DECISION MAKING TOOL FOR PRODUCED WATER MANAGEMENT: AN APPLICATION OF MULTICRITERIA DECISION MAKING APPROACH

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DECISION MAKING TOOL FOR PRODUCED WATER MANAGEMENT: AN APPLICATION OF MULTICRITERIA DECISION MAKING APPROACH

by

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Abstract

Produced water (PW) is the most significant source of waste discharge from the oil and gas operations. As such, development of an effective PW management system is important to minimize/mitigate the environmental impacts. However, there are challenges with respect to the selection of the best option due to competing and conflicting criteria. Selection of the best alternative often involves multiple criteria, which requires sophisticated multiple-criteria decision making (MCDM) methods. The Analytical Hierarchy Process (AHP) has widespread application in MCDM problems. It can effectively handle both qualitative and quantitative data. In this study AHP is integrated with an additive value model to enhance the decision making process. Linguistic terms are used to capture the subjective judgment of decision makers in the absence of quantitative data.

However, the traditional AHP involves human subjectivity which leads to decision uncertainty. The vagueness type uncertainty associated in the decision making process is considered using the fuzzy based technique. The traditional AHP is modified to fuzzy AHP using extent analysis and integrated with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) algorithm to solve the decision matrix. A hypothetical case study for PW management is demonstrated to illustrate and compare both traditional AHP and fuzzy based AHP methodology.

The ecological risk assessment (ERA) of PW is conducted for this study and the ERA results for different PW management options are used in the integrated MCDM model under ecological risk criteria.

This study has provided a framework for a decision support system which will be helpful for oil and gas industry persons to seclect the best PW management options with minimum efforts.

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
BAT	Best Available Technology
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
BDNF	Buoyancy Dominated Near Field
BDFF	Buoyancy Dominated Far Field
CHARM	Chemical Hazard Assessment and Risk Management
CAPP	Canadian Association of Petroleum
CNRC	Canadian National Research Council
CFU	Compact Flotation Unit
CPI	Corrugated Plate Interceptor
CI	Consistency Index
CR	Consistency Ratio
CCME	Canadian Council of Ministers of the Environment
CDF	Cumulative Distribution Function
DM	Decision Matrix
DOWS	Down Hole Oil-Water Separation
EC	Exposure Concentration
EPA	Environmental Protection Agency
ERA	Ecological Risk Assessment
EC_{50} or LC_{50}	The Measure of Lethal Concentration at Which Mortality is 50%
EC	Exposure Concentration
FA	Fluoranthene
FAHP	Fuzzy Analytical Hierarchy Process
FMCDM	Fuzzy Multiple Criteria Decision Making
FPCM	Fuzzy Pair Wise Comparison Matrix
FF	Far-Field
GM	Geometric Mean
GHG	Green House Gas
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environment Protection
HQ	Hazard Quotient
MCDM	Multicriteria Decision Making
MPPE	Macro Porous Polymer Extraction

MAUF	Multiple Attribute Utility Functions
NOEC	No-Observed-Effect Concentration
NORM	Naturally Occurring Radioactive Material
NGL	Natural Gas Liquid
NPD	Naphtalenes, Phenanthrenes, Dibenzothiophenes
NIS	Negative Ideal Solution
NF	Near-Field
O&G	Oil and Gas
OSPAR	Oslo/Paris convention
PW	Produced Water
PPI	Parallel Plate Interceptor
PCM	Pair Wise Comparison Matrix
PARCOM	Peacetime Airborne Reconnaissance Program
PAHs	Polyaromatic Hydrocarbons
PNEC	Predicted No Effect Concentration
PEC	Predicted Environmental Concentration
PIS	Positive Ideal Solution
RE	Representative Values
RO	Reverse Osmosis
SAW	Simple Additive Weighting
TORR	Total Oil Recovery and Remediation
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TFN	Triangular Fuzzy Number
UF	Ultrafiltration
U.K	United Kingdom
U.S.A	United States of America

Chapter 1

INTRODUCTION

The main purpose of this research was to develop and apply a multi-criteria decision making (MCDM) approach to evaluate offshore produced water (PW) management technologies. During evaluation the major components considered in this study were environmental, technical feasibility, cost and safety. This study focuses on all these components to evaluate offshore PW management technologies. A hypothetical case study is also presented to demonstrate the developed methodology.

1.1 Background

The discharge of PW from the offshore oil and gas production characterizes the main source of toxicity into the marine environment; it is by far the largest volume of byproducts or waste stream associated with oil and gas production. PW, which naturally occurs in the reservoir, is commonly known as formation water. During oil and gas production, the formation water reaches the production wells to maintain the hydraulic pressure and is brought up from the hydrocarbon bearing strata during the extraction of oil and/or gas. PW includes formation water, injection water, small volumes of condensed water and trace amounts of treatment chemicals (CAPP, 2001).

The composition of PW is strongly field-dependent and includes a variety of inorganic and organic compounds. PW contains small amounts of emulsified oil, organic compounds including dissolved hydrocarbons, organic acids, phenols and traces of chemicals added during production, inorganic compounds, suspended solids, dissolved solids and natural low-radioactive elements.

According to the National Research Council (1985), worldwide petroleum hydrocarbon input to the oceans from PW represents less than 0.4% of the total amount of petroleum hydrocarbons entering the world's oceans from all sources. This implies that PW discharges are unlikely to have large-scale environmental impacts. Other ingredients in PW such as heavy metals and radionuclides also are of environmental concern.

