood of occurrence of Risk to Marine Eco-system (RME), Risk to Human Health (RHH), and Risk to Climate Change (RCC), respectively, are provided in Table 4.8. The matrixes mentioned at step 4 for generating membership functions of input variables were obtained from questionnaires filled out by 20 hypothetical experts (hence forth referred to as experts). Table 4.9 provides the membership functions of output variables defined by a group of experts. Table 4.10 gives part of the rule base (mentioned earlier in step 6) used in this numerical application. These rules were developed based on the author's own knowledge.

For step 11, the pair-wise comparison matrix is established (see Table 4.11). The following steps given in Figure 4.2, weights' vector can be calculated.

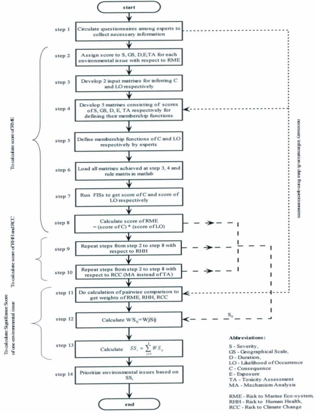


Figure 4.6 The implementation procedure of the numerical application

Table 4.8 Input matrixes for FISs to infer consequence and likelihood

Environmental issues	Matrix for RME					Matrix for RHH					Matrix for RCC				
	C			LO		C			LO		C			LO	
	S	GS	D	E	TA	S	GS	D	E	TA	S	GS	D	E	MA
produced water discharge	40	30	70	90	30	20	10	20	10	5	0	0	0	0	0
drilling waste discharge	60	30	70	90	60	30	20	20	30	10	0	0	0	0	0
deck drainage discharge	20	30	50	60	50	20	20	30	20	20	0	0	0	0	0
storage displacement water discharge	15	30	50	50	20	15	30	50	50	10	0	0	0	0	0
flaring emissions	30	50	70	70	20	50	10	70	70	50	70	80	70	90	60
waste gas emissions	25	40	70	80	10	30	10	70	80	50	60	70	70	90	50
chemical use and exposure	60	20	30	50	80	90	10	30	70	90	0	0	0	0	0
oil spill (drilling accident)	80	40	10	30	70	80	40	10	30	50	0	0	0	0	0
oil spill (transportation accident)	90	60	5	10	70	90	60	5	10	50	0	0	0	0	0
physical disturbance (seismic survey)	10	20	20	50	40	60	20	20	50	40	0	0	0	0	0
decommissioning and rehabilitation	35	10	60	40	45	40	10	60	40	50	0	0	0	0	0

Table 4.9 Membership functions of output variables

Output variables		Linguistic description	Shape of Membership function	Parameters
RME	C	very slight	trapezoid	[0 0 15 25]
		slight	trapezoid	[15 25 40 50]
		medium	trapezoid	[40 50 65 75]
		serious	trapezoid	[65 75 85 90]
		very serious	trapezoid	[85 90 100 100]
	LO	very low	trapezoid	[0 0 15 25]
		low	trapezoid	[15 25 40 50]
		medium	trapezoid	[40 50 65 75]
		high	trapezoid	[65 75 85 90]
		very high	trapezoid	[85 90 100 100]
RHH	C	very slight	trapezoid	[0 0 10 15]
		slight	trapezoid	[10 15 30 40]
		medium	trapezoid	[30 40 55 65]
		serious	trapezoid	[55 65 70 85]
		very serious	trapezoid	[70 85 100 100]
	LO	very low	trapezoid	[0 0 15 25]
		low	trapezoid	[15 25 40 50]
		medium	trapezoid	[40 50 65 75]
		high	trapezoid	[65 75 85 90]
		very high	trapezoid	[85 90 100 100]
RCC	C	very slight	trapezoid	[0 0 5 15]
		slight	trapezoid	[5 15 20 30]
		medium	trapezoid	[20 30 45 55]
		serious	trapezoid	[45 55 60 75]
		very serious	trapezoid	[60 75 100 100]
	LO	very low	trapezoid	[0 0 15 25]
		low	trapezoid	[15 25 40 50]
		medium	trapezoid	[40 50 65 75]
		high	trapezoid	[65 75 85 90]
		very high	trapezoid	[85 90 100 100]

Table 4.10 Rule base used in the numerical application

	Rule	S	GS	D	→	C
RME	1	low	local	short	→	very slightly
	2	low	local	moderate	→	very slightly
	3	low	local	long	→	slightly
	4	low	regional	short	→	slightly
	5	low	regional	moderate	→	slightly
	...					
	12	moderate	local	long	→	medium
	13	moderate	regional	short	→	medium
	14	moderate	regional	moderate	→	medium
	15	moderate	regional	long	→	medium
	16	moderate	global	short	→	medium
	...					
	23	high	regional	moderate	→	medium
	24	high	regional	long	→	very serious
	25	high	global	short	→	serious
	26	high	global	moderate	→	very serious
	27	high	global	long	→	very serious
	Rule	**E**	**TA**	**→**	**LO**	
	1	uncommon	Uncommon	→	very low	
	...					
	6	common	common	→	medium	
	...					
	9	frequent	frequent	→	very high	
RHH	...					
RCC	...					

Table 4.11 Pair-wise comparisons for major concerns

	RME	RHH	RCC
RME	(1, 1, 1)	(1, 3/2, 2)	(1, 3/2, 2)
RHH	(1/2, 2/3, 1)	(1, 1, 1)	(1, 3/2, 2)
RCC	(1/2, 2/3, 1)	(1/2, 2/3, 1)	(1, 1, 1)

Table 4.12 summarizes all of the results achieved in this example. The results show that flaring emissions should be the significant issue that should immediately be addressed by the EMS. This application clearly presents how the proposed approach can be performed and validates the approach.

The results of the proposed approach are quite dependent on the data or information used for the computation, which is determined by experts' preference, attitude and knowledge. For example, changes in experts' preferences in pair-wise comparisons of RME, RHH, and RCC, assignments of values in the input matrixes of the FISs, and rule base will lead to different rankings of environmental issues. Therefore, it is important that agreement has been reached among with a group of experts with similar preferences to ensure that qualified results can be achieved.

The proposed approach needs to be validated in real-world cases and work on this direction is in progress. For example, in the recent BP oil spill in the Gulf of Mexico the approach can be applied to support the development of a priority list of responses to minimize damage to the environment. A derivate of the proposed approach is one in which FISs are implemented at Level 2 and 3 of the hierarchy (see Figure 4.4). The outputs of the FIS at Level 3 go as the inputs of the FIS at level 2 and finally to infer the Significance Score. This derivative approach has been implemented in the same case and the same rank of environmental issues was achieved. This provides testing and validation of the proposed approach.

Table 4.12 Results of the numerical application

Environmental Issues	RME				RHH				RCC				Significance Score (SS_i)
	W_1=0.450				W_2=0.343				W_3=0.207				
	C	LO	S_{i1}	WS_{i1}	C	LO	S_{i2}	WS_{i2}	C	LO	S_{i3}	WS_{i3}	
flaring emissions	47.5	52.8	2506	1128	49.3	64.7	3193	1095	76.8	79.5	6103	1263	3486
chemical use and exposure	44.2	67.5	2983	1342	43.2	81.7	3532	1211	25.9	35.0	906	188	2741
waste gas emissions	46.7	48.8	2277	1025	35.5	66.4	2360	810	68.7	57.4	3942	816	2651
oil spill (transportation accident)	58.4	54.1	3160	1422	58.3	45.1	2629	902	25.9	35.0	906	188	2511
drilling waste discharge	60.5	67.2	4068	1830	34.0	35.0	1191	409	25.9	35.0	906	188	2427
oil spill (drilling accident)	56.8	54.3	3081	1386	46.2	47.1	2174	746	25.9	35.0	906	188	2320
decommissioning and rehabilitation	43.4	50.9	2207	993	38.0	51.4	1953	670	25.9	35.0	906	188	1851
produced water discharge	50.2	59.7	2998	1349	29.1	27.7	808	277	25.9	35.0	906	188	1814
physical disturbance (seismic survey)	37.1	53.5	1987	894	38.5	55.4	2134	732	25.9	35.0	906	188	1814
deck drainage discharge	44.3	59.9	2650	1192	30.8	38.5	1184	406	25.9	35.0	906	188	1786
storage displacement water discharge	43.8	45.4	1987	894	32.3	41.7	1347	462	25.9	35.0	906	188	1544

Chapter 5

ENVIRONMENTAL DECISION-MAKING USING ROUGH SET-BASED GAME THERETICAL APPROACH

PREFACE

This work has been submitted for possible publication: Yang, M., Khan, F., Sadiq, R., Amyotte, P. A rough set-based game theoretical approach for environmental decision-making: a case of offshore oil and gas operations. *Environmental Modeling and Software*. (Submitted on May 19, 2011).

The first author (Ming Yang) identified the research problem, developed the approach, executed the case study, and drafted the manuscript. The co-authors (Drs. Faisal Khan, Rehan Sadiq, and Paul Amyotte) supervised the work, critically reviewed the developed approach, and provided valuable comments to improve the manuscript.

5.1 INTRODUCTION

To deal with the significant environmental issues that can be identified using the proposed method in Chapter 4, pollution prevention (P2) and other sustainable waste management alternatives are developed. There is an enormous drive and enthusiasm in the offshore oil and gas (OOG) industry to implement environmentally friendly technologies and develop sustainable waste management strategies. The selection of the alternate strategies often involves conflicting objectives, such as minimizing environmental degradation while maximizing economic profit. In these situations, decision-makers need to find an optimal solution based on uncertain information. It can become even more complicated when decision-makers with different priorities are involved, such as operators, regulators and service engineers. Each group may have different preferences on decision objectives or criteria. Moreover, the decisions of one group may affect or be affected by the decisions of other groups. One of the appropriate approaches to deal with this type of multi-criteria conflict resolution problem is game theory (GT).

Most of the literature on the development of offshore environmental decision support tools ignore conflicting preferences and interdependency between multiple decision makers due to their competing interests (e.g., Falck *et al*., 2000; Suslick & Furtado, 2001; Chen & Fu, 2003; Sadiq *et al*., 2004; Sadiq *et al*., 2005; Yang *et al*., 2010). GT provides an effective platform that can be adopted to address the above limitation due to the following reasons:

(1) GT is able to simulate different aspects of the conflict between different groups of decision makers on economic benefits, the need to protect the environment, and technical feasibility; and

(2) A GT-based approach does not require a large amount of information that is often unavailable in environmental decision problems to seek possible solutions.

Game theoretical concepts have been applied to a number of fields, such as water resource management (Raquel *et al.*, 2007; Kerachian *et al.*, 2010; Madani & Lund, 2011), transportation planning (Xiao & Yang, 2007), analysis of land and property development (Pak & Brieva, 2010; Samsura *et al.*, 2010), and process integration (Chew *et al.*, 2009). However, there is limited literature on the application of GT to offshore environmental problems.

Considering the lack of information and/or uncertainty in games, fuzzy set theory has been introduced in game theoretical approaches (Butnariu, 1978; Butnariu, 1980; Vijay *et al.*, 2005; Kacher & Larbani, 2008; Borkotokey, 2008; Kerachian *et al.*, 2010). The solution to fuzzy games requires defuzzification of the fuzzy numbers by α-cut (Chen & Larbani, 2006; Larbani, 2009). The subjective determination of α-cut and membership functions of fuzzy parameters is a limitation of fuzzy-based game theoretical approaches. In the current study, rough set theory is proposed to handle uncertainty in a game because:

(1) Rough set theory is also capable of approximating vague descriptions using the boundary region of a set; and

(2) Rough set theory does not require any preliminary or additional information about data like membership function or the value of possibility in fuzzy set theory (Pawlak, 1985).

This chapter aims to develop a rough set-based game theoretical approach for offshore environmental decision-making. According to the authors' knowledge, this is the first application of game theory coupled with rough set theory for solving environmental decision problems.

5.2 GAME THEORY

Game theory, proposed by Von Neumann and Morgenstern (1944), is a mathematical analysis of interactions among rational and intelligent agents. Game theory attempts to mathematically define behavior in strategic situations. In these situations, an individual's success in making choices depends on the choices of others (Myerson, 1991). A game is any interaction that involves two or more players. It usually contains a set of players, available strategies, and specifications for payoffs for all combinations of strategies. Four forms are used to represent games, which include extensive, normal, characteristic function, and partition function forms. The extensive form represents a game in a tree consisting of decision nodes (i.e., possible states of a played game). The normal form represents a game in a matrix which shows the players, strategies, and payoffs. The payoff for each coalition is used instead of individual payoff in the characteristic function form. In the partition function form, the payoff of a coalition depends not only on its members, but also on the way the rest of the players are partitioned, which is ignored in the characteristic function form.

Games are categorized into (a) cooperative games in which players focus on coalition formation, and (b) non-cooperative games in which players do not make binding agreements as the choice or coordination of their strategies (Larbani, 2009). In cooperative games, a Pareto optimal solution needs to be found by the players. It is a coordinated strategy that leads to the best payoff (i.e., no player can improve his/her payoff without lessening others). The most common concepts to solve cooperative games are the Von Neumann stable set, the Shapley value, the nucleolus, and the Nash bargaining solution (Maali, 2009). In non-cooperative games, the Nash equilibrium is the most common solution. Equilibrium is reached when no player can unilaterally deviate from his or her selected strategy to enhance the payoff. Since a non-cooperative game is a more realistic representation of environmental decision-making, this will be further discussed. A non-cooperative game is usually defined using a set of players, strategy profiles, and payoffs under the following assumptions:

(1) All players are rational;

(2) No coalitions are formed between players;

(3) All players know all the available information of the game.

In environmental decision-making, it is often the case that more than one attribute should be considered. In this sense, the proposed approach should be developed based on a multi-criteria non-cooperative game. Multi-criteria games analyze decision problems when several criteria are considered by groups of decision makers. The first publication on multi-criteria normal form game was Blackwell (1956). Since then, different formulations of multi-criteria games have been introduced (Li, 1998; Cubiotti, 2000). An n-person multi-criteria game where all players consider the same set of criteria can be defined as follows:

$$G = (I, S) \tag{5.1}$$

where $I = \{1,\ldots, n\}$ is the set of players, and S is the set of all feasible payoffs that can be represented by the following matrix,

$$S=\begin{Bmatrix} x_1^1 & x_1^2 & \cdots & x_1^n \\ \vdots & \vdots & \ddots & \vdots \\ x_m^1 & x_m^2 & \cdots & x_m^n \end{Bmatrix} \tag{5.2}$$

where x_m^n represents the payoff assigned by the n^{th} player with respect to the m^{th} criterion. The maximin solution concept is often used to solve the above class of games. This concept aims to maximize the worst value under each criterion (Fernandez & Puerto, 1996). The idea behind it is that each player may compromise on those outcomes whose minimum value can not be improved simultaneously with respect to each criterion (Marmol *et al*., 2007). Hinojosa & Marmol (2005) proposed a generalized maximin solution as an extension of the solution concept developed by Puerto *et al*. (1999) for n-person multi-criteria games. They characterized the generalized maximin solution as the solution of a vector optimization problem that is given below. This solution concept is adopted in the proposed methodology.

$$\max \quad z_1, \ldots, z_m \tag{5.3}$$

$$\text{s.t.}: \quad x_1^i \geq z_1 \; \forall \; i = 1, \ldots, n;$$

$$\vdots$$

$$x_m^i \geq z_m \; \forall \; i = 1, \ldots, n;$$

where $x \in S$, z is the minimum payoff vector.

5.3 ROUGH SET THEORY

Rough set theory, first introduced by Pawlak (1982), is a generalization of classical set theory for handling vagueness and ambiguity. It expresses indiscernibility between objects by employing a boundary region of a set. This boundary region usually has precise values of lower and upper approximations. The lower approximation is the union of all objects that can be positively (i.e., unambiguously) classified as belonging to the target set while the upper approximation is the union of all objects that can possibly be identified as members of the target set (i.e., equivalence classes that have non-empty intersection with the target set). Figure 5.1 is a graphical representation of the above statement. Typical applications of rough set theory are in areas such as attributes reduction (Wu, 2008; Wang *et al.*, 2008) and rule extraction (Tsumoto, 2004; Wang & Wang, 2009). Recently, rough set theory has also been applied to environmental decision support (Hu & Lu, 2009; Bai & Sarikis, 2010). In the current study, a concept known as rough number (Zhai *et al.*, 2009) is used to handle the imprecise data in the game. The outline of the concept is described in Figure 5.2.

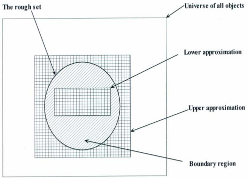


Figure 5.1 A rough set environment (adapted from Bai & Sarkis, 2010)

Rough Sets

A. Definitions

1. Lower approximation of C_i:

$$\underline{apr}(C_i)=\cup\{X \in U / A(X) \le C_i\}$$

2. Upper approximation of C_i:

$$\overline{apr}(C_i)=\cup\{X \in U / A(X) \ge C_i\}$$

3. Boundary region of C_i:

$$BR(Ci)=\cup\{X \in U / A(X) \ne C_i\}$$
$$=\{X \in U / A(X) > C_i\} \cup \{X \in U / A(X) < C_i\}$$

Where

a) U is a universe consisting of all the objects in an information table,
b) X is an arbitrary object of U
c) A is a set of n assessment classes defined in the universe $A=\{C_1, C_2, ..., C_n\}$
d) $C_1 < C_2 < .. < C_n$, $C_i \in A \ (1 \le i \le n)$

Rough Numbers (RN): $RN=[\underline{\lim}(C_i), \overline{\lim}(C_i)]$

A. Basic notions

1. Lower limit:

$$\underline{\lim}(C_i)=\frac{1}{N_l}\sum A(X) | X \in \underline{apr}(C_i)$$

N_l is the number of objects in lower limit set

2. Upper limit:

$$\overline{\lim}(C_i)=\frac{1}{N_u}\sum A(X) | X \in \overline{apr}(C_i)$$

N_u is the number of objects in upper limit set

3. Boundary region:

$$\overline{\lim}(C_i) - \underline{\lim}(C_i)$$

B. Arithmetic operations

1. Addition

$$RN_1 + RN_2 = [l_1, u_1] + [l_2, u_2] = [l_1 + l_2, u_1 + u_2]$$

2. Multiplication

$$RN \times k = [kl, ku]$$
$$RN_1 \times RN_2 = [l_1 l_2, u_1 u_2]$$

where l, u are lower and upper limits, k is a constant.

Figure 5.2 The concept of rough numbers

5.4 THE PROPOSED METHODOLOGY

The proposed methodology (Figure 5.3) is designed in four main stages in addition to the initiation and ending stages:

(1) Setting up the decision-making problem;

(2) Processing the data;

(3) Developing and solving the game; and

(4) Identifying the best alternative.

Each of these four stages comprises several sub-steps. A step-by-step description of this methodology is presented below.

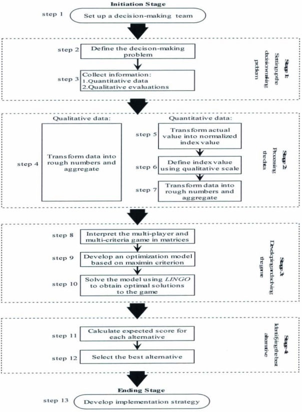


Figure 5.3 The proposed methodology

5.4.1 INITIATION STAGE

Step 1: First, a decision-making team is established. This team includes three groups of decision-makers who have different preferences:

(1) *Operators* who run the company and are usually cost oriented;

(2) *Regulators* who are from regulatory agencies and may give priority to environmental issues;

(3) *Service engineers* who are offshore facilities service providers and may care more about technical feasibility.

5.4.2 STAGE 1

Step 2: The decision-making team should gather and study background information to define the problem. Three key elements of the problem need to be identified:

(1) Goals/objectives;

(2) Attributes/criteria that must be evaluated;

(3) Available alternatives.

Step 3: Based on the identified attributes/criteria, the team needs to collect data to assess the alternatives. These data can be either qualitative or quantitative. In the proposed methodology, qualitative evaluations are made using the "9-point scale" assessment (1, very bad; 3, bad; 5, moderate; 7, good; 9, very good). Quantitative data may be collected from various sources (e.g., operators who have implemented the technology or strategy). All data are converted into an information table. Table 5.1 gives an example of part of such a formulation. It summarizes the qualitative evaluations of three service engineers, while the quantitative data are collected from three different sources.

Table 5.1 Basic information

Criterion category	Criterion	Alternative								
		A_1			A_2			A_3		
Technical feasibility	Ease of operation	7	9	9	7	5	7	7	9	7
	Efficiency (%)	75	68	72	55	59	63	84	89	80

5.4.3 STAGE 2

Qualitative and quantitative data are processed separately. Rough set theory is proposed to deal with the uncertainty associated with subjective information. The arithmetic averaging operator is used for aggregation.

Step 4: Qualitative evaluations made by each group of decision-makers are processed independently. For example, the evaluations of a group of three service engineers on alternative- A_1 with respect to "ease of operation" in Table 5.1 can be treated in the following way:

(1) Rough number calculation:

a) The evaluation by service engineer #1:

$$\underline{\lim}(7) = R(C_1) = 7$$

$$\overline{\lim}(7) = (R(C_1) + R(C_2) + R(C_3))/3 = (7+9+9)/3 = 8$$

$$RN(7) = [\,\underline{\lim}(7), \overline{\lim}(7)\,] = [7, 8]$$

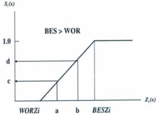
b) The evaluation by service engineer #2 : $RN(9) = [8, 9]$

c) The evaluation by service engineer #3 : $RN(9) = [8, 9]$

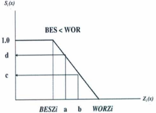
(2) Aggregation: ([7, 8] + [8, 9] + [8, 9])/3 = [(7+ 8+ 8)/ 3, (8+ 9+ 9)/ 3] = [8, 9]

Step 5: Considering different units of quantitative data, Lee *et al.* (1991) proposed to normalize the actual data of each attribute into an index value - $S_i(x)$ using the best (BES) or the worst (WOR) value (Figure 5.4). When BES=WOR, $S_i(x)$ equals to 1. All quantitative data are transformed into $S_i(x)$.

Step 6: This step aims to tune index values into the same scale as that of the qualitative data. Table 5.2 presents the manner in which these index values are defined.



$$S_i(x)=\begin{cases}1 & \text{if } Z_i(x)\geq BESZ_i\\ \dfrac{Z_i(x)-WORZ_i}{BESZ_i-WORZ_i} & \text{if } WORZ_i<Z_i(x)<BESZ_i\\ 0 & \text{if } Z_i(x)\leq WORZ_i\end{cases}$$



$$S_i(x)=\begin{cases}1 & \text{if } Z_i(x)\leq BESZ_i\\ \dfrac{Z_i(x)-WORZ_i}{BESZ_i-WORZ_i} & \text{if } BESZ_i<Z_i(x)<WORZ_i\\ 0 & \text{if } Z_i(x)\geq WORZ_i\end{cases}$$

Figure 5.4 Normalization of actual data into index values (Sadiq *et al.*, 2005)

Table 5.2 The qualitative scales used to define the index values

Index value		Assessment scale
$0 \leq S_i(x) < 0.2$	↔	1, *very bad*
$0.2 \leq S_i(x) < 0.4$	↔	3, *bad*
$0.4 \leq S_i(x) < 0.6$	↔	5, *moderate*
$0.6 \leq S_i(x) < 0.8$	↔	7, *good*
$0.8 \leq S_i(x) \leq 1$	↔	9, *very good*

Step 7: Rough numbers are calculated based on the data achieved in step 6. To illustrate steps 5-7, the efficiency data in Table 5.1 can be processed as follows:

(1) Calculate index values: $S_1 = \frac{75-55}{89-55} = 0.6$, $S_2 = 0.4$, $S_3 = 0.5$, $S_4 = 0$, $S_5 = 0.1$, $S_6 = 0.2$, $S_7 = 0.9$, $S_8 = 1$, $S_9 = 0.7$;

(2) Define index values in qualitative scales:

$S_1 = 0.6 \leftrightarrow 7$, good; $S_2 = 0.4 \leftrightarrow 5$, moderate; $S_3 = 0.5 \leftrightarrow 5$, moderate;

$S_4 = 0 \leftrightarrow 1$, very bad; $S_5 = 0.1 \leftrightarrow 1$, very bad; $S_6 = 0.2 \leftrightarrow 3$, bad;

$S_7 = 0.9 \leftrightarrow 9$, very good; $S_8 = 1 \leftrightarrow 9$, very good; $S_9 = 0.7 \leftrightarrow 7$, good

(3) Calculate the aggregated rough numbers for each alternative:

For A_1: [5, 6]; For A_2: [1, 2]; For A_3: [8, 9]

At this point, all data have been prepared for the analysis in the next stages.

5.4.4 STAGE 3

Step 8: A three-player and k-criteria bargaining game is defined in matrices. The three players are the three groups defined in the initiation stage:

(1) Player 1 (P_1) - a group of operators;

(2) Player 2 (P_2) - a group of regulators;

(3) Player 3 (P_3) - a group of service engineers.

The k criteria may fall into three major categories including costs, environmental risks (i.e., human health and ecological risks), and technical feasibility.

Assume these three players consider the same set of k criteria to evaluate a set of n alternatives, $A = \{A_N\}$, $(N = 1,\ldots, n)$. We also assume that all criteria are to be maximized. Moreover, the three players are assumed to be equally important in making the decision. Thus, the game can be represented by a set of payoff matrices, $M = \{M_N\}$, $(N = 1,\ldots, n)$. For each A_N, there is a M_N:

$$M_N = \left\{ \begin{matrix} x_1^1 a_1^1 & x_1^2 a_1^2 & x_1^3 a_1^3 \\ \vdots & \vdots & \vdots \\ x_r^1 a_r^1 & x_r^2 a_r^2 & x_r^3 a_r^3 \\ x_{r+1}^1 a_{r+1}^1 & x_{r+1}^2 a_{r+1}^2 & x_{r+1}^3 a_{r+1}^3 \\ \vdots & \vdots & \vdots \\ x_{r+s}^1 a_{r+s}^1 & x_{r+s}^2 a_{r+s}^2 & x_{r+s}^3 a_{r+3}^3 \\ x_{r+s+1}^1 a_{r+s+1}^1 & x_{r+s+1}^2 a_{r+s+1}^2 & x_{r+s+1}^3 a_{r+s+1}^3 \\ \vdots & \vdots & \vdots \\ x_{r+s+t}^1 a_{r+s+t}^1 & x_{r+s+t}^2 a_{r+s+t}^2 & x_{r+s+t}^3 a_{r+s+t}^3 \end{matrix} \right\} \qquad \textbf{(5.4)}$$

where

(1) a_i^j ($i = 1,\ldots, k$; $j = 1, 2, 3$) represents either of the following:

a) The qualitative evaluation by the j^{th} player with respect to the i^{th} criterion;

b) The quantitative data with respect to the i^{th} criterion.

{ a_i^j } are those aggregated rough numbers obtained in stage 2.

(2) x_i^j represents the feasible weight of the i^{th} criterion assigned by the j^{th} player, which can be achieved by mutual agreement among players.

(3) $x_i^j a_i^j$ represents the feasible payoff of the j^{th} player with respect to the i^{th} criterion.

(4) r, s, t are the number of criteria associated with cost, environmental issues, and technical feasibility, respectively; $r + s + t = k$.

The reasons why x_i^j is introduced to tune a_i^j to model the feasible payoff are:

(1) a_i^j is obtained without considering the interactions among decision-makers.

(2) The conflict in this game is the determination of the relative importance (weights) of each criterion in making the decision.

Step 9: The objective of this step is to develop an optimization model based on the maximin criterion to solve the game. This solution concept is adopted from Hinojosa & Marmol (2005). From a conservative perspective, players will select a feasible outcome that can ensure its minimum payoff vector is as good as possible. Therefore, they proposed a multi-criteria optimization model that aims to maximize the vector of payoffs with respect to each criterion. Based on this idea, the following model can be developed:

$$\max \quad z_1, \ldots, z_k \tag{5.5}$$

$$\text{s.t.}: \quad x_1^j a_1^j \geq z_1 \;\; \forall j = 1, 2, 3;$$

$$\vdots$$

$$x_k^j a_k^j \geq z_k \;\; \forall j = 1, 2, 3;$$

$$\sum_{i=1}^{k} x_i^1 = 1, \; \sum_{i=1}^{k} x_i^2 = 1, \; \sum_{i=1}^{k} x_i^3 = 1;$$

$$0 < x_i^j < 1 \quad i = 1, \ldots, k \;\; j = 1, 2, 3;$$

$x_u^1 > x_v^1$, $x_u^1 > x_w^1$ $\forall u = 1,\ldots,r$, $\forall v = r+1,\ldots,r+s$, $\forall w = r+s+1,\ldots,r+s+t$;

$x_v^2 > x_u^2$, $x_v^2 > x_w^2$ $\forall u = 1,\ldots,r$, $\forall v = r+1,\ldots,r+s$, $\forall w = r+s+1,\ldots,r+s+t$;

$x_w^3 > x_u^3$, $x_w^3 > x_v^3$ $\forall u = 1,\ldots,r$, $\forall v = r+1,\ldots,r+s$, $\forall w = r+s+1,\ldots,r+s+t$;

Extra constrains…

where

(1) $z_1, \ldots, z_k$ is the non-dominated minimum payoff vector.

(2) r, s, t have the same definitions as in M_N.

(3) The last three constraints are designed to show the preferences of each player with respect to each of the three categories of criteria, e.g., $x_u^1 > x_v^1$, $x_u^1 > x_w^1$ show that operators (P_1) may consider costs as more important than environmental issues and technical feasibility. More specific constraints can also be used, e.g., $x_u^1 > 3x_v^1$ indicates that operators consider costs to be more than three times the importance of environmental issues.

(4) Extra constraints are added when players have some uncertain requirements related to the weights, e.g., $0.1 < x_1^1 < 0.3$, $0.3 < x_3^2 < 0.4$.