The main contributors to acute toxicity (short-term effects) of PW have been found to be the phenolic and aromatic fractions of the dissolved hydrocarbons (Frost et al., 1998). The existing separation equipment cannot remove all of the oil and grease to meet regulatory limits particularly with deep offshore operations. In these cases, chemicals are used, but some of these chemicals have toxic effects. The impacts of PW constituents in the short term largely depend on concentration at the discharge point, discharge location and other hydrodynamic characteristics of the receiving water body. For example, where there is a rapid dilution, it may limit the potential biological effects. Studies have shown that the acute toxicity effects of PW to marine organisms are generally low, except possibly in the mixing zone, due to rapid dilution and biodegradation of the aromatic and phenol fractions (Frost et al., 1998). The international agreement peacetime airborne reconnaissance program (PARCOM) limited the effluent concentration with the hydrocarbon content to 40 mg/l. Additionally some countries have also developed their own regulatory discharge standards for the effluent with oil and grease limit, as example a 30 days average of 40 mg/l for Canada, a monthly average 29 mg/l for U.S., a 40 ppm monthly average for U.K., and a 40 ppm monthly average for Norway (CAPP, 2001).

1.2 Scope

In the first stage of this research, management technologies for PW, both currently in use and under development, are studied in detail. Particular focus was given to:

- Technologies to manage PW during the on-going production operations
- Technologies suitable or having potential for offshore applications, and
- Technologies which were able to meet the standard discharge limits for PW.

Secondly an integrated MCDM methodology is developed on the basis of three levels criteria hierarchy structure, and finally the proposed methodology is used to compare the selected PW management technology based on the established set of criteria. Technical feasibility, environmental, cost, and health and safety aspects were the main factors used to compare the options. Due to the large number of options and criteria, a deterministic decision making approach was applied, and uncertainty and sensitivity analysis were also conducted for this study.

1.3 Objectives

The objectives of the research are:

- To identify baseline management technologies for offshore platform as well as some innovative PW management technologies.

- To evaluate selected PW management technologies using MCDM analysis. The focus of the evaluation was on offshore-based applications with consideration of environmental, technical feasibility, marine ecology, cost, and health and safety issues.
- To integrate ecological risk assessment methodology with proposed MCDM method.
- To recommend the optimum PW management technologies according to the evaluation.
- To identify the most important factors affecting the evaluation.

1.4 Structure of the thesis

This study consists of seven chapters. Chapter 1 presents the problems background, scope of the study, and objectives of this research. The background of PW, available management options of PW and other information which are related to this research are presented in Chapter 2. Information, specifically on the mathematical techniques, used to develop the MCDM framework are presented in Chapter 3, and this chapter also presents an overview on widely used MCDM techniques. Chapter 4 describes the ecological risk assessment methodology for PW discharge into sea. As the major part of this study Chapter 5 introduces the development process of the proposed methodology. The proposed methodology is applied on a hypothetical example and its efficacy is demonstrated through an application dealing with the selection of PW management systems for offshore oil and gas operations and this information is presented in Chapter 6.

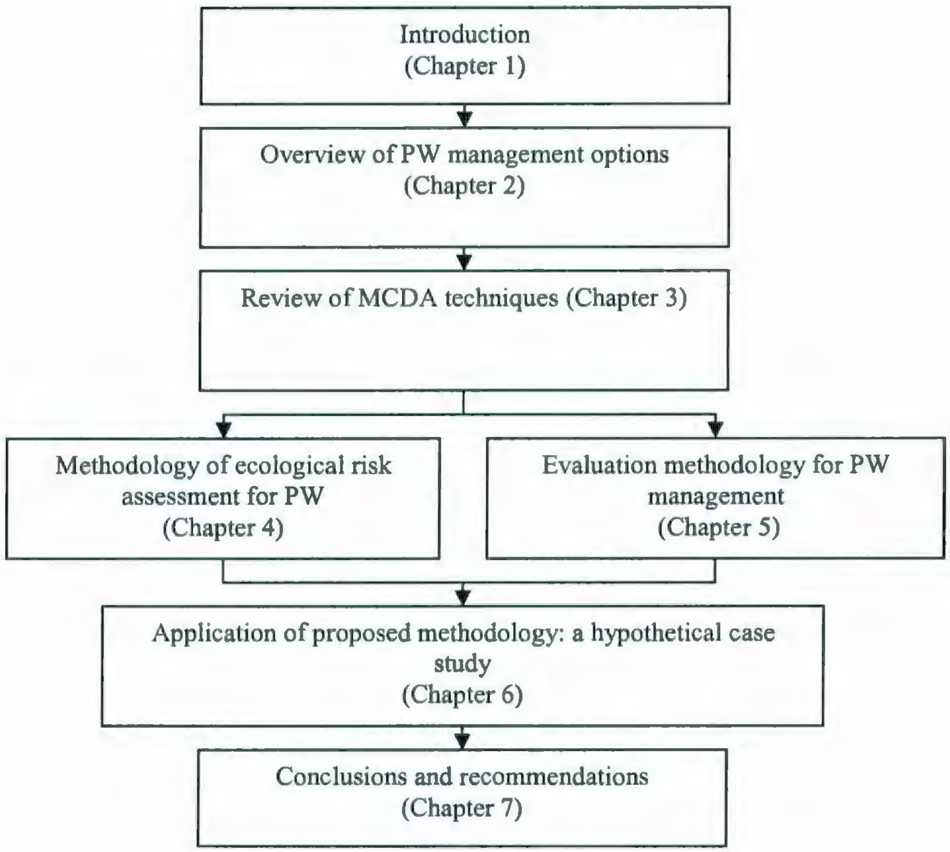

Figure1.1: Structure of the thesis

This study is concluded in Chapter 7 and some recommendations for future works are also highlighted in this section. Figure 1.1 schematically shows how the various chapters are organized in the study.