Step 10: *LINGO* 9.0 is used to solve this optimization model; it is a software tool developed to efficiently build and solve various optimization models. Since a_i^j is a predetermined non-variable, the above model can be simplified to an equitable model that will be solved using *LINGO*:

max $z_1', \ldots, z_k'$ **(5.6)**

s.t. : $x_1^j \geq z_1' \ \forall j = 1, 2, 3;$

$\vdots$

$x_k^j \geq z_k' \ \forall j = 1, 2, 3;$

$\sum_{i=1}^{k} x_i^1 = 1, \ \sum_{i=1}^{k} x_i^2 = 1, \ \sum_{i=1}^{k} x_i^3 = 1;$

$0 < x_i^j < 1 \quad i = 1, \ldots, k \ \ j = 1, 2, 3;$

$x_u^1 > x_v^1, \ x_u^1 > x_w^1 \ \ \forall u = 1, \ldots, r, \ \forall v = r+1, \ldots, r+s, \ \forall w = r+s+1, \ldots, r+s+t;$

$x_v^2 > x_u^2, \ x_v^2 > x_w^2 \ \ \forall u = 1, \ldots, r, \ \forall v = r+1, \ldots, r+s, \ \forall w = r+s+1, \ldots, r+s+t;$

$x_w^3 > x_u^3, \ x_w^3 > x_v^3 \ \ \forall u = 1, \ldots, r, \ \forall v = r+1, \ldots, r+s, \ \forall w = r+s+1, \ldots, r+s+t;$

Extra constraints…

where

(1) $z_1', \ldots, z_k'$ is the non-dominated minimum vector.

(2) r, s, t are defined in the same way as in M_N.

The above multi-objective optimization model can be solved using a weighted sum method in LINGO. This method scalarizes the multiple objectives into a single objective by multiplying each objective with a weight. In this case, all objective functions are treated as equal to solve the optimization model.

Finally, $\{x_i^{j*}\}$ (i.e., the optimal solution of the game) are obtained. Thus, the conflicts between three different groups of players (i.e., operators, regulators and service engineers) are resolved. The best alternative will be identified in the next stage.

5.4.5 STAGE 4

Step 11: For each alternative, the total expected payoffs (TEP) of the three players can be obtained:

$$\mathbf{TEP} = \sum_{j=1}^{3}\sum_{i=1}^{k} x_i^{j*} a_i^j \tag{5.7}$$

where

(1) x_i^{j*} is the optimal solution achieved in stage 3.

(2) a_i^j is defined in the same way as in M_N.

Step 12: Since TEP is a rough number that is not easy to compare, we introduce the weights Ω and $1-\Omega$ ($\Omega \in [0, 1]$) to calculate the expected score (ES) of each alternative:

$$\mathbf{ES} = \Omega \times A^U + (1-\Omega) \times A^L \tag{5.8}$$

where A^U and A^L represent the upper and lower limits, respectively, of TEP.

The determination of Ω depends on how decision-makers want to compare the scores. Agreement should be reached upon this issue. For instance, if they want to compare by the upper limit, they can choose $\Omega = 1$. Finally, the best alternative can be selected by ranking the expected scores.

5.4.6 ENDING STAGE

Step 13: The decision-making team should develop a proper strategy to implement the identified alternative in this stage.

5.5 A CASE STUDY

Drilling wastes (i.e., residual drilling fluids and cuttings) usually represent the largest amount of waste generated from OOG operations aside from produced water. Oil-based fluids (OBFs) are always not allowed to be discharged offshore while water-based fluids (WBFs) and synthetic-based fluids (SBFs) can be discharged with or without certain treatment when approval is granted.

Using SBFs is a preferred P2 opportunity to WBFs and OBFs because of its reduced volume of drilling wastes discharge, air emissions and energy use (US.EPA, 2000). A more detailed study on SBFs as an effective P2 option during offshore drilling can be found in Veil *et al.*, (1995). Despite some environmentally benign features, SBF attached drilling wastes may still impose potential adverse impacts on the offshore environment. These impacts can be caused by the base fluid (ester) and trace heavy metals (arsenic, copper, and lead) in barite used as a weighting agent in SBFs. It is therefore important to select the best management scenario. Considering a hypothetical case, the following scenarios need to be assessed:

(1) Offshore discharge of drilling wastes with 3% (by wet weight) SBF retention;

(2) On-site re-injection of drilling wastes with 3% SBF retention;

(3) Onshore landfill disposal of drilling wastes with 10% SBF retention.

In Scenario 1, drilling cuttings are treated before discharge using solid separation equipment (e.g., centrifuge and shale shakers) to reduce SBF retention to 3%. This scenario is the least technically complicated and expensive of the three scenarios; however, it depends largely on regulatory requirements for discharge. For example, drilling waste discharge is prohibited in the North Sea (Sadiq & Husain, 2005). In this case, we assume that discharge of drilling wastes with 3% SBF retention is legal. In Scenario 2, drilling wastes need to be ground into small particles and pumped into an underground formation. This scenario is the most complicated because it requires specialized equipment, integrated design, and intensive monitoring. However, less effort or investment is needed to develop the waste treatment system. Scenario 3 involves the transportation of drilling wastes by vessels to onshore for disposal. This transportation results in high costs, potential for spillage, and atmospheric emissions, which are regarded as disadvantages of this scenario. Nevertheless, a higher SBF retention was allowed in this scenario. Since each scenario has pros and cons, the selection of the best alternative becomes a challenging task in which the currently proposed approach should be applied.

The decision-making team consists of three operators, three regulators, and three service engineers. Both qualitative and quantitative data with respect to eight criteria are given in Table 5.3. The data for costs and efficiency were assumed to be collected from three offshore platforms. The carcinogenic, non-carcinogenic, and ecological risks were assumed to be calculated based on data provided by the three platforms. Several methods have been proposed to calculate environmental risks related to pollutants in offshore oil production (Sadiq *et al*., 2003a; Sadiq *et al*., 2003b; Sadiq & Husain, 2005; Zhao *et al*., 2008; Chen *et al*., 2010). All members of the team were required to qualitatively evaluate each scenario with respect to the status of technology and ease of operation. Following steps 4-10 in Figure 5.3, all data were transformed into rough numbers. Additionally, the optimal weights assigned by each player for each criterion could also be calculated by solving the optimization model given in step 10. These results are shown in Table 5.4. Finally, the expected scores of all the scenarios were obtained and are given in Table 5.5. The results indicate that the best option is the Scenario 1 - offshore discharge of drilling wastes with 3% SBF retention. Then, decision-makers need to build a proper strategy to implement the selected scenario. They may encounter other decision problems that can be handled using the proposed approach; e.g., the solid separation equipment that should be chosen for drilling waste treatment. To verify the results achieved in the above example, sensitivity analysis was performed in which the weight of each criterion was varied and expected scores of Scenarios 1, 2, 3 were calculated when $\Omega = 0.5$ (i.e., decision makers want to compare the scores by both the upper and lower limits). The results in Table 5.6 show that the final decision is stable to the variation of weights. Moreover, Figures 5.5, 5.6, 5.7 indicate that expected scores of the three scenarios are most sensitive to variations in the weight of status of technology. The status of technology may include reliability of the technology and availability of skilled workers. These are the factors that all of the three groups of decision-makers/players will give preference to.

Since the application is based on a hypothetical case, the results should not be interpreted as an accurate depiction of any specific OOG practice. However, the example clearly demonstrates that the proposed approach can be effectively realized in practice.

Table 5.3 The information table for basic criteria

Criterion category	Criterion		Scenario 1			Scenario 2			Scenario 3		
Costs	Capital cost (million $)		1	1.05	1.1	0.72	0.8	0.77	0.5	0.56	0.47
	Operation & maintenance cost (million $/year)		0.12	0.11	0.14	0.09	0.08	0.09	0.07	0.06	0.05
Environment	Carcinogenic risk (log scale)		-11.3	-10.9	-12	-10.6	-10.3	-9.9	-9.5	-9	-9.9
	Non-carcinogenic risk (log scale)		-2.3	-2.7	-2.4	-1.9	-2.1	-1.7	-1.8	-1.6	-1.5
	Ecological risk		0.13	0.15	0.11	0.23	0.25	0.2	0.26	0.3	0.25
Technical feasibility	Ease of operation	O:	7	7	5	7	7	7	7	9	9
		R:	7	7	5	7	5	7	7	9	9
		SE:	7	9	7	7	5	9	9	9	9
	Efficiency (%)		84	89	80	75	68	72	77	72	80
	Status of technology	O:	9	9	7	7	7	5	5	5	7
		R:	9	9	7	7	7	5	5	5	7
		SE:	7	7	9	5	5	7	5	5	3

Note: O - operators; R – regulators; SE – service engineers

Table 5.4 Rough numbers and optimal weights for each criterion

Criteria	P_1: operators				P_2: regulators				P_3: service engineers			
	x_i^{1*}	S_1	S_2	S_3	x_i^{2*}	S_1	S_2	S_3	x_i^{3*}	S_1	S_2	S_3
Capital cost (million $)	0.25	[1,1]	[5,6]	[9,9]	1E-04	[1,1]	[5,6]	[9,9]	0.12	[1,1]	[5,6]	[9,9]
Operation & maintenance cost (million $/year)	0.25	[1,2]	[5,6]	[8,9]	1E-04	[1,2]	[5,6]	[8,9]	0.12	[1,2]	[5,6]	[8,9]
Carcinogenic risk (log scale)	1E-04	[7,8]	[4,5]	[1,2]	0.25	[7,8]	[4,5]	[1,2]	0.06	[7,8]	[4,5]	[1,2]
Non-carcinogenic risk (log scale)	1E-04	[7,8]	[2,4]	[1,2]	0.25	[7,8]	[2,4]	[1,2]	0.06	[7,8]	[2,4]	[1,2]
Ecological risk	1E-04	[8,9]	[3,4]	[2,3]	0.25	[8,9]	[3,4]	[2,3]	0.12	[8,9]	[3,4]	[2,3]
Ease of operation	0.25	[6,7]	[7,7]	[8,9]	1E-04	[6,7]	[6,7]	[8,9]	0.12	[7,8]	[6,8]	[9,9]
Efficiency	1E-04	[6,8]	[1,2]	[3,5]	1E-04	[6,8]	[1,2]	[3,5]	0.12	[6,8]	[1,2]	[3,5]
Status of technology	0.25	[8,9]	[6,7]	[5,6]	0.25	[8,9]	[6,7]	[5,6]	0.31	[7,8]	[5,6]	[4,5]

Note: S_1, S_2, and S_3 represent scenarios 1, 2, and 3.

Table 5.5 The expected scores of the discharge scenarios

Scenarios	$\Omega = 1$	$\Omega = 0$	$\Omega = 0.5$
1	19	17	18
2	17	14	15
3	17	15	16

Table 5.6 Sensitivity of best scenario to variation of weights of criteria

Criteria	Variation of weights	Expected scores (Ω = 0.5)			Best scenario
		Scenario 1	Scenario 2	Scenario 3	
Capital cost	15%	19	16	16	Scenario 1
	30%	19	16	17	Scenario 1
	50%	19	15	16	Scenario 1
	-15%	18	15	16	Scenario 1
	-30%	18	15	15	Scenario 1
	-50%	18	14	14	Scenario 1
Operation & maintenance cost	15%	19	16	16	Scenario 1
	30%	19	16	17	Scenario 1
	50%	19	16	18	Scenario 1
	-15%	18	15	16	Scenario 1
	-30%	18	15	16	Scenario 1
	-50%	18	14	14	Scenario 1
Carcinogenic risk	...	...			Scenario 1
Non-carcinogenic risk	...	...			Scenario 1
Ecological risk	...	...			Scenario 1
Ease of operation	...	...			Scenario 1
Efficiency	...	...			Scenario 1
Status of technology	...	...			Scenario 1

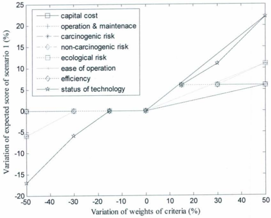


Figure 5.5 Sensitivity of expected score of Scenario 1 to variation of criteria weights

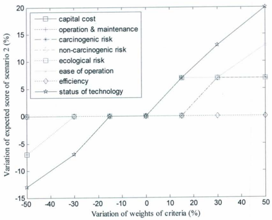


Figure 5.6 Sensitivity of expected score of Scenario 2 to variation of criteria weights

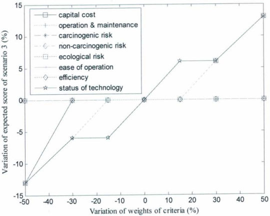


Figure 5.7 Sensitivity of expected score of Scenario 3 to variation of criteria weights

Chapter 6

ENVIRONMENTAL PERFORMANCE EVALUATION USING ROUGH SET-BASED QUALITY FUNCTION DEPLOYMENT APPROACH

PREFACE

This work has been published: Yang, M., Khan, F., Sadiq, R., Amyotte, P. (2011). A rough set-based quality function deployment (QFD) approach for environmental performance evaluation: a case of offshore oil and gas operation. *Journal of Cleaner Production*, 19(13), 1513-1526.

The first author (Ming Yang) and co-author (Dr. Faisal Khan) formulated the research problem. The first author structured the approach, designed and conducted a numerical example. The co-authors (Drs. Faisal Khan, Rehan Sadiq, and Paul Amyotte) critically reviewed the developed approach and provided suggestions to improve both the approach and the manuscript.

6.1 INTRODUCTION

Current EMSs, such as ISO 14001 (ISO, 2004) or the EU-EMAS (ECC, 1993), require an explicit commitment for continuous improvement of environmental performance. The connection between EMSs and environmental performance is discussed in several studies (Perotto *et al*., 2008; Nawrocka & Parker, 2009). Environmental performance evaluation (EPE) is therefore an essential component of an EMS.

A number of studies have been conducted on environmental performance measurements. KPMG (1992) proposed two categories of measures, including impact and contributor measures. James (1994) suggested that environmental performance measures could be grouped into several categories - impact, risk, emissions/waste, input resource, efficiency, customer, and financial. Ilinitch *et al*. (1998) advocated four dimensions of environmental performance measures - organizational systems, stakeholder relations, regulatory compliance, and environmental impacts. ISO (1999) proposed two types of indicators – environmental performance indicators (EPI) and environmental condition indicators (ECI). EPI can be divided further into management performance indicators (MPI) and operational performance indicators (OPI). Jung *et al*. (2001) suggested five categories, namely general environmental management, input, process, output, and outcome.

In addition, various quantitative models have been established to assist with environmental performance evaluation. Jung *et al*. (2001) proposed a framework called

"GScore" to evaluate corporate environmental performance based on voluntary environment, health, and safety (EHS) reports by aggregating the points of five categories of measurement. Shen *et al.* (2005) suggested calculations of the environmental performance score through an information technology supported program. Hermann *et al.* (2007) proposed an evaluation approach that combines life cycle assessment, multi-criteria analysis and environmental performance indicators. Data envelopment analysis (DEA), a well-established nonparametric methodology for evaluating the relative efficiency of a set of comparable entities with multiple inputs and outputs, was applied to develop performance evaluation models (Zhou *et al.*, 2008). Based on fuzzy multiple attribute analysis, Nasiri & Huang (2008) developed a decision aid model for environmental performance assessment in waste recycling.

Several frameworks that provide lists of environmental indicators were developed (Veleva *et al.*, 2000; Azapagic & Perdan, 2000; Krajnc & Glavic, 2003), but these lists give limited insight into how these indicators can be used for different cases to more precisely assess environmental performance. Moreover, no framework is applicable as a whole to evaluate environmental performance (Veleva & Ellenbecker, 2001).

This chapter presents an approach which employs quality function deployment (QFD) as a tool to identify key indicators and evaluate environmental performance. Moreover, the rough set theory is suggested to handle uncertain information in QFD analysis. The proposed approach identifies and establishes specific indicators on a case-by-case basis to evaluate environmental performance more accurately. To the authors' knowledge this is the first application of rough set theory in QFD analysis that has been used for the evaluation of the environmental performance.

6.2 QUALITY FUNCTION DEPLOYMENT (QFD)

QFD was originally developed in 1972 at Mitsubishi as a systematic approach for identifying the product feathers that strongly contribute to product quality (Akao, 1990). QFD aims to translate customer requirements into engineering characteristics, process specifications, and production requirements in sequence. This translation requires a series of matrices or houses in four phases of a conventional QFD as given in Figure 6.1. Through these four phases, customer requirements are systematically cascaded into the design, process, and production of the product (Zhang *et al*., 1999). However, traditional QFD has some limitations (Law & Hua, 2007):

(1) Identification of customer requirements is not systematic and ambiguous; and

(2) The engineering characteristics of a complex product/process cannot be easily determined.

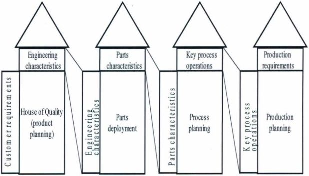


Figure 6.1 Four phases of a conventional QFD (Bossert, 1991)

The House of Quality (HoQ) is the most important tenet of QFD. Figure 6.2 gives a standard structure of HoQ, which consists of the following six elements (Bossert, 1991):

(1) *Customer requirements (WHATs)* organized into proper classifications is one of the most significant contributions that QFD can make to the successful development of a product or production process;

(2) *Planning matrix* usually contains the information regarding the relative importance of customer requirements and the customer's satisfaction levels with the organization's current operation;

(3) *Technical or engineering characteristics* (*HOWs*) corresponding to the customer requirements are identified by translating qualitative requirements into measurable quantitative characteristics;

(4) *Relationship matrix* indicates the extent to which each *HOW* affects the satisfaction of each *WHAT*;

(5) *Correlation matrix* presents the interdependencies among *HOW*s to capture the trade-offs between various engineering parameters;

(6) *Technical characteristic importance rankings* (the priorities of the *HOW*s) provide information for the innovative design of a new product or system.

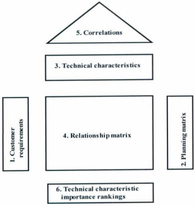


Figure 6.2 House of Quality (HoQ) (Bergquist & Abeysekera, 1996)

Since QFD was originally proposed, it has been applied to a variety of fields, among which production development and quality management are the two most popular (Chan & Wu, 2002). Apart from these, QFD has also been used to form a customer or market driven decision-making and management process. Published examples include selecting design options (Cook & Wu, 2001), determining improvement priorities (Barad & Gien, 2001), and deciding facility locations (Chuang, 2001). Moreover, some studies have proposed Eco-QFD approaches for environmentally conscious manufacturing by integrating life cycle assessment (LCA) and life cycle costing (LCC) into QFD (Zhang *et al.*, 1999); for environmental improvement analysis of selected techniques (Halog *et al.*, 2001); to develop a sustainable fishing fleet by combining environmental issues with stakeholder requirements (Utne, 2009); to ensure sustainable product design (Vinodh & Rathod, 2010), and to analyze environmental production requirements using QFD and analytic network processes (ANP) (Lin *et al.*, 2010). However, no papers have yet proposed the application of QFD for evaluating environmental performance.

6.3 HANDLING UNCERTAINTIES IN QFD

The successful implementation of QFD requires a number of subjective perceptions and judgements achieved through surveys and questionnaires. As a result, uncertain information becomes inevitable and an inherent part of QFD analysis. There are three major types of uncertainties that can be encountered in the analysis:

(1) Vague descriptions, e.g., *strong* relationship, *low* importance;

(2) Inconsistent information, e.g., differences in the opinions of different experts or customers on the same issue;

(3) Incomplete or missing information, e.g., information is missing when an expert cannot decide the relative importance of technical requirements or cannot provide any information about such assessments.

Conventional mathematical logic is incapable of handling these uncertainties. In this respect, a significant number of studies on quantitative approaches to deal with uncertain information in QFD have been conducted. Fuzzy set theory (Zadeh, 1965) has been widely used in QFD in various areas to translate vague descriptions into fuzzy numbers that can be manipulated through fuzzy operators (Chan *et al.*, 1999; Bevilacqua *et al.*, 2006; Chen *et al.*, 2006; Zhang & Chu, 2009). Rough set theory, first introduced by Pawlak (1982), is another generalization of classical set theory for handling vagueness and uncertainty. Recent studies (Zhai *et al.*, 2009; Li *et al.*, 2009) show that rough set theory provides an effective tool for dealing with inconsistency in QFD analysis. The Dempster-Shafer theory of evidence (Shafer, 1967) has been recently applied in QFD to model incomplete information using a belief structure such as {(0-9, 100%)} (Chin *et al.*, 2009). Table 6.1 summarizes the advantages and disadvantages of the above-mentioned methods that are used to handle uncertainties in QFD.

Table 6.1 Proposed methods in the literature to handle uncertainties in QFD analysis

Types of uncertainties	Proposed handling methods	Advantages (A) and disadvantages (D)
Vague descriptions	Fuzzy set theory	(A) Effectively deals with the qualitative definition of linguistic expressions (D) Selection of the membership functions is difficult and is affected by the subjectivity (D) Increase in fuzzy interval after fuzzy arithmetic operations may affect QFD analysis
Inconsistent information	Rough set theory	(A) Effectively characterizes inconsistency in describing opinions in terms of definable concepts (A) No subjective adjustment or external information is required for data analysis (D) Unable to model missing information
Incomplete or missing information	Evidence theory	(A) Effectively deals with missing information (D) Algorithm is relatively complicated and the computational requirement is tremendous

In our proposed approach, rough set theory is selected to deal with uncertain information due to the following reasons:

(1) Rough sets are also capable of approximating vague descriptions by means of the boundary region of a set;

(2) The subjective selection of membership functions is avoided;

(3) Data availability is very limited for the learning or training process to generate and adjust membership functions objectively, for example, through neural networks;

(4) Fuzzy sets alone cannot handle inconsistent information;

(5) Compared to evidence theory, the computational process is less complicated.

The basics of rough set theory have been discussed in Section 5.3. Based on the basic notions of rough sets, Zhai *et al*. (2009) proposed a novel concept of rough numbers along with their arithmetic operations to handle uncertain information in QFD. The outline of this concept is elaborated in Figure 5.2. In the study by Zhai *et al*. (2009), the illustrated concept proved to be robust enough to handle vague and inconsistent information; however, the authors ignored another type of uncertainty, i.e. incomplete or missing information. In order to make this concept also capable of addressing missing information in QFD, steps to implement it are proposed in Figure 6.3. The reason why the information is missing is that a decision maker is unable to select a suitable value from a set of assessment scales (e.g., 9-point assessment scale: 1, very low; 3, low; 5, moderate; 7, high; 9, very high), which indicates either one in this set is possible to express his or her opinion. Therefore, the missing information (null value) can be modeled using an interval covering the whole region of the set of the assessment scale, for example 1~9. Another simple method of addressing missing data is mean substitution, which is accomplished by estimating missing values by using the mean of the available values. However, this is not suitable in QFD because the data size available for analysis is usually very small.

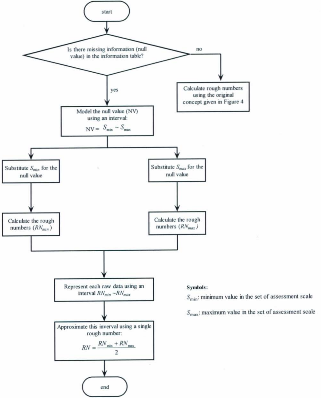


Figure 6.3 The proposed procedure to implement the concept of rough numbers in QFD

6.4 THE PROPOSED METHODOLOGY

In this study, an approach is proposed which describes a QFD-based process for evaluating environmental performance based on the identified key indicators (i.e., indicators that can represent the environmental performance of a system from the decision makers' perspectives). The proposed approach (Figure 6.4) consists of two major stages. Stage I consists of six houses that are used to identify:

(1) *Performance indicators* that provide information about the environmental performance of the operations within an organization and the management efforts to influence the organization's environmental performance; and

(2) *Condition indicators* that describe the direct impacts on the environment and the status of regulatory compliance.

The identified indicators are used in the House of Environmental Performance Evaluation (HoEPE) at Stage II to compute the environmental performance indices for the operations, based on which decision makers can determine whether improved performance has been achieved.

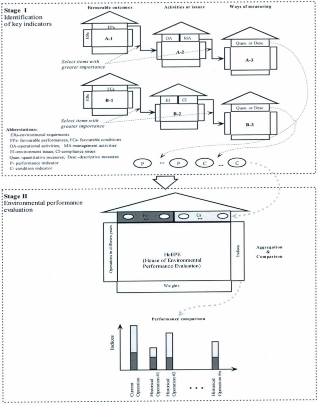


Figure 6.4 QFD approach for environmental performance evaluation

6.4.1 STAGE I- IDENTIFICATION OF KEY INDICATORS

Stage I aims to identify the key indicators. First, a novel scheme that identifies the key environmental performance indicators needs to be proposed:

(1) Describe the environmental requirements within a system boundary, e.g., the environmental policy and objectives of an EMS within an offshore platform;

(2) Determine favorable outcomes that are aligned with these requirements, i.e., favorable performance and conditions;

(3) Identify activities or issues that must be implemented to reach favourable outcomes, i.e., activities or issues associated with operational and management performance, environmental condition, and compliance condition;

(4) Search for ways of measuring or monitoring the activities and issues; Warren & Craig (1996) proposed two general categories:

   a) *Quantitative measures* that refer to traditional means of measuring the amount of pollution discharged into the environment; and

   b) *Descriptive measures* that provide an indication of the quality of the system and whether progress has been achieved, but do not quantify the degree of progress in terms of environmental impacts.

(5) Generate a list of key indicators based on identified measures.

QFD is preferred to be used as a planning tool that implements the above scheme due to the following reasons:

(1) Through a series of interactive matrices, QFD is robust enough to address the prioritization considering all relevant issues and ensure that the key indicators can be identified; and

(2) QFD gives proper consideration to the requirements of a system and deploys them throughout the identification process (Figure 6.4).

Since ISO 14031 classifies environmental performance indicators into two general categories (i.e., performance and condition indicators), two parallel series of houses have been designed to identify the indicators (as shown in Figure 6.4):

(1) Houses A-1, 2, 3 for performance indicators; and

(2) Houses B-1, 2, 3 for condition indicators.

Figure 6.5 gives a general structure of the six houses at Stage I (in Figure 6.4). The major components of this house are described in detail as follows.

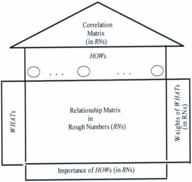


Figure 6.5 General structure of the houses at Stage I

WEIGHT OF *WHATs*

Perceptions of the importance of the *WHATs* in Houses A-1 and B-1 (in Figure 6.4) can be solicited from decision makers and represented in the form of an information table. Based on this, rough numbers are calculated using the method presented in Section 5.3. For illustrative purposes, suppose some opinions expressed by three decision makers for a pollution prevention program within an office building are given in Table 6.2. This evaluation was conducted using the "9-point" assessment scale for importance. The rough numbers for the classes concerning the importance scale were calculated and are given in Table 6.3. For example, the rough numbers of "class 7" (shaded value in Table 6.2) can be calculated as follows:

$\underline{\lim}(7) = R(C_1) = 7$

$\overline{\lim}(7) = (R(C_1) + R(C_2) + R(C_3))/3 = (7+9+9)/3 = 8$

Rough number: $RN(7) = [\,\underline{\lim}(7), \overline{\lim}(7)\,] = [7,8]$

Table 6.2 Decision makers' evaluations on *WHATs*

Environmental requirements- *WHATs* (W_i)	**Decision makers (DM)**		
	DM_1	DM_2	DM_3
Environmental degradation is reduced at its source (W_1)	7	9	9
Resources are reused or recycled within the office building (W_2)	7	5	7

Note:
9- Point Scale Assessment for importance: 1, very low; 3, low; 5 moderate; 7, high; 9, very high.

Table 6.3 Quantification of the evaluations on *WHATs* using rough numbers

Environmental requirements- *WHATs* (W_i)	**Decision makers (DM)**		
	DM_1	DM_2	DM_3
Environmental degradation is reduced at its source (W_1)	[7,8]	[8,9]	[8,9]
Resources are reused or recycled within the office building (W_2)	[6,7]	[5,6]	[6,7]

A method is proposed to aggregate the individual evaluations into group consensus:

$$W_i = \frac{1}{n}\sum_{j=1}^{n} IR_j \qquad \textbf{(6.1)}$$

where W_i denotes the weight of *WHAT*s, n is the number of decision makers, and IR_j denotes the importance ratings of each *WHAT* determined by the j^{th} decision maker and quantified into rough numbers.

Using Equation 1, the individual evaluations in the previous example can be aggregated:

W_1 = ([7,8]+[8,9]+[8,9])/3= [8,9]

W_2 = ([6,7]+[5,6]+[6,7])/3= [6,7]

Moreover, the weights of *WHAT*s in Houses A-2, A-3, B-2, and B-3 are the importance of the key *HOW*s directly obtained from the previous houses (as given in Figure 6.4). For example, the weights of *WHAT*s in House A-2 are the importance of the key *HOW*s in House A-1.

RELATIONSHIP MATRIX

The relationship matrix describes the degree of impact of each *HOW* on the satisfaction/achievement of each *WHAT* in Houses A-1, A-2, B-1, and B-2. For example, the favourable performances (*HOW*s in House A-1) can generally be an efficient use of energy, material, and water, small quantity of emissions/effluent/waste with less hazardous compositions, safe transport, low cost, etc. In Houses A-3 and B-3, the relationship matrix describes the degree of importance of each "*HOW*" in representing the status or performance of each "*WHAT*".

Following the previous example, for instance, decision makers' evaluations on the relationship between *HOWs* and *WHATs* are given in Table 6.4. The so called *null value* is used to indicate the missing information in this table. The rough numbers were calculated through the proposed procedure (Figure 6.3) and summarized in Table 6.5. For example, the shaded numbers in Table 6.4 were treated in the following way to achieve a single rough number:

Null value (NV) = 1~9

(1) Substitute 1 for "*" and calculate the rough numbers

$RN_{min}(7) = [4,8]$; $RN_{min}(1) = [1,6]$; $RN_{min}(9) = [6,9]$

(2) Substitute 9 for "*" and calculate the rough numbers

$RN_{max}(7) = [7,8]$; $RN_{max}(9) = [8,9]$; $RN_{max}(9) = [8,9]$

(3) $RN(7) = [4,8]\text{-}[7,8] \approx [(4+7)/2,(8+8)/2] = [6,8]$

$RN(*) \approx [5,8]$

$RN(9) \approx [7,9]$

(4) Aggregation (group consensus)

$RN = [(6+5+7)/3,(8+8+9)/3] = [6, 8]$

Table 6.4 Decision makers' evaluations on the relationship between *HOW*s and *WHAT*s

Environmental requirements- *WHAT*s (W_i)	Favorable Performances - *HOW*s								
	Energy conservation			Water conservation			Paper use reduction		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Environmental degradation is reduced at its source (W_1)	7	*	9	7	5	7	7	9	9
Resources are reused or recycled within the office building(W_2)	5	5	3	5	*	5	9	7	9

Note: "*" denotes a *null value*.