Chapter 2

OVERVIEW OF PRODUCED WATER MANAGEMENT OPTIONS

A number of studies (CAPP, 2001; OGP, 2005; Frost et al., 1998) have been conducted to address concerns about the environmental impacts associated with PW. The studies can be classified into two main categories: studies on the marine environmental impacts from PW discharges, and studies on PW management. This chapter discusses the most common approaches to managing PW. Management of PW at a given location depends on several factors, including site characteristics, regulatory acceptance, technical feasibility, cost, and availability of infrastructure and equipment. The main management alternatives being used today are underground injection, surface discharge, and beneficial re-use.

2.1 Background of produced water

2.1.1 Definition of produced water

The reservoir rocks normally contain both petroleum hydrocarbons (liquid and gas) and water. Sources of PW may include flow from above or below the hydrocarbon zone, flow from within the hydrocarbon zone, or flow from injected fluids and additives resulting from production activities. This water is frequently referred to as "connate water" or "formation water" and becomes PW when these fluids are brought to the surface (Veil et al., 2004).

2.1.2 Composition of produced water

Physical and chemical properties of the PW mainly depend on the geographical location, geological formation and type of hydrocarbons of the field and may differ from one place to another. Since the PW has been in contact with geological formations for millions of years, its composition is strongly field-dependent (OGP, 2005).

Table 2.1: Typical composition of PW discharged from an oil field

	(1)			(2)	
Materials	Range	Median	Unit	Range	Unit
Dispersed oil	15-60	44	mg/l		
BTEX	1-67	6	mg/l		
NPD	0.06-2.3	1.2	mg/l		
PAHs	130-575	468	μg/l		
Organic Acids (<C6)	55-761	368	mg/l		
Phenols (C0-C4)	0.1-43	8	mg/l		
Arsenic (As)	-	-	-	<0.11-320	μg/l
Barium (Ba)	0.2-228	87	mg/l	1.0-650000	μg/l
Cadmium(Cd)	0.5-5	2	μg/l	0.06-98	μg/l
Chromium (Cr)	-	-	μg/l	<0.01-390	μg/l
Copper (Cu)	22-82	10	μg/l	<0.05-210	μg/l
Lead (Pb)	0.4-8.3	1.9	μg/l	<0.08-5700	μg/l
Mercury (Hg)	<0.1-26	0.7	μg/l	0.06-0.19	μg/l
Nickel (Ni)	0.02-0.3	0.14	mg/l	0.1-1674	μg/l
Zinc (Zn)	0.5-13	7	mg/l	7.3-10200	μg/l
Radium (226RA)	1.66	1.66	Bq/l	0-1565	μg/l
Radium (228RA)	3.9	3.9	Bq/l	0-1509	μg/l
Manganese (Mn)	0.1-0.5	0.45	mg/l	-	-
Berllium (Be)	0.02	0.02	mg/l	-	-
Cobalt (Co)	0.3-1	0.35	mg/l	-	-
Vanadium(V)	0.02-0.5	0.24	mg/l	-	-

(1) Compiled from Frost 1998, section 1.2 and E& P 1994, P.4
(2) Neff, J.M. (1997).

The major part of the PW is water, and the minor amounts are organic and inorganic constituents including dissolved hydrocarbons, organic acids, phenols and traces of chemicals added during production, inorganic compounds, suspended solids, dissolved solids and natural low-radioactive elements from the source geologic formation and the associated hydrocarbons (Veil. et al., 2004; CAPP, 2001; OGP, 2005). The composition of PW changes through the production lifetime of the reservoir, because more water is injected to maintain the pressure of the reservoir. PW may also contain small amounts of chemicals that have been added during the treatment of water. These treatment chemicals could be listed as: hydrate inhibitors, dehydrators, scale inhibitors, corrosion inhibitors, bactericides, emulsion breakers, coagulants, flocculants, defoamers, paraffin inhibitors and solvents (CAPP, 2001). In terms of salinity, most PW is more saline than sea water (Neff, 1997). Table 2.1 reports the typical composition of PW with their concentration.

2.1.3 Impacts of produced water discharges in a marine environment

The previous sections outlined many chemical constituents found in PW. These chemicals, either individually or collectively, when present in high concentrations in PW, could be a threat to aquatic life when they are discharged in the environment. PW can have different potential impacts depending on where it is discharged. For example, discharges to small streams are likely to have a larger environmental impact than discharges made to the open ocean by virtue of the dilution that takes place. Numerous variables determine the actual impacts of PW discharges. These include the physical and chemical properties of the constituents, temperature, content of dissolved organic material, presence of other organic contaminants, and internal factors such as metabolism, fat content, reproductive state, and feeding behavior of aquatic organisms

(Frost et al., 1998). The following sections discuss the potential impact of PW discharges in a marine environment.

Impacts are related to the exposure of organisms to concentrations of various chemicals. To understand the environmental impact of PW when discharged to the sea, it is necessary to consider the fate of the individual components and how their concentrations vary with time. Physical and chemical mechanisms determine the dilution, volatilization, chemical reaction, adsorption on suspended solids, and biodegradation affect the fate and transport of PW (Stephenson et al., 1994). According to Georgie et al., (2001) factors that affect the amount of PW constituents and their concentrations in seawater, and therefore their potential impacts on aquatic organisms include the following:

- Dilution of the discharge into the receiving environment,
- Instantaneous and long-term precipitation,
- Volatilization of low molecular weight hydrocarbons,
- Physical-chemical reactions with other chemical species present in seawater that may affect the concentration of produced water components,
- Adsorption onto particulate matter, and
- Biodegradation of organic compounds into other simpler compounds

Numerous studies have been conducted on the fate and effects of PW discharges in the marine environments. These studies have shown that PW can contaminate sediments and the zone of contamination positively correlates with PW discharge volume and hydrocarbon concentration (Rabalais et al., 1992). The aromatic and phenolic fractions of the dissolved hydrocarbons are the main contributors to acute toxicity of PW (Frost et al., 1998). Besides these, chemicals used by the existing separation equipment particularly with the deep offshore operations may have toxicity effects (CAPP, 2001). The acute impacts of PW depend largely on the concentration of contaminants and discharge point and discharge location (Frost et al., 1998).