Table 6.5 *WHAT-HOW* relationships represented by rough numbers

Environmental requirements- *WHATs* (W_i)	**Favorable Performances - *HOWs* (H_j)**		
	Energy conservation	Water conservation	Paper use reduction
Environmental degradation is reduced at its source (W_1)	[6,8]	[6,7]	[8,9]
Resources are reused or recycled within the office building (W_2)	[4,5]	[4,7]	[8,9]

CORRELATION MATRIX

Before prioritizing the *HOW*s, their correlations need to be defined in order to adjust the relationship matrix between *WHAT*s and *HOW*s. Chin *et al*. (2009) proposed a way to incorporate the impact of correlations into the relationship matrix using the following equation:

$$R_{ij}^{'} = \sum_{k=1}^{n} R_{ik} r_{kj}, \qquad i = 1,\ldots, \text{m};\ j = 1,\ldots, \text{n} \qquad \textbf{(6.2)}$$

where $R_{ij}^{'}$ denotes the adjusted relationship between the i^{th} *WHAT* and j^{th} *HOW*, m is the number of *WHAT*s, and n is the number of *HOW*s; r_{kj} denotes the correlations between the k^{th} and the j^{th} *HOW*s. $R_{ij}^{'}$, R_{ik}, and r_{kj} are in rough numbers.

Following the example, Table 6.6 provides information on the correlations between *HOW*s. Based on Table 6.6, rough numbers were calculated and given in Table 6.7. Then, the adjusted relationship matrix can be calculated as given in Table 6.8. The shaded value in Table 6.5 was adjusted in the following way:

$$R_{11}^{'} = R_{11}r_{11} + R_{12}r_{21} + R_{13}r_{31}$$

$$= [6,8]*[9,9]+[6,7]*[0,0]+[8,9]*[1,2]$$

$$= [62, 90]$$

Table 6.6 Assessments on the correlations between *HOWs*

	Energy conservation			Water conservation			Paper use reduction		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Energy conservation	9	9	9	0	0	0	3	1	1
Water conservation	0	0	0	9	9	9	0	0	0
Paper use reduction	3	1	1	0	0	0	9	9	9

Assessment scales: 9, very strong positive correlation; 7, strong positive correlation; 5 moderate positive correlation; 3, weak positive correlation; 1, very weak positive correlation; 0, no correlation; -1, very weak negative correlation; -3, weak negative correlation; -5, moderate negative correlation; -7, strong negative correlation; -9, very strong negative correlation

Table 6.7 Correlations between *HOWs* represented by rough numbers

	Energy conservation	Water conservation	Paper use reduction
Energy conservation	[9,9]	[0,0]	[1,2]
Water conservation	[0,0]	[9,9]	[0,0]
Paper use reduction	[1,2]	[0,0]	[9,9]

Table 6.8 *WHAT-HOW* relationships considering the correlations of *HOWs*

Environmental requirements- *WHATs* (W_i)	Favorable Performances - *HOWs* (H_j)		
	Energy conservation	Water conservation	Paper use reduction
Environmental degradation is reduced at its source	[62,90]	[54,63]	[78,97]
Resources are reused or recycled within the office building	[44,63]	[36,63]	[76,91]

IMPORTANCE OF *HOWs*

The *HOW*s are prioritized according to their importance. The importance ratings are calculated through the following two steps:

(1) Aggregation:

$$I_j^{bn} = \sum_{i=1}^{m} (W_i \times R_{ij}^{'}) \qquad \textbf{(6.3)}$$

where I_j^{bn} denotes the importance of the j^{th} *HOW* before normalization, W_i is the weight of the i^{th} *WHAT*, $R_{ij}^{'}$ is the adjusted relationship between the i^{th} *WHAT* and the j^{th} *HOW*, and m is the number of *WHAT*s.

(2) Normalization:

$$I_j = [\frac{(I_j^{bn})^L}{(I_j^{bn})^L + \sum_{i \neq j}(I_i^{bn})^U} \times 100, \frac{(I_j^{bn})^U}{(I_j^{bn})^U + \sum_{i \neq j}(I_i^{bn})^L} \times 100], \quad i \text{ and } j = 1,\ldots,\text{n} \qquad \textbf{(6.4)}$$

where I_j denotes the importance of the j^{th} *HOW*, $(I_j^{bn})^L$ and $(I_j^{bn})^U$ are the lower and upper limits of the importance of the j^{th} *HOW* before normalization, respectively, and n is the number of *HOW*s. This equation aims to normalize the numbers into a scale of 100 instead of 1 to avoid narrowing the variance of the importance values.

Still following the previous example, the importance of *HOW*s was achieved and is given in Table 6.9. For example, I_1 (the importance of energy conservation) was calculated:

$$I_1^{bn} = [8, 9] \times [62, 90] + [6, 7] \times [44, 63] = [760, 1251]$$

$$I_1 = [\frac{760}{760 + (1008 + 1510)} \times 100, \frac{1251}{1251 + (648 + 1308)} \times 100] = [23, 40]$$

Table 6.9 Importance (in terms of rough numbers) of *HOW*s

	Favorable Performances – *HOW*s (H_j)		
	Energy conservation	Water Conservation	Paper use reduction
Importance before normalization (I_j^{bn})	[760,1251]	[648,1008]	[1308,1510]
Importance of *HOW*s (I_j)	[23,40]	[19,33]	[37,52]

Table 6.9 indicates that energy conservation and paper use reduction are the two critical performances that will be analyzed in the next house. The above illustrates the calculation procedure in House A-1. This procedure needs to be iterated in Houses A-2 and A-3 to obtain the performance indicators. Table 6.10 gives some examples of *HOW*s that can be used in House A-2. Through the analysis, critical operational and management activities can be achieved and used as *WHAT*s in House A-3. Following the example, if House A-2 indicates that the double-sided printing and performing routine analysis on implemented energy saving opportunities are the critical activities, Table 6.11 gives the potential measures that can be used as *HOW*s in House A-3. If the results show that the "percentage of paper use reduction on a monthly basis (%)" and "number of implemented energy saving opportunities (#/year)" are of greater importance than the others, then these two measures will be used as performance indicators at Stage II.

Table 6.10 Examples of HOWs in House A-2

HOWs / *WHATs*	**Operational activities**	**Management activities**
Energy conservation	Replacing incandescent bulbs with fluorescent bulbs	Performing routine identification of energy saving opportunities
	Turning off electrical machines such as fans, typewriters, calculators, and copiers when not in use	Performing routine analysis on the results of implemented energy saving opportunities
	Properly insulating walls, floors, and ceilings with weather stripping, caulking, storm doors, and windows	Monitoring the maintenance of equipment or facilities
	Planting shrubs on the windward side of the building to block wind and decrease building heat loss	Distributing questionnaires to collect employees' responses to the energy saving actions
Paper use reduction	Expanding and encouraging the use of electronic mail	Monitoring the implementation of facility wide double-sided printing or copying policy
	Using blank side of used paper	Performing routine identification of opportunities to reuse paper and paper products
	Double-sided printing	

Table 6.11 Examples of HOWs in House A-3

HOWs / *WHATs*	Quantitative or Descriptive Measures		
Double-sided printing	Percentage of paper use reduction compared to the 5 years' average (%)	Number of signs reminding people of double-sided printing (#/office)	Percentage of people among employees who are in favour of double sided printing (%)
Performing routine analysis on implemented energy saving opportunities	Energy conserved (kWh/year)	Number of implemented energy saving opportunities (#/year)	Number of the routine analyses (#/year)

By implementing the above-described methods, key performance and condition indicators could be obtained to proceed with the environmental performance evaluation at the next stage. The proposed methodology provides a systematic process to transform qualitative requirements into quantitative indicators. It contributes to easier identification of environmental indicators.

6.4.2 STAGE II - ENVIRONMENTAL PERFORMANCE EVALUATION

The objective of this stage is to evaluate the environmental performance of current operations and historical operations based on the indicators that have been identified at Stage I. Figure 6.6 presents the House of Environmental Performance Evaluation (HoEPE) designed for this purpose. The components of the house are described as follows.

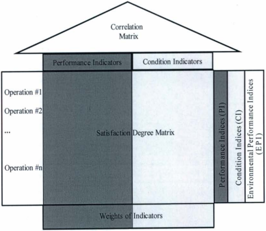


Figure 6.6 House of Environmental Performance Evaluation (HoEPE)

WEIGHT OF INDICATORS

The weights of indicators are crisp numbers that are calculated by averaging the upper and lower limits of the rough numbers representing the importance of key *HOW*s in Houses A-3 and B-3. For instance, For instance, using the importance value [37, 52] found in Table 6.9, the weight will be (37+52)/2= 45.

SATISFACTION DEGREE (SD_{ij})

$$SD_{ij} = \frac{M_{ij}}{\max(M_{1i}, M_{2i}, ..., M_{ni})}, \ (i = 1, 2, \dots, \text{ and } j = 1, 2, \dots, n) \qquad \textbf{(6.5)}$$

when a greater value indicates a better performance/condition (positive development);

$$SD_{ij} = \frac{\min(M_{1i}, M_{2i}, ..., M_{ni})}{M_{ij}}, \ (i = 1, 2, \dots, k \text{ and } j = 1, 2, \dots, n) \qquad \textbf{(6.6)}$$

when a smaller value indicates a better performance/condition (negative development); where M_{ij} is the measured value of the j^{th} indicator in the i^{th} operation; n is the number of indicators; and k is the number of operations to be evaluated. No matter whether it is a positive or negative development, the increase of the *SD* always reflects improved environmental performance, and vice versa. For example, if the average percentages of paper use reduction on a monthly basis (positive development) in the years 2010, 2009, and 2008 are 30%, 20%, and 25%, respectively, then SD_{ij} values for these three years are:

$$SD_{11} = \frac{30}{\max(20,25,30)} = 1,\ SD_{21} = \frac{20}{\max(20,25,30)} = 0.7, \text{ and } SD_{31} = \frac{25}{\max(20,25,30)} = 0.8.$$

If the monthly average of oil and grease content in ambient water at 1 km away from the platform in the years 2010, 2009, and 2008 are 5 ppm, 7ppm, and 9 ppm, respectively, then SD_{ij} values are:

$$SD_{11} = \frac{\min(5,7,9)}{5} = 1, SD_{21} = \frac{\min(5,7,9)}{7} = 0.7, \text{ and } SD_{21} = \frac{\min(5,7,9)}{9} = 0.6$$

CORRELATION MATRIX

Correlations are directly achieved from Houses A-3 and B-3. Before aggregating the $SD_{ij}s$, it is not necessary to adjust them using the correlation matrix again due to the following reasons:

(1) Weights of the indicators are calculated considering the correlations among the performance and condition indicators, respectively; and

(2) The performance and condition indices are calculated independently.

INDICES

$$PI_i = \sum_{j=1}^{k} (SD_{ij}^p \times W_j^p), (i = 1, 2, \ldots, \text{k and } j = 1, 2, \ldots, \text{n}); \quad \textbf{(6.7)}$$

$$CI_i = \sum_{j=k+1}^{l+k} (SD_{ij}^c \times W_j^c), (i = \text{k+1, k+2}, \ldots, \text{l+k and } j = 1, 2, \ldots, \text{n}); \quad \textbf{(6.8)}$$

$$EPI_i = PI_i + CI_i \quad \textbf{(6.9)}$$

where PI_i is the performance index of the i^{th} operation. CI_i is the condition index of the ith operation. EPI_i is the environmental performance index of the i^{th} operation; An EPI has no value if it is not measured over time. SD_{ij}^p and SD_{ij}^c are the satisfaction degrees of the

j^{th} performance and condition indicator in the i^{th} operation, respectively. W_j^p and W_j^c are the weights of the j^{th} performance and condition indicator, respectively. k is the number of performance indicators, l is the number of condition indicators, and n is the number of operations to be evaluated. For instance, based on Table 6.12, the indices were calculated using Equations 6.7, 6.8, and 6.9: $PI = 0.9\times17+1\times20+0.7\times22= 51$; $CI = 1\times24+0.6\times17+0.5\times14 = 41$; $EPI = 51+41= 92$.

Table 6.12 Assumed satisfaction degrees and weights of indicators

	Performance indicators			Condition indicators		
	P_1	P_2	P_3	C_1	C_2	C_3
Satisfaction degrees	0.9	1	0.7	1	0.6	0.5
Weights of indicators	17	20	22	24	17	14

Analyzing calculated indices and the other achieved results, decision makers will be able to determine whether environmental performance is improved and they may identify areas where potential improvements can be made.

6.5 A CASE STUDY

Considering an offshore operator needs to evaluate the environmental performance of its operations in the years 2008, 2009, and 2010. During these three years, an environmental management system (EMS) has been implemented to manage all activities that give rise to environmental impacts. The two unique features of this system are:

(1) Pollution prevention (P2) rather than pollution control and mitigation options are routinely identified, evaluated, and implemented throughout the operation; and

(2) All the environmental protection options are evaluated based on a minimum environmental risk and the selected options are properly implemented.

To assist with the environmental performance evaluation in the above case, the proposed approach was implemented following the steps given in Figure 6.7. This is relatively straightforward to carry out on a Microsoft Excel worksheet. W_1 and W_2 in both Houses A-1 and B-1 (in Figure 6.4) are the above-mentioned two features of the EMS. The authors are the decision makers who made the required evaluations in this case study.

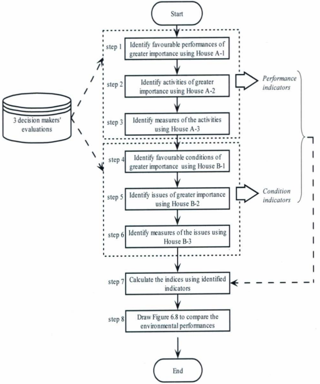


Figure 6.7 Implementation procedure of the numerical application

Table 6.13 summarizes the decision makers' evaluations required for the analysis and the results at steps 1, 2, and 3 in Figure 6.7. H_1 to H_8 of House A-3 in Table 6.13 are listed as follows and they were used as performance indicators (P_1 to P_8):

(1) H_1 - percentage of achieved documented environmental objectives or targets (%);

(2) H_2 - number of employees who participated in an environmental training program versus the number that need training (ratio);

(3) H_3 - number of environmental improvement suggestions from employees;

(4) H_4 - savings achieved through reductions in resource usage, control of pollution or wastes ($/yr);

(5) H_5 - research and development funds applied to environmental improvement projects with great significance;

(6) H_6 - number of advanced drilling tools implemented to enable operation to penetrate precise targets;

(7) H_7 - percentage of synthetic based fluids (SBFs) usage in the total consumption of drilling fluids (%/yr);

(8) H_8 - reduction of produced water discharge compared to a 3-year average (in 2005~2007) (%/yr).

Table 6.13 Inputs and results in the identification of performance indicators

House A-1											
Decision makers' evaluations								**Calculated rough numbers**			
Weights of *WHATs*											
	W_1	9, 7, 9				→	W_1	[8,9]			
	W_2	7, 7, 9					W_2	[7,8]			
Relationship matrix											
		H_1	H_2	H_3	H_4			H_1	H_2	H_3	H_4
	W_1	9,7,9	9,9,7	7,5,7	7,7,9	→	W_1	[8,9]	[8,9]	[6,7]	[7,8]
	W_2	5,3,*	9,9,7	9,9,9	7,7,9		W_2	[3,6]	[8,9]	[9,9]	[7,8]
Correlation matrix											
		H_1	H_2	H_3	H_4			H_1	H_2	H_3	H_4
	H_1	9,9,9	7,7,5	0,0,0	7,9,7	→	H_1	[9,9]	[6,7]	[0,0]	[7,8]
	H_2	7,7,5	9,9,9	0,0,0	9,9,7		H_2	[6,7]	[9,9]	[0,0]	[8,9]
	H_3	0,0,0	0,0,0	9,9,9	7,7,9		H_3	[0,0]	[0,0]	[9,9]	[7,8]
	H_4	7,9,7	9,9,7	7,7,9	9,9,9		H_4	[7,8]	[8,9]	[7,8]	[9,9]
Results											
		H_1	H_2	H_3	H_4						
Importance of *HOWs*		[17, 30]	[19,32]	[13,23]	[27, 42]						
H_4 and H_2 will enter House A-2 as W_1 and W_2											
House A-2											
Decision makers' evaluations								**Calculated rough numbers**			
...						→		...			
Results											
	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8			
Importance of *HOWs*	[7,23]	[5,18]	[6,21]	[4,13]	[9,26]	[8,23]	[9,26]	[5,20]			
H_5,H_7,H_6,H_1,H_3 will enter House A-3 as W_1, W_2, W_3, W_4, W_5											
House A-3											
Decision makers' evaluations								**Calculated rough numbers**			
...						→		...			
Results											
	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8			
Importance of *HOWs*	[4,34]	[5,39]	[4,37]	[3,32]	[5,42]	[3,30]	[3,32]	[2,25]			
Weights of indicators	19	22	20	17	24	17	18	14			

Note:

(a) H_i in House A-1: ***H_1*** *- The use of materials (e.g., water, hazardous materials) and energy are minimized;* ***H_2*** *- The quantity of drilling wastes and emissions are reduced at their sources;* ***H_3*** *- The occurrence of oil spills in drilling operations and transportation is significantly reduced;* ***H_4*** *- The environmental programs are effectively and efficiently managed.*

(b) H_i in House A-2: ***H_1*** *- Use of synthetic oil-based fluids (SBF) in drilling;* ***H_2*** *- Produced water is separated from oily-body down the well using sub-sea separation technology;* ***H_3*** *- Apply advanced drilling tools (e.g., down-hole directional tool, three-dimensional seismic data interpretation) to enable operations to penetrate precise targets;* ***H_4*** *- Reuse the waste natural gas condensate as fuel (e.g., power turbine generator for electricity);* ***H_5*** *- Document, monitor, and update environmental objectives or targets;* ***H_6*** *- Maintain proper investment or costs of the environmental improvement projects;* ***H_7*** *- Organize environmental training programs for every employee;* ***H_8*** *- Use service provider with a certified environmental management system.*

Table 6.14 gives the evaluations and results at steps 4, 5, 6 in Figure 6.7. H_1 to H_4 of House B-3 in Table 6.14 are listed as follows and H_1, H_2, and H_3 were used as condition indicators (C_1 to C_3):

(1) H_1 - monthly average of oil and grease content in ambient water at 1 km away from the platform (ppm);

(2) H_2 - monthly average of the concentration of benzopyrene in the ambient water at 1 km away from the platform (ppm);

(3) H_3 - number of non-compliance;

(4) H_4 - number of audits on regulatory compliance.

Both H_3 and H_4 can be used to represent the performance with respect to regulatory compliance. In this case, only H_3 is selected to be the indicator due to its greater importance.

Table 6.14 Inputs and results in the identification of condition indicators

House B-1										
Decision makers' evaluations							**Calculated Rough Numbers**			
Weights of *WHAT*										
	W_1	9, 7, 9				→	W_1	[8,9]		
	W_2	7, 7, 9					W_2	[7,8]		
Relationship matrix										
		H_1	H_2	H_3				H_1	H_2	H_3
	W_1	3,3,1	3,3,1	3,3,*		→	W_1	[2,3]	[2,3]	[3,5]
	W_2	1,3,3	5,3,3	7,5,5			W_2	[3,4]	[3,4]	[5,6]
Correlation matrix										
		H_1	H_2	H_3				H_1	H_2	H_3
	H_1	9,9,9	0,0,0	7,7,5		→	H_1	[9,9]	[0,0]	[6,7]
	H_2	0,0,0	9,9,9	7,7,5			H_2	[0,0]	[9,9]	[6,7]
	H_3	7,7,5	7,7,5	9,9,9			H_3	[6,7]	[6,7]	[9,9]
Results										
		H_1	H_2	H_3						
Importance of *HOWs*		[18,41]	[20,43]	[29,55]						
H_3 and H_2 will enter House B-2 as W_1 and W_2										
House B-2										
Decision makers' evaluations							**Calculated Rough Numbers**			
...						→	...			
Results										
		H_1	H_2	H_3	H_4					
Importance of *HOWs*		[15,54]	[15,55]	[9,41]	[6,35]					
H_2, H_1, and H_3 will enter House B-3 as W_1, W_2, and W_3										
House B-3										
Decision makers' evaluations							**Calculated Rough Numbers**			
...						→	...			
Results										
		H_1	H_2	H_3	H_4					
Importance of *HOWs*		[11,68]	[10,67]	[5,52]	[3,44]					
Weights of indicators		40	38	29	24					

Note:

*(a) H_i in House B-1: **H_1** - Low contaminant concentrations in ambient air; **H_2** - Low contaminant concentrations in ambient water; **H_3** - High degree of regulatory compliance.*

*(b) H_i in House B-2: **H_1** -The concentrations of PAHs in ambient water are low; **H_2** - The oil and grease content in ambient is low; **H_3** - national and regional offshore environmental regulations are satisfied; **H_4** - Water recent developed industrial guidelines are followed.*

In Tables 6.13 and 6.14, H_is of Houses A-1 and B-1 are favorable outcomes that are aligned with the environmental requirements (i.e., two features of the EMS in this case study); and H_is of Houses A-2 and B-2 are the activities or issues that must be implemented to reach these favorable outcomes.

Table 6.15 and 6.16 summarize the inputs and results in HoEPE. Based on the results, Figure 6.8 was developed. Figure 6.8 presents an improving trend of the environmental performance, which indicates that better environmental performance has been achieved by implementing the EMS. The average of EPIs (the acceptable line in Figure 6.8) can be used to determine whether the outcomes of the EMS are acceptable or not. Since this application is based on a hypothetical case, the results should not be interpreted as an accurate depiction of any specific OOG operation. However, the example demonstrates how the proposed methodology can be realized in practice.

Table 6.15 Inputs of HoEPE

Inputs	Years	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	C_1	C_2	C_3
Data for calculating satisfaction degrees	2010	80%	4/7	16	180000	100000	6	90	30	8	4	1
	2009	70%	5/7	20	150000	120000	4	92	35	10	3	6
	2008	65%	3/7	10	120000	60000	3	85	20	7	6	3
Weights of indicators		19	22	20	17	24	17	18	14	40	38	29

Table 6.16 Calculated indices in HoEPE

Indices	Years		
	2010	2009	2008
Performance indices (PI)	136	140	95
Condition indices (CI)	93	71	69
Environmental performance indices (EPI)	229	211	164

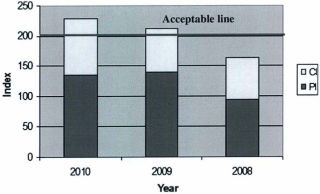


Figure 6.8 Comparisons of environmental performances

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

This chapter provides conclusions based on the proposed EMS framework (RP2EMS) and the developed methodologies. A statement of originality of this research is also presented. Recommendations for future research directions are discussed at the end of this chapter.

7.1 CONCLUSIONS

This research was conducted by adopting a new EMS to support environmental management in OOG operations. The following are the major conclusions of this research:

(1) A new EMS framework that integrates paradigms of P2 and risk-informed decision-making was developed in Chapter 3. As a preferred approach for environmental protection, P2 is integrated with a conventional EMS framework. This integration helps to implement environmental management from a more holistic perspective. Effort and cost that are needed to develop waste treatment systems can be reduced. The paradigm of risk-informed decision-making is coupled with P2 in the proposed framework. Risk assessments need to be carried out for each option developed to deal with the identified significant environmental issues. Based on the calculated risks and other attributes, better options can be

selected using a certain decision-making method. To facilitate implementation of this framework, quantitative approaches were developed. This proposed EMS framework eliminates the major limitations of conventional EMS frameworks:

(a) Quantitative approaches are established to convey and interpret information for decision-making in an EMS;

(b) Methodology for environmental performance evaluation is developed to estimate improvement;

(c) P2 is integrated with the conventional EMS framework to achieve better sustainability;

(d) All of the developed quantitative tools are proposed to be made into a comprehensive software package to reduce the burden of extensive documentation in an EMS.

(2) A methodology for the prioritization of environmental issues was developed in Chapter 4. Integrating a fuzzy inference system (FIS) with a fuzzy analytic hierarchy process (FAHP), the proposed approach enables the decision makers to account for the impacts of uncertainty in determining the overall priority. Additionally, by implementing FIS at the lower levels of the analytic hierarchy, the computation is simplified, the problem of consistency is resolved and adding or deleting criteria in the hierarchy becomes easy to operate in the algorithm; thus, the limitations of the conventional fuzzy AHP methods are eliminated. Finally, the prioritization of environmental issues is performed in terms of environmental

risks. These features make this approach robust for prioritization of the environmental issues in OOG operations. This is validated through a hypothetical case study to prioritize eleven environmental issues.

(3) A methodology for risk-informed decision-making was developed in Chapter 5. Game theory is coupled with rough set theory to structure this proposed approach. The strength of this approach is that it incorporates game theory to model decision-making by different groups of players with conflicting preferences on decision criteria. A multi-criteria game that has three categories of criteria (i.e., costs, environmental risks, and technical feasibility) was established. It was solved using the generalized maximin solution concept. Additionally, uncertain qualitative and quantitative data in the game are transformed into rough numbers using rough set theory. The proposed approach has been successfully applied to a hypothetical case study on selection of the management scenario of drilling wastes. The case study demonstrated that this approach is capable of handling environmental decision problems that involve conflicting objectives or criteria, imprecise data, and interdependency between groups of decision-makers.

(4) An environmental performance evaluation (EPE) methodology was developed in Chapter 6. EPE is essential for monitoring the improvements that an EMS has brought to OOG operations. Adopting QFD to implement a novel scheme to identify the specific indicators on a case-by-case basis, the proposed approach

provides a transparent process for EPE. Moreover, rough set theory was integrated in the approach to account for the impacts of incomplete and vague information in the evaluation process. The applicability of this approach was demonstrated through assessment of environmental performance of OOG operations in three consecutive years. This case study shows that the proposed approach enables one to generate case-specific indicators to more accurately measure environmental performance.

7.2 STATEMENT OF ORIGINALITY

The original contribution of the present research can be viewed from the following perspectives:

(1) Integration of EMS with paradigms of pollution prevention (P2) and risk-informed decision-making (RIDM) for more effective environmental management in OOG operations;

(2) Development of a hybrid approach for prioritization which integrates fuzzy inference system (FIS) and fuzzy analytic hierarch process (FAHP) for the first time and eliminates the limitations of FAHP;

(3) Development of a new approach which incorporates game theory in conjunction with rough set theory for the first time to handle interactive environmental decision-making with imprecise data;

(4) Introduction of a new concept of using quality function deployment (QFD) coupled with rough set theory to identify specific environmental indicators on a

case-by-case basis.

7.3 RECOMMENDATIONS

The following recommendations are provided for future research:

(1) The proposed approach for prioritization of environmental issues adopts fuzzy numbers to model uncertainty. The prospect to use fuzzy numbers to integrate richer information should be studied in future research. For instance, it is possible that the widths of the triangular fuzzy numbers (TFNs) adopted in this study can be used to reflect the degree of certainty of the assessment. Lastly, a proper way to check the consistency of the proposed approach may also need to be developed.

(2) An integration of game theory, rough set, and analytic hierarchy process (AHP), a comprehensive framework for multi-criteria decision-making (MCDA), is also worth studying in the future. Also the problem that how rough numbers can be properly compared should be further examined.

(3) Although multiplicative preference relations (e.g., high-9) with rough set theory handle the uncertainty well in the proposed approach for environmental performance evaluation, the prospect to use fuzzy preference relations with rough sets in QFD is an area worthy of further study. A problem also exists in ensuring that the indicators measure what they are intended to measure. Future research is needed to reduce this uncertainty in the proposed approach.

(4) The developed quantitative approaches are suggested to be integrated in one common platform for easier implementation of RP2EMS.

(5) Due to a lack of practical data, all of the proposed quantitative approaches were validated through hypothetical cases. Further validation on a real-world case is required as future work when data is obtained.

REFERENCES

Aboulnaga, I. A. (1998). Integrating quality and environmental management as competitive business strategy for 21st century. *Environmental Management and Health*, 9 (2), 65-71.

Akao,Y. (1990). *Quality Function Deployment*, Cambridge, MA, USA: Productivity Press

Ammenberg, J. & Sundin, E. (2005). Products in environmental management systems: drivers, barriers and experiences. *Journal of Cleaner Production*, 13 (4), 405-415.

Anderson, Cheryl M. & LaBelle Robert P. (2000). Update of Comparative Occurrence Rates for Offshore Oil Spills. *Spill Science and Technology Bulletin* 6 (10): 303-21.

Arulanantham, R. & Feldman, L. (2003). Sustaining risk-informed decision-making (RIDM) measures. *Ecosystem and Sustainable Development*, I, 539-547.

Azapagic, A. (1999). Life cycle assessment and its application to process selection, design and optimisation. *Chemical Engineering Journal*, 73 (1), 1-21.

Azapagic, A. & Perdan, S. (2000). Indicators of sustainable development for industry: a general framework. *Trans IChemE*, 78B, 243-261.

Bai, C.G. & Sarkis, J. (2010). Green supplier development: analytical evaluation using rough set theory. *Journal of Cleaner Production*, 18 (12), 1200-1210.

Barad, M. & Gien, D. (2001). Linking improvement models to manufacturing strategies- a methodology for SMEs and other enterprises. *International Journal of Production Research*, 39(12), 2675-2695.

Bellman, R.E. & Zadeh, L.A. (1970). Decision-making in a fuzzy environment. *Management Science*, 17(4), B141-B164.

Bergquist, K. & Abeysekera, J. (1996). Quality function deployment (QFD) — A means for developing usable products. *International Journal of Industrial Ergonomics*, 18(4), 269-275.

Beskese, A., Kahraman, C., Irani, Z. (2004). Quantification of flexibility in advanced manufacturing systems using fuzzy concept. *International Journal of Production Economics*, 89 (1), 45-56.