2.2 Produced water management options

The oil and gas industry produces large amounts of PW as one of the by products of production. The handling and disposal of PW is critical, as it must adequately protect the environment and should be the least costly (Janks and Cadena, 1992). PW treatment and purification has been accomplished through a variety of chemical and physical separation techniques. Since PW composition varies from location to location, a proven purification method is difficult to develop. Therefore companies are trying to develop new technologies to minimize the production of PW and consequently reduce the costs of PW treatment, and at the same time they are looking for ways that existing facilities can handle larger volumes of water. The handling of PW depends on its composition, location, quantity and the availability of resources. There are different ways for managing PW that can be summarized as follows:

Avoid production of water onto the surface: Using polymer gels or mechanical devices, water can be separated from oil or gas streams down hole and re-injected into suitable formations. This option reduces waste water and is one of the most elegant solutions, but not always straightforward because it depends on the formation characteristics.

Re-inject produced water: PW can be re-injected into the same formation or another suitable formation. It involves transportation of water from the producing zone to the injection site. Treatment of PW is necessary to reduce fouling and scaling agents and bacteria before re-injecting.

Table 2.2: Offshore PW discharged Standards (CAPP, 1991)

Country	Effluent Limits	Monitoring Requirements	Routine Reporting
USA	29 mg/L monthly avg. 42 mg/L daily max.	Total O&G Gravimetric	Annual
UK	40 ppm monthly avg. 30 ppm annual avg.	Dispersed O&G 1/day composite O&G 1/yr comprehensive	Monthly O&G Annual Comprehensive
Norway	40 ppm monthly avg.	Dispersed O&G 1/day composite O&G 1/yr comprehensive	Quarterly O&G Annual Comprehensive
Canada	40 ppm 30 day avg. 80 ppm 2 day avg.	Dispersed O&G 2x/day	Monthly

Discharge produced water: This involves discharging PW into the environmental media like, ocean, river, lakes etc. There is a necessity to treat the produced water to meet onshore or offshore discharge regulations.

Reuse in oil and gas operations: Treated PW can be reused for drilling, stimulation, and work over operations if it meets the standard water quality requirements. This option is not feasible for offshore platforms.

Consume in beneficial uses: Ensuring the standard water quality requirements, the treated PW can be used for beneficial purpose such as irrigation, rangeland restoration, road construction work, cattle and animal consumption, and drinking water for private use or in public water systems. This option is not feasible for offshore platforms.

It should be noted that the choice of PW disposal methods depends on several factors (mentioned in previous sections) and is strictly controlled by the legislation. Besides some international rules, some countries have their own tough and strict regulations which prevent companies from discharging contaminated PW into the environment. According to rules, the amount of discharged water per day should be controlled and limited. Table 2.2 compares existing PW discharged standard for USA, UK, Norway and Canada.

2.2.1 Water Minimization Techniques

In a producing formation, water and petroleum hydrocarbons are not fully mixed; they exist as separate adjacent fluid layers. The hydrocarbon layer typically lies above the water layer by virtue of its lower specific gravity (Veil et al., 2004). When hydrocarbons are pumped out from the formation, the pressure gradient changes and the water layer rises up in the vicinity of the well. As production continues, the water portion in the production well is increased (Veil et al. 2004). It is challenging to minimize the amount of water produced into the well, but there are some techniques that can be used to restrict water from entering the well bore. Some of these techniques are described below:

Down hole oil-water separation (DOWS)

Down hole oil water separation is a technique in which the oil-water mix is separated at the bottom of a production well. DOWS technology reduces the quantity of PW that is handled at the surface. This system separates water from the oil at the bottom of the well and simultaneously injecting it underground. A DOWS system includes many components, but the two primary ones are an oil/water separator and at least one pump to lift oil to the surface and inject the water (Veil et al., 2004). Two basic types of DOWS have been developed, one type using hydrocyclones to separate oil and water and another one relying on gravity separation that takes place in the well bore.

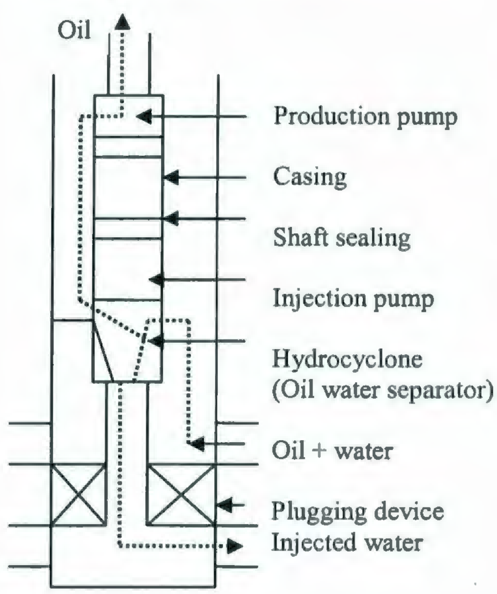

Figure 2.1: Schematic of DOWS (modified from OSPAR, 2002)

Hydrocyclones use centrifugal force to separate fluids of different specific gravity without any moving parts. A mixture of oil and water enters the hydrocyclone at a high velocity from the side of a conical chamber. The subsequent swirling action causes the heavier water to move to the outside of the chamber and exit through one end, while the lighter oil remains in the interior of the chamber and exits through another opening. The water fraction, containing a low concentration of oil (typically less than 500 mg/L), is then injected to the underground formation, and the oil fraction along with some water are pumped to the surface (Veil et al., 1999).

Gravity separator type DOWS are designed to allow the oil droplets that enter a well bore through the perforations to rise and form a discrete oil layer in the well (Veil et al., 2004). Most gravity separator tools are vertically oriented and have two intakes, one in the oil layer and the other in the water layer. This type of gravity separator DOWS uses rod pumps. The sucker rods move up and down, the oil is lifted to the surface and the water is injected. DOWS have a capacity to reduce the amount of PW more than 50%. (Ekins et al., 2005). Figure 2.1 describes the principle of DOWS technique. This method claims higher oil production, a relatively low water production and the use of fewer chemicals comparing than the traditional method without the downhole operations.

Chemical water shut off

When water breakthrough occurs with oil or gas production, the zones with high water cuts can be sealed by the placement of special polymers as shown in Figure 2.2. In chemical shut-off process polymers are injected into the reservoir to increase the water viscosity by forming a stable gel (Green et al. 2001). When injected, the gel solutions secretly enter the cracks and pathways that the water follows displacing the water. The gels set up in the cracks and block most of the water movement to the well while allowing oil to flow to the well. Chemical sealing is often applied in higher production zones (Green et al. 2001).

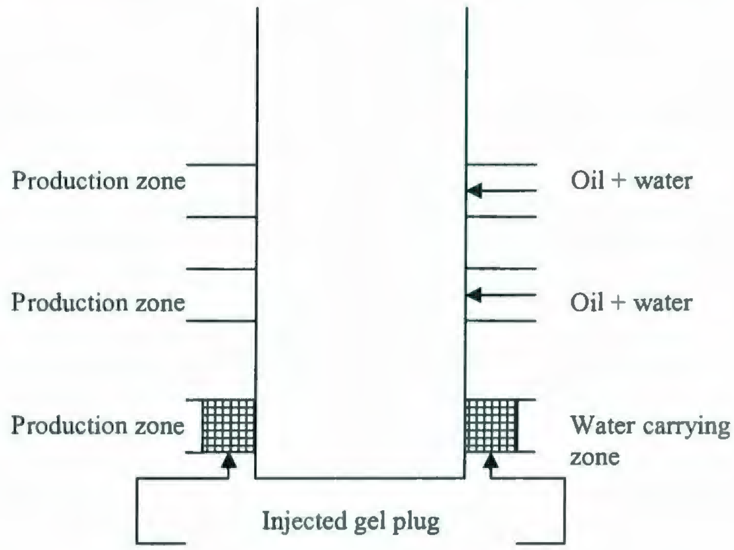

Figure 2.2: Schematic of chemical water shut-off (modified from OSPAR, 2002)

Different types of gels are using, depending on the type of water flow and its compositions. Thomas et al. (2000), Seright et al. (2001) and Green et al. (2001) have suggested several factors to be considered when designing and conducting a gel treatment as:

The component ingredients such as:

- Type of gel polymer (polyacrylamide polymer; microbial products or lignosulfonate)
- Type of cross linking agent (metal ion or organic)
- Fluid used to mix the gel (freshwater or produced water)

The properties of the gel like,

- Concentration of polymer
- Molecular weight of polymer
- Degree of cross linking
- Viscosity (affects the size of cracks or fractures that can be penetrated at a given pressure; can inject as pre-mixed gel or as gelant)
- Density (if gel is heavy, it can sink too far into the water layer and lose effectiveness)
- Set-up time (this determines how far into the cracks or fractures the gel will penetrate)

The treatment procedure depends on the factors, such as:

- Preparation of well before treatment
- Volume of gel used
- Injection pressure
- Injection rate.

Many successful gel treatment jobs have been reported in the literature. Seright et al. (2001) reported on 274 gel treatments conducted in naturally fractured carbonate formations. The disadvantage is that the gel normally cannot be removed anymore water when production proves less (OSPAR, 2006).

Mechanical water shut-off

The basic principle involved in this process is to reduce the water flow to the well production zones with the help of a mechanical device shown in Figure 2.3. During mechanical shut-off, mechanical devices block the water pathway by plugging the perforated production section. Dependent on well configuration, this may be achieved by mechanical or inflatable plugs, cementing, placement of a patch (expansion pipe) or pack-off. If total sealing of the water production is not desired, a regulating mechanism or restriction plate may be placed in the well. This is a best available technology (BAT) candidate (OSPAR 2006, 2002). According to Seright et al. (2001) mechanical approaches can be used to treat the block casing leaks.

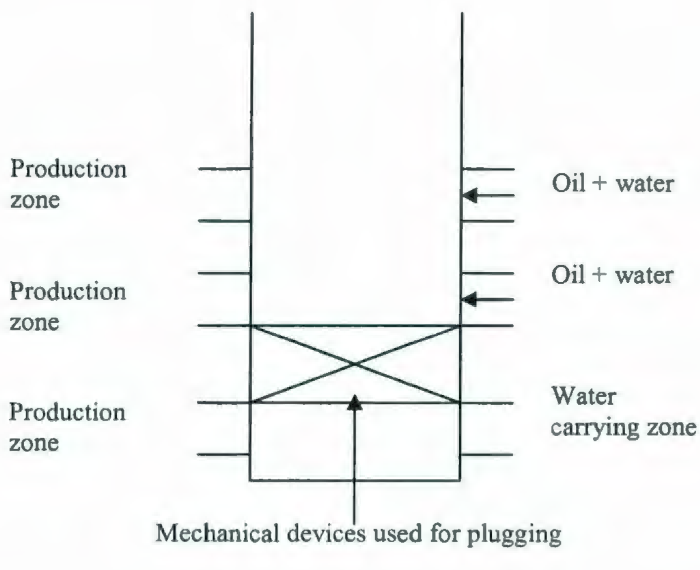

Figure 2.3: Schematic of Mechanical water shut-off (modified from OSPAR, 2002)