Bevilacqua, M., Ciarapica, F.E., Giacchetta, G. (2006). A fuzzy-QFD approach to supplier selection. *Journal of Purchasing & Supply Management,* 12 (1), 14-27.

Blackwell, D. (1956). An analog of the minimax theorem for vector payoff. *Pacific Journal of Mathematics* 6 (2), 1-8.

Boender, C.G.E. & Lootsma, F. A. (1989). Multicriteria decision analysis with fuzzy pair-wise comparison. *Fuzzy Sets and Systems*, 29 (2), 133-143.

Borkotokey, S. (2008). Cooperative games with fuzzy coalition and fuzzy characteristic functions. *Fuzzy Sets and Systems*, 158 (2), 138-151.

Bossert, J.L. (1991). *Quality function deployment: a practitioner's approach*. New York: ASQC Quality Press.

Bozbura, F. T., Beskese, A., Kahraman, C. (2007). Prioritization of human capital measurement indicators using fuzzy AHP. *Expert System with Applications*, 32(4), 1100-1112.

Brans, J.P., Mareshal, B., Vincke, P. (1984). PROMETHEE: a new family of outranking methods in multicriteria analysis. In *Proc. of the 10th IFORS international conference on operational research*, pp. 477-490.

Buckley, J.J. (1985). Fuzzy hierarchical analysis. *Fuzzy Sets and Systems*, 17(3): 233-247.

Butnariu, D. (1978). Fuzzy games, a description of the concept. *Fuzzy Sets and Systems*, 1 (3), 53-58.

Butnariu, D. (1980). Stability and shapley value for n-persons fuzzy game. *Fuzzy Sets and Systems*, 4(1), 63-72.

Buyukozkan, G., Kahraman, C., Ruan, D. (2004). A fuzzy multicriteria decision approach for software development strategy selection. *International Journal of General System*, 33(April-June), 259-280.

Carraro, C. & Leveque, F. (1999). *Voluntary approaches in environmental policy*. Dordrecht, Germany: Kluwer Academic Publishers.

Chan, L-K. & Wu, M-L. (2002). Quality function deployment: a literature review. *European Journal of Operational Research*, 143(3), 463-497.

Chan, L.K., Kao, H.P., Ng, A., Wu, M.L. (1999). Rating the importance of customer needs in quality function deployment by fuzzy and entropy methods. *International Journal of Production Research*, 37(11), 2499-2518.

Chang, D. Y. (1996). Applications of the extent analysis method on fuzzy AHP. *European Journal of Operational Research*, 95(3), 649-655.

Chang, Y.H., Chung, H.Y., Wang, S.Y. (2007). A survey and optimization-based evaluation of development strategies for the air cargo industry, *International Journal of Production Economics*, 106 (2), 550–562.

Chen, S. & Fu, G. (2003). A fuzzy approach to the lectotype optimization of offshore platforms. *Ocean Engineering*, 30 (7), 877-891.

Chen, Y., Fung, R.Y.K., Tang, J. (2006). Rating technical attributes in fuzzy QFD by integrating fuzzy weighted average method and fuzzy expected value operator. *European Journal of Operational Research*, 174 (3), 1553-1566.

Chen, Y-W. & Larbani, M. (2006). Two-person zero-sum game approach for fuzzy multiple attribute decision making problems. *Fuzzy Sets and Systems*, 157 (1), 34-51.

Chen, Z., Zhao, L., Lee, K. (2010). Environmental risk assessment of offshore produced water discharges using a hybrid fuzzy-stochastic modeling approach. *Environmental Modeling and Software*, 25(6), 782-792.

Cheng, C-H., Yang, K.,-L., Hwang, C.-L. (1996). Evaluating naval tactical missile systems by fuzzy AHP based on the grade value of membership function. *European Journal of Operational Research*, 96 (2), 343-350.

Chew, I.M.L., Tan, R., Foo, D.C.Y., Chiu, A.S.F. (2009). Game theory approach to the analysis of inter-plant water integration in an eco-industrial park. *Journal of Cleaner Production*, 17 (18), 1611-1619.

Chin, K.S., Wang, Y.M., Yang, J.B., Poon, K.K.G. (2009). An evidential reasoning based approach for quality function deployment under uncertainty. *Expert Systems with Applications*, 36 (3), 5684-5694.

Christou, M. D. & Mattarelli, M. (2000). Land-use planning in the vicinity of chemical sites: Risk-informed decision making at a local community level. *Journal of Hazardous Materials*, 78 (1-3), 191-222.

Christie, I. & Rolfe, H. (1995). *Cleaner production in industry: integrating business goals and environmental management*. London, UK: Policy Studies Institute Publishing.

Chu, K. (2003). *Integrated Environmental Management Systems: a Design for the Environment Approach*. Retrieved Jun 6, 2009, from http://www.newmoa.org/prevention/greengovconf/presentations/chu.pdf.

Chuang, P.T. (2001). Combing the analytic hierarchy process and quality function deployment for a location decision from a requirement perspective. *International Journal of Advanced Manufacturing Technology*, 18(11), 842-849.

Clayton, A. M.H & Radcliff, N. J. (1996). *Sustainability: A Systems Approach*. London, UK: Earthscan Publications Limited.

Cook, H.E. & Wu, A. (2001). On the valuation of goods and selection of the best design alternative. *Research in Engineering Design*, 13(1), 42-54

Cubiotti, P. (2000). Existence of generalized Pareto Equilibria for constrained multiobjective games. *International Game Theory Review*, 2 (4), 329-344.

Curran, K.J., Wells, P.G., Potter, A.J. (2006). Proposing a coordinated environmental effects monitoring (EEM) program structure for the offshore petroleum industry, Nova Scotia, Canada. *Marine Policy*, 30 (4), 400-411.

Davies, J.M., Addy, J.M., Blackman, R.A., Blanchard, J.R., Ferbrache, J.E., Moore, D.C, Somerville, H.J., Whitehead, A. and Wilkinson, T. (1984). Environmental Effects of the Use of Oil-based Drilling Muds in the North Sea. *Marine Pollution Bulletin* 15(10): 363-370.

ECC. (1993). *Council-Regulation (EEC) No. 1836/93 allowing voluntary participation by companies in the industrial sector in a community.* Brussels, Belgium: EEC.

Eni. (2009a). *World Oil and Gas Review 2008*. Retrieved April. 22nd 2009, from http://www.eni.it/wogr_2008/pdf/wogr2008-oil.pdf.

Eni. (2009b). *World Oil and Gas Review 2008*. Retrieved April. 22nd , 2009, from http://www.eni.it/wogr_2008/pdf/wogr2008-gas.pdf.

Environment Canada. (1990). Environmental code of practice for treatment and disposal of waste discharges from offshore oil and gas operations. Ottawa: Beauregard Printers Limited.

Erensal, Y.C., Oncan, T., Demircan, M. L., (2006). Determining key capabilities in technology management using fuzzy analytic process: a case study of Turkey. *Information Science*, 176 (18), 2755-2770.

Ersdal, G. & Aven, T. (2008). Risk informed decision-making and its ethical basis. *Reliability Engineering and System Safety*, 93(2), 197-205.

Esquer-Peralat Javier. (2007). *Sustainability Management System (SMS): an integrative approach to management systems towards sustainable development*. PhD thesis. University of Massachusetts-Lowell. Retrieved from http://proquest.umi.com AAT 3260118.

European Commission. (2008).*EMAS and ISO/EN 14001: differences and complementarities*. Retrieved May 12th, 2009, from http://ec.europa.eu/environment/emas/pdf/factsheet/fs_iso_en_low.pdf

Facchinetti, G., Ricci, R. G., Muzzioli, S. (1998). Note on ranking fuzzy triangular numbers. *International Journal of Intelligent Systems*, 13 (7), 613-622.

Falck, A., Skramstad, E., Berg, (2000). Use of QRA for decision support in the design of an offshore oil production installation. *Journal of Hazardous Materials*, 71(1-3), 179-192.

Fernandez, F.R. & Puerto, J. (1996). Vector linear programming in zero-sum multicriteria matrix games. *Journal of Optimization Theory and Applications*, 89 (1), 115-127.

GESAMP. (1993). Impact of Oil and Related Chemicals and Wastes on the Marine Environment. *Rep. Stud.GESAMP* 50 (2): 180-191.

Halog, A., Schultmann, F., Rentz, O. (2001). Using quality function deployment for technique selection for optimum environmental performance improvement. *Journal of Cleaner Production*, 9(5), 387-394.

Hermann, B.G., Kroeze, C., Jawjit, W. (2007). Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. *Journal of Cleaner Production*, 15 (18), 1787-1796.

Hinojosa, M. A. & Marmol, A. M. (2005). Generalized maximin solutions in multicriteria bargaining. *Annals of Operations Research*, 137 (1), 243-255.

Hossain, K.A. (2009). *Integrated approach for pollution prevention in process design and decision-making*. PhD thesis. Memorial University of Newfoundland. Retrieved from http://proquest.umi.com.

Hu, Q.Z. & Lu, H.P. (2009). Rough set comprehensive evaluation model for environmental security effect of highway construction projects. In *Proceedings of the 2009 International Conference on Energy and Environment Technology*. DOI 10.1109/ICEET.2009.78.

Hwang, C.-L., & Yoon, K. (1981). *Multiple attribute decision making methods and applications*. New York, USA: Springer-Verlag.

Ilinitch, AY., Soderstrom, NS., Thomas, TE. (1998). Measuring corporate environmental performance. *Journal of Accounting and Public Policy*, 17 (4-5), 383-408.

ISO. (1996). *Implementation of ISO 14004: 1996*. London, UK: British Standards Institution.

ISO. (1999). *Environmental management - Environmental performance evaluation – Guidelines (ISO 14031: 1999)*. Geneva, Switzerland: International Organization for Standardization.

ISO. (2004). *Environmental management systems – requirements with guidance for use (ISO 14001:2004)*. Geneva, Switzerland: International Organization for Standardization.

James, P. (1994). Business environmental performance measurement. *Business Strategy and the Environment*, 3 (2), 59-67.

Juang, Y-S., Lin, S.-S., Kao, H-P. (2007). Design and implementation of a fuzzy inference system for supporting customer requirements. *Expert Systems with Applications*, 32(3), 868-878.

Jung, E.J., Kim, J.S., Rhee, S.K. (2001). The measurement of corporate environmental performance and its application to the analysis of efficiency in oil industry. *Journal of Cleaner Production*, 9 (6), 551-563.

Kacher, F. & Larbani, M. (2008). Existence of equilibrium solution for a non-cooperative game with fuzzy goals and parameters. *Fuzzy Sets and Systems*, 159 (2), 164-176.

Kahraman, C., Cebeci, U., Ruan, D. (2004). Multi-attribute comparison of catering service companies using fuzzy AHP: the case of Turkey, *International Journal of Production Economics*, 87 (2), 171–184.

Katambara, Z., & Ndiritu, J. (2009). A fuzzy inference system for modelling streamflow: Case of Letaba River, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 34(10-12), 688-700.

Kenchington, Trevor J. (1997). *A Review of the Marine Environmental Effects of the Sable Offshore Energy Project.* Halifax, N.S.: Ecology Action Centre.

Kerachian, R., Fallahnia, M., Bazargan-Lari, M. R., Mansoori, A., Sedghi, H. (2010). A fuzzy game theoretic approach for groundwater resources management: application of Rubinstein Bargaining Theory. Resources, *Conservation and Recycling*, 54 (10), 673-682.

Khan, F.I., Ravinder, V., Husain, T. (2002). Effective environmental management through life cycle assessment. *Journal of Loss Prevention in Process Industries,* 15(6), 455-466.

Khan, M. I. (2006). *Towards sustainability in offshore oil and gas operations*. PhD thesis. Dalhousie University. Retrieved from http://proquest.umi.com. AAT NR42713.

Klir, G.J. & Yuan, B. (1995). *Fuzzy sets and fuzzy logic: theory and applications*. Upper Saddle River, New Jersey: Prentice Hall International.

Koottungal, L. (2004). World offshore oil, gas production has risen 'steadily'. *Oil and Gas Journal,* 102 (14), 1-3.

KPMG. (1992). *A measure of commitment: guidelines for measuring environmental performance*. London, United Kingdom: KPMG, Inc

Krajnc, D. & Glavič, P. (2003). Indicators of sustainable production. *Clean Technologies and Environmental Policy*, 5, (3), 279-288.

Larbani, M. (2009). Non-cooperative fuzzy games in normal form: A survey. *Fuzzy Sets and Systems*, 160 (22), 3184-3210.

Law, H-W. & Hua, M. (2007). Using quality function deployment in singular process analysis. Engineering Letters, 14(1), EL_14_1_6

Lawrence, L., D. Andrews, B. Ralph, C. F. (2002). Identifying and assessing environmental impacts: investigating ISO14001 approaches. *The TQM Magazine,* 14(1), 43-50.

Lee, Y. W., Bogardi, I., Stansbury, J. (1991). Fuzzy decision-making in dredged material management. *Journal of Environmental Engineering*, 117(5), 614-630.

Leung, L.C., & Cao, D. (2000). On consistency and ranking of alternatives in fuzzy AHP. *European Journal of Operational Research*, 124 (1), 102-113.

Lewandowska, A., Matuszak-Flejszman, A., Joachimiak, K., Ciroth, A. (2011). Environmental life cycle assessment (LCA) as a tool for identification and assessment of environmental aspects in environmental management systems (EMS). *The International Journal of Life Cycle Assessment*, 16 (3), 247-257.

Li, S.X. (1998). Cone concavity and multiple-payoff constrained n person games. *Journal of Optimization Theory and Application*, 97 (2), 119-149.

Li, L., Shi,Z.H., Yin, W., Zhu, D., Ng, S.L., Cai, C-F. Lei, A-L. (2009). A fuzzy analytic hierarchy process (FAHP) approach to eco-environmental vulnerability assessment for the danjiangkou reservoir area, China. *Ecological Modeling*, 220(23), 3439-3447.

Li, Y.L., Tang, J.F., Luo, X.G., Xu, J. (2009). An integrated method of rough set, Kano's model and AHP for rating customer requirements' final importance. *Expert Systems with Applications*, 36(2), 7045-7053.

Lin, Y.H., Cheng, H-P., Tseng, M-L., Tsai, Jim.C.C. (2010). Using QFD and ANP to analyze the environmental production requirements in linguistic preferences. *Expert Systems with Applications*, 37(3), 2186-2196.

Liu, K.F.R., & Lai J-H. (2009). Decision-support for environmental impact assessment: a hybrid approach using fuzzy logic and fuzzy analytic network process. *Expert Systems with Applications*, 36(3), 5119-5136.

Maali, Y. (2009). A multi-objective approach for solving cooperative n-person games. *Electrical Power and Energy Systems*, 31 (10), 608-610.

Madani, K. & Lund, J.R. (2011). A Monte-Carlo game theoretical approach for multi-criteria decision making under uncertainty. *Advances in Water Resources*, 34(5), 607-616.

Marmol, A.M., Monroy, L., Rubiales, V. (2007). An equitable solution for multi-criteria bargaining games. *European Journal of Operational Research*, 177 (3), 1523-1534.

Matthews, D.H. (2001). *Assessment and Design of Industrial Environmental Management Systems*. PhD Thesis. Carnegie Mellon University. Retrieved from http://proquest.umi.com. AAT 3040481.