2.2.2 Treatment system of produced water

Produced water is the largest wastewater stream in oil and gas production. With the increasing amount of produced water, handling of produced water has become one of the main issues in the petroleum industry. Treatment of PW is important to ensure the regulatory standard before re-injection to the formation, discharge or re-use. Treatment of PW begins with primary three-phase separation where water is removed from the bulk produced fluid. The components included in a PW treatment system will depend on the site specific characteristics of the producing field, characteristics of the produced fluids, and the space available on the platform (CAPP, 2001). The components of PW a treatment system is shown in Figure 2.4. Depending on the exact characteristics of the particular source of PW, different treatment processes are applied.

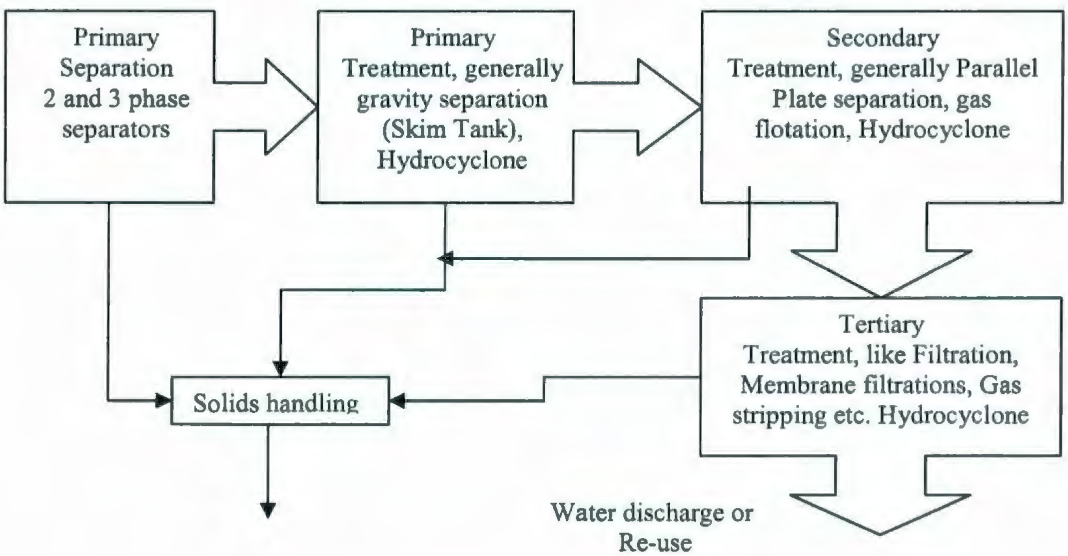

Figure 2.4: Produced water treatment system sequence (CAPP, 2001)

Hydrocyclones, centrifuges, membrane filtration, and activated carbon or depth filters are all techniques that have been tested to perform PW treatment (Roy and Johnsen, 1996; Rey et al., 1996). The review of various PW treatment technologies are considered as options in the evaluation. The following sections discuss widely used PW treatment technology. Some emerging technologies are also reviewed.

Primary Separation technologies

Primary separation mainly removes suspended solids from PW which exists as distinct particles of varying sizes and densities. The suspended solids have a tendency to plug the injection formation or filtration media. Particles that are heavier than water will tend to drop to the bottom of the pipe, vessel or other type of container at various rates. Stokes's Law describes the vertical velocity at which a particle falls through a liquid phase. In separation process relatively large, high-density solids are settled by gravity to the bottom of a tank or vessel. This is termed gravitational settling. This is the most simple and least costly solution to solids removal. Following technologies are used to separate suspended solids:

Skimmer tanks

Gravitational settling can be accomplished by using settling tanks or skimmer tanks. This is the simplest form of PW treatment. A skimmer tank is a simple vessel with enough capacity to allow adequate retention time to separate heavier solids, oil and water. Some vessels may be equipped with a heat source, electro-magnetic field source, or baffles and weirs to improve efficiency or treat emulsions. The primary limitation of a skimmer tank in offshore operations is the size and weight of the vessel. However, almost any treatment system can gain significant benefits from inclusion of a gravity separator in the primary stage of PW treatment. The treatment and installation cost of a skimmer tank is relatively low. This technique is suitable only for non-dissolved components such as dispersed oil with a sufficiently large particle size. Dissolved materials such as benzene and heavy metals cannot be separated using this technique (Ekins et al., 2005). By-product hydrocarbons are skimmed off at the top. The sludge at the bottom is potentially toxic and requires special attention.

API Separator

API is gravity type oil-water separator tank that is designed to promote the quiescent separation of water and free oil. Oil is mechanically collected as a floated material or as a settled mass in the process. The treatment is often used in conjunction with chemical pre-treatment employed to break emulsions. The system is useful as a first line treatment process. Some systems use corrugated plates to collect oil. The treatment process can achieve 50-99% of free oil, and suspended solid particulates above 150 μm are removed (Hayes and Arthur, 2004). Dissolved or emulsion components are not efficiently removed with the process. By product hydrocarbons are skimmed off at the top. Sludge at the bottom is potentially hazardous.

Parallel Plates Separator

The speed of solids removal via gravitational settling can be greatly enhanced by use of inclined parallel plates (Figure 2.5). In this system a section of closely spaced, inclined parallel plates are placed in a rectangular tank or in a cylindrical vessel. The PW stream containing suspended solids flows through these plates. This is also called a parallel plate interceptor (PPI) or a corrugated plate interceptor (CPI). The main advantage of the plates pack is it shortens the distance that a solid particle must travel before it reaches a settling surface; and it provides plenty of surface area for solids to settle out from the water stream. This equipment is lighter and the area required is smaller than for a skimmer tank. However, the capital cost of the equipment may be more than a simple gravity separator.

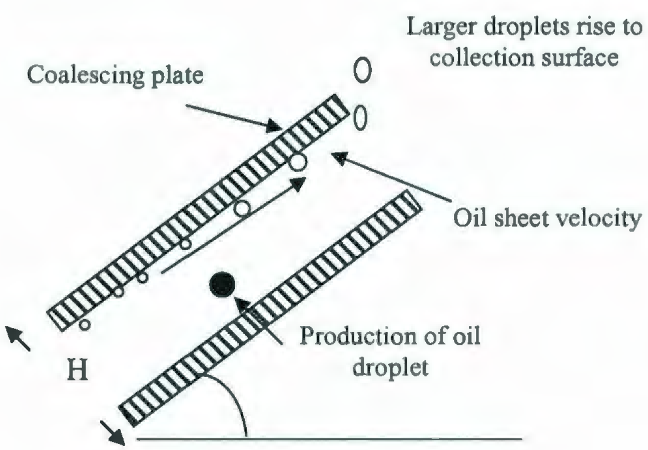

Figure 2.5: Parallel plate separator

Hydrocyclone

Hydrocyclone is a cylindrical device that is fitted with one or more tangential inlets which cause the fluid entering the cyclone to follow a circular path around the wall of the equipment. Rotation of the fluid generates a centrifugal acceleration field which is thousands of times greater than earth's gravity (Hayes and Arthur, 2004). Heavier water and solids move toward the outer wall, lighter material moves toward the center and the light oil is rejected from the process. A liquid/liquid hydrocyclone is one of the most popular devices used in offshore platforms for oil/water separation. It provides maximum separation efficiency for the smallest space impact on the platform.

Hydrocyclones operate under system pressure, and use pressure drop as the primary source of energy. Each hydrocyclone liner in a vessel is fed tangentially to initiate a high radial velocity. The spinning motion of the fluid is accelerated by the tapered shape of the hydrocyclone liner, and the spinning motion creates a centrifugal force up to 4000 times or more of gravity which causes the oil and water to separate rapidly. The oil forms a core at the axis of the hydrocyclone and is forced out via a centered opening. The water hugs the walls and exits through the opposite end. A hydrocyclone is a very compact, oil/water separator with no moving parts.

Polishing technologies

Polishing technologies are suitable for the removal of dissolved aromatic hydrocarbons. These technologies are used for tertiary separation. Polishing technologies are basically integrated with a system of technology. Table 2.3 shows the commercially available polishing technologies. The advantages and disadvantages of several polishing technologies are briefly discussed here.

Table 2.3: Integrated system of PW management

No	System of technologies	Comments
1	Hydrocyclone + Absorption	Commercially available and known as MPPE based technology
2	Hydrocyclone + Produced water re-injection	Commercially available and known as Produced water re-injection
3	Gravity separation + Steam/Air stripping	Commercially available and known as Steam/Air stripping
4	Hydrocyclone + Solvent extraction	This is commercially under development and known as C-Tour
5	Hydrocyclone + Gas flotation	Commercially available and known as Compact Flotation Unit
	Gravity separation + filtration + coalescence	This is commercially under development and known as Total Oil Recovery and Remediation (TORR)

The Macro Porous Polymer Extraction (MPPE)

MPPE system is based on Macro Porous Polymers (MPP). The porous polymer particles have a diameter of 1000 micron, with pore sizes of 0.1- 10 micron and the porosity is 70 to 80% (Meijer & Kuijvenhoven 2001). In the MPPE process, hydrocarbon-contaminated water is passed through a column packed with MPP particle beads, which contain a specific extraction liquid. The extraction liquid immobilize the MPP matrix and removes the hydrocarbons from the water (OSPAR 2002). Only the hydrocarbons, which have a high affinity for the extraction liquid, are removed by the bed (Meijer & Kuijvenhoven, 2001).

The main advantage of this process is regeneration of extraction liquid. The regeneration of the extraction liquid is accomplished by stripping the hydrocarbons with low-pressure steam (Meijer 2007). The stripped hydrocarbons are condensed and then separated from the water phase by gravity. The condensed aqueous phase is recycled within the system.

A typical cycle of MPPE system is shown in Figure 2.6. The application of two columns allows continuous operation with simultaneous extraction and regeneration. A typical system cycle takes one to two hours for extraction and regeneration (OSPAR, 2002).