Myerson, Roger B. (1991), *Game theory: analysis of conflict*, Harvard University Press, ISBN 978-0-674-34116-6

Nan, C., Khan, F., Iqbal, M. T. (2008). Real-time fault diagnosis using knowledge-based expert system. *Process Safety and Environmental Protection*, 86 (1), 55-71.

Nasiri, F. & Huang, G. (2008). A fuzzy decision aide model for environmental performance assessment in waste recycling. *Environmental Modelling & Software*, 23 (6), 677-689.

Nawrocka, D. & Parker, T. (2009). Finding the connection: environmental management systems and environmental performance. *Journal of Cleaner Production*, 17 (6), 601-607.

Novak, V. & Pedrycz, W. (1988). Fuzzy sets and t-norms in the light of fuzzy logic. *International Journal of Man-Machine Studies*, 29 (2), 113-127.

NRC (National Regulatory Commission). (2004). *Overview of a framework for risk-informed decision-making in NMSS*. Retrieved May.22nd,2009, from http://www.nrc.gov/reading-rm/doccollections/commission/secys/2004/secy2004-0182/attachment1.pdf.

Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J.L., Schuhmacher, M. (2006). Assessing water quality in rivers with fuzzy inference systems: A case study. *Environment International*, 32(6), 733-742.

Olsgard F & Gray JS. (1995). A comprehensive analysis of effects of offshore oil and gas exploration and production on the benthic communities of the Norwegian continental shelf. *Mar. Ecol. Prog. Ser*. 122: 277-306.

Pak, M.V & Brieva, D.C. (2010). Designing and implementing a role-playing game: a tool to explain factors decision making and landscape transformation. *Environmental Modeling and Software*, 25(11), 1322-1333.

Patin S. (1999). *Environmental impact of the offshore oil and gas industry*. New York: EcoMonitor Publishing.

Pawlak, Z. (1982). Rough sets. *International Journal of Computer and Information Sciences*, 11(5), 341-356.

Pawlak, Z. (1985). Rough sets and fuzzy sets. *Fuzzy sets and systems*, 17(1), 99-102.

Perotto, E., Canziani, R., Marchesi, R., Butelli, P. (2008). Environmental performance, indicators and measurement uncertainty in EMS context: a case study. *Journal of Cleaner Production*, 16 (4), 517-530.

Petak, W. J. (1981). Environmental management, a systematic approach. *Environmental Management,* 5 (3), 213-224.

Pollard, S.J.T., Davies, G.J., Coley, F., Lemon, M. (2008). Better environmental decision making — Recent progress and future trends. *Science of The Total Environment,* 400 (1-3), 20-31.

Promentilla, M.A., Furuichi, T., Ishii, K., Tanikawa, N. (2008). A fuzzy analytic network process for multi-criteria evaluation of contaminated site remedial countermeasures. *Journal of Environmental Management*, 88(3), 479-495.

Puerto, J., Hinojosa, M.A., Marmol, A.M., Monroy, L. Fernandez, F.R. (1999). Solution concepts for multiple objective n-person games. *Investigacao Operational*, 19 (2), 193-209.

Ramik, J., & Korviny, P. (2010). Inconsistency of pair-wise comparison matrix with fuzzy elements based on geometric mean. *Fuzzy Sets and Systems*, 161(11), 1604-1613.

Raquel, S., Ferenc, S., Emery, C. Jr., Abraham, R. (2007). Application of game theory for a groundwater conflict in Mexico. *Journal of Environmental Management*, 84 (4), 560-571.

Rene, van B., Michela, van K., Kortman, J. (1999). Opportunities and constraints for product oriented environmental management system (P-EMS). *Journal of Cleaner Production,* 7(6), 447-455.

Rocha, C. & Brezel, H. (1999). Product oriented environmental management systems. *Journal of Sustain Prod Des,* 10(5), 30-42.

Sadiq, R., Husain, T., Bose, N., Veitch, B. (2003a). Distribution of heavy metals in sediment pore water: an ecological risk assessment. *Environmental Modeling and Software*, 18 (5), 451-461.

Sadiq, R., Husain, T., Bose, N., Veitch, B. (2003b). Distribution of arsenic and copper in sediment pore water: an ecological risk assessment case study for offshore drilling waste discharges. *Risk Analysis*, 23 (6), 1309-1321.

Sadiq, R., Husain, T., Veitch, B., Bose, N. (2004). Risk-based decision-making for drilling waste discharges using a fuzzy synthetic evaluation technique. *Ocean Engineering*, 31(16), 1929-1953.

Sadiq, R. & Husain, T. (2005). A fuzzy-based methodology for an aggregative environmental risk assessment: a case study of drilling waste. *Environmental Modeling and Software*, 20 (1), 33-46.

Sadiq, R., Khan, F. I., Veitch, B. (2005). Evaluating offshore technologies for produced water management using GreenPro-I- a risk-based life cycle analysis for green and clean process selection and design. *Computers and Chemical Engineering*, 29 (15), 1023-1039.

Salem, Y. L., Khan, M.I., Rafiqul, M. I. (2009). An "Olympic" framework for a green decommissioning of an offshore oil platform. *Ocean & Coastal Management,* 52 (2), 113-123.

Salter, E. & Ford, J. (2000). Environmental pollution challenges and associated planning and management issues facing offshore oil and gas field development in the UK. *Journal of Environmental Planning and Management,* 43 (2), 253–276.

Samsura, D.A.A., Van der Krabben, E., Van Deemen, A.M.A. (2010). A game theory approach to the analysis of land and property development processes. *Land Use Policy*, 27 (2), 564-578.

Sangle, S. (2005). Redefining environmental management system boundaries through stakeholder management across product life-cycle. *International Journal of Environmental and Sustainable Development,* 4(2), 193-207.

Satty, T. L. (1980). *The analytic hierarchy process: planning, priority setting, resource allocation*. New York, USA: McGraw-Hill.

Satty, T.L. (1996). *Decision making with dependence and feedback: The analytic network process*. Pittsburgh, USA: RWS Publications.

Sergei V. V. & Jay Paul Wagner. (1996). *International Legal Regime for the Protection of the Marine Environment Against Operational Pollution from Offshore Petroleum Activities*. In Gao Zhiguo, Environmental Regulation of Oil and Gas (2nd ed, pp 156). London, UK: Kluwer Law International Ltd.

Shafer, G.A. (1976). *Mathematical theory of evidence*. Princeton, NJ: Princeton University Press.

Sheldon, C. & Yoxon, M. (2006). *Environmental management systems, a step by step guide to implementation and maintenance.* London, UK: Cromwell Press.

Shen, LY., Lu, WS., Yao, H., Wu, DH. (2005). A computer-based scoring method for measuring the environmental performance of construction activities. *Automation in Construction*, 14 (3), 297-309.

Shepard, R. B. (2005). *Quantifying Environmental Impact Assessment Using Fuzzy Logic*. New York, USA: Springer.

Simola, K. & Pulkkinen, U. (2004). Risk-informed decision- making, a pre-study. Retrieved Jun 6, 2009, from http://www.risoe.dk/rispubl/nks/nks-93.pdf.

Sisk W. S. (2005*). Compliance-focused environmental management system-enforcement agreement guidance*. Denver, USA: National Enforcement Investigations Center, EPA.

Sivanandam, S.N., Sumathi, S. Deepa, S.N. (2007). *Introduction to fuzzy logic using Matlab*. New York, USA: Springer.

Spires, E.E. (1991). Using the analytic hierarchy process to analyze multi-attribute decisions. *Multivariable Behavioural Research*, 26 (2), 345-361.

Suslick, S.B. & Furtado, R. (2001). Quantifying the value of technological, environmental and financial gain in decision models for offshore oil exploration. *Journal of Petroleum Science and Engineering*, 32(2-4), 115-125.

Tesfamariam, S. & Sadiq, R. (2006). Risk-based environmental decision-making using fuzzy analytic hierarchy process (F-AHP). *Stochastic Environmental Research and Risk Assessment*, 21 (1), 35-50.

Tseng, M-L., Lin, Y-H., Chiu, A.S.F. (2009). Fuzzy AHP-based study of cleaner production implementation in Taiwan PWB manufacturer. *Journal of Cleaner Production*, 17(14), 1249-1256.

Tsumoto, T. (2004). Mining diagnostic rules from clinical databases using rough sets and medical diagnostic model. *Information Sciences*, 162 (2), 65-80.

U.S. EPA. (2000). *Integrated environmental management systems-implementation guide*. Washington DC: Design for the Environment (DfE) Program, U.S. EPA. Retrieved from http://www.epa.gov/dfe/pubs/iems/iems_guide/.

Utne, I. B. (2009). Improving the environmental performance of the fishing fleet by use of Quality Function Deployment (QFD). *Journal of Cleaner Production,* 17(8), 724-731.

Van Laarhoven, P.J.M., & Pedrycz, W. (1983). A fuzzy extension of Saaty`s priority theory. *Fuzzy Sets and Systems*, 11(1-3), 199-227.

Veil, J., A., Christonpher J.Burke, David O. Moses. (1995). *Synthetic Drilling Fluids-A Pollution Prevention Opportunity for the Oil and Gas Industry*. Argonne National Laboratory. Retrieved on July 21. 2008 from: http://www.osti.gov/bridge/servlets/purl/18427zuPM9/webviewable/184270.pdf

Veleva, V.& Ellenbecker, M. (2001). Indicators of sustainable production: framework and methodology. *Journal of Cleaner Production*, 9(6), 519-549.

Veleva, V., Hart, M., Greiner, T., Crumbley, C. (2001). Indicators of sustainable production. *Journal of Cleaner Production*, 9(5), 447-452.

Vijay, V., Chandra, S., Bector, C. R. (2005). Matrix games with fuzzy goals and fuzzy payoffs. *Omega*, 33 (5), 425-429.

Vinodh, S. & Rathod, G. (2010). Integration of ECQFD and LCA for sustainable product design. *Journal of Cleaner Production*, 18 (8), 833-842.

Von Neumann, J. & Morgenstern, O. (1944). *Theory of Games and Economic Behavior*, New York, U.S.A.: Princeton University Press.

Wang, C.Z., Wu, C.X., Chen, D.G. (2008). A systematic study on attribute reduction with rough sets based on general binary relations. *Information Sciences*, 178 (9), 2237-2261.

Wang, H. & Wang, S.H. (2009). Discovering patterns of missing data in survey databases: an application of rough sets. *Expert Systems with Applications*, 36 (3), 6256-6260.

Wang, T.-L., & Chen, Y.-H. (2008). Applying fuzzy linguistic preference relations to the improvement of consistency of fuzzy AHP. *Information Sciences*, 178(19), 3755-3765.

Warren, J. & Craig, J. (1996). Measuring pollution prevention progress. In Freeman, H. M. (Ed.), *Industrial pollution prevention handbook* (pp. 238). Montreal, Canada: McGraw-Hill, Inc.

White, C. J., & Lakany, H. (2008). A fuzzy inference system for fault detection and isolation: Application to a fluid system. *Expert Systems with Applications*, 35(3), 1021-1033.

Wolnik, C. & Fischer, P. (2005). Advancing pollution prevention and cleaner production: Canada's contribution, Journal of Cleaner Production, 14(6), 539-541.

Wu, W.Z. (2008). Attribute reduction based on evidence theory in incomplete decision systems. *Information Sciences*, 178 (5), 1355-1371.

Xiao, F. & Yang, H. (2007). Three-player game theoretic model over a freight transportation network. *Transportation Research Part C*, 15 (4), 209-217.

Yang, M., Khan, F., Sadiq, R. (2011). Prioritization of environmental issues in offshore oil and gas operations: A hybrid approach using fuzzy inference system and fuzzy analytic hierarchy process. *Process Safety and Environmental Protection*, 89 (1), 22-34.

Zadeh, L. (1965). Fuzzy sets. *Information and Control,* 8(3), 338-353.

Zarker, K. A. & Kerr, R. L. (2008). Pollution prevention through performance-based initiatives and regulation in the United States. *Journal of Cleaner Production,* 16 (6), 673-685.

Zhai, L.Y., Khoo, L.P., Zhong, Z. W. (2009). A rough set based QFD approach to the management of imprecise design information in product development. *Advanced Engineering Informatics*, 23(2), 222-228.

Zhang, Y., Wang, H.-P., Zhang, C. (1999). Green QFD-II: a life cycle approach for environmental conscious manufacturing by integrating LCA and LCC into QFD matrices. *Journal of Production Research*, 37(5), 1075-1091.

Zhang, Z.F. & Chu, X.N. (2009). Fuzzy group decision-making for multi-format and multi-granularity linguistic judgments in quality function deployment. *Expert System with Applications*, 36 (5), 9150-9158.

Zhao, L., Chen, Z., Lee, K. (2008). A risk assessment model for produced water discharge from offshore petroleum platforms-development and validation. *Marine Pollution Bulletin*, 56 (11), 1890-1897.

Zhou, P., Ang, B.W., Poh, K.L. (2008). Measuring environmental performance under different DEA technologies. *Energy Economics*, 30 (1), 1-14.

APPENDICES

Appendix I: QUESTIONNAIRE ON ENVIRONMENTAL RISKS CAUSED BY MAJOR CATEGORIES OF WASTE STREAMS IN OFFSHORE OIL AND GAS OPERATIONS

Instruction:

Answer the following questions by assigning a score [0-100] to assess the subjects listed below, where 0 represents "least significant" and 100 represents the "most significant".

A. Risk to Marine Eco-system

Risk parameters	Sub- parameters	Waste streams	Score $\in$ [0, 100]
Consequence	Severity	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Geographical scale	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Duration	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
Likelihood of Occurrence	Exposure	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Toxicity assessment	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	

B. Risk to Human Health

Risk parameters	Sub- parameters	Waste streams	Score ∈ [0, 100]
Consequence	Severity	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Geographical scale	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Duration	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
Likelihood of Occurrence	Exposure	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Toxicity assessment	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	

C. Risk to Climate Change

Risk parameters	Sub- parameters	Waste streams	Score ∈ [0, 100]
Consequence	Severity	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Geographical scale	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Duration	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
Likelihood of Occurrence	Exposure	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	
	Mechanism assessment	Drilling waste	
		Atmospheric emission	
		Physical disturbance (noise, light)	
		Living waste	
		Accidental pollution	

Appendix II: QUESTIONNAIRE USED TO FACILITATE COMPARISONS OF MAJOR ENVIRONMENTAL CONCERNS OF ENVIRONMENTAL ISSUES IN OFFSHORE OIL AND GAS OPERATIONS

Instruction:

Read the following questions and put check marks on the pair-wise comparison matrices. If an attribute on the left is more important than the one matching on the right, put your check mark to the left of the importance ''just equal'' under the importance level you prefer. If an attribute on the left is less important than the one matching on the right, put your check mark to the right of the importance 'just equal' under the importance level you prefer.

Risk to Marine Eco-system (RME), Risk to Human Health (RHH), Risk to Climate Change (RCC)

with respect to significance of one environmental issue	Importance of one over another												
	Absolutely more important	Very strongly more important	Strongly more important	Weakly more important	Equally important	Just equal	Equally important	Weakly more important	Strongly more important	Very strongly more important	Absolutely more important		
RME													RHH
RME													RCC
RHH													RCC