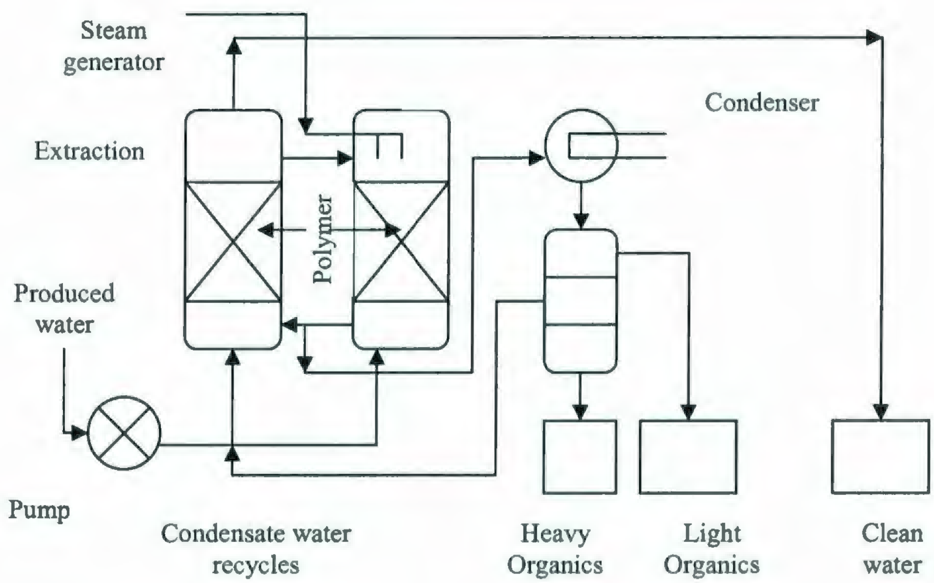

Figure 2.6: Process diagram of MPPE (modified from Meijer, 2007)

MPPE systems have been proven to remove of dissolved and dispersed aromatic hydrocarbons, BTEX components (Benzene, Toluene, Ethylbenzene, Xylene) Polyaromatic hydrocarbons (PAHs), and NPD (naphtalenes, phenanthrenes, dibenzothiophenes). The MPPE process has performance of removal of all BTEX components from PW streams of 90% to 99.99%. There are no negative effects of salt, heavy metals and other present polyaromatic and aliphatic hydrocarbons. The MPPE has removal efficiency for PAHs and NPD's of 98 to 99.99% and for total dispersed oil from PW streams > 99% (OSPAR 2002, Meijer 2007).

Re-injection of produced water

Re-injection of PW is a management system which combines the hydrocyclone and injection pump. In this system PW and sea water are mixed and injected under high pressure to the production aquifers or another suitable zone. In some cases treatment of PW is required before injection. PW is injected directly into the producing reservoir in order to replace the voids in the formation layer to maintain reservoir pressure or water flooding (OSPAR, 2002). During re-injection, attaining the pressure is important because it affects the life span of the wells and the amount of oil and gas that will be extracted. Re-injection has been successfully applied since the 1980's in several areas around the world such as in North America and the North Sea area (Abou-sayed and Guo, 2002). Deep-well injection is the most frequently practiced management alternative in oil and gas production and it occurs where underground geology makes it feasible and cost effective (Fillo et al., 1992). The main environmental concern is that the contaminant may reach into the seabed surface and pollute aquifers. The restriction of the deep well re-injection is mainly covered by the characteristics of the disposal zone. If the receiving zone is a drinking water source, PW can only be injected after meeting the regulatory standard. This may increase the costs of deep well injection. According to Murray (1996), there are serious concerns about injectivity losses and formation damage by the contaminants. Plugging effects of the dissolved organics could for example interrupt the injectivity and can cause production delay. Further scale formation can lead to permanent loss of injectivity and the cost involved to control this effect can be tremendous (Murray, 1996). The re-injection process starts with selection of a suitable formation, or an injection zone. The selected receiving formation should have the capability of receiving the specific volume. Other factors including well location and depth and injection pressure should be consider during selection of a receiving formation. The re-injection process consists of a few steps. Figure 2.7 describes the detailed steps involve in re injection.

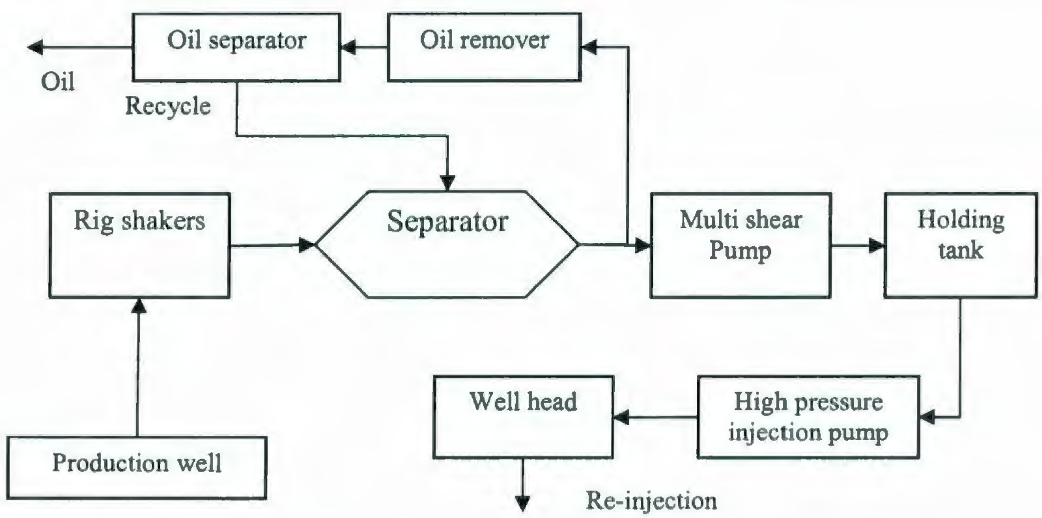

Figure 2.7: Process diagram of re-injection (Modified from OSPAR, 2002)

According to Saasen et al. (2000) and Bruno et al. (2000) the best receiving zone should be a highly porous sand formation with a confined impermeable layer to keep the injected waste in a confined zone. The high pressure of the slurry injection creates a facture in the receiving formation, where the cuttings particles are retained while the fluid phase in the slurry leaks off through the sand layer (Saasen et al., 2000). The rate of injection ranges from 0.6 to 1.75 m^3/min and the pressure ranging from 63 to 100 bars (Wilson et at., 1993). According to the United Kingdom offshore operators Association (UKOOA, 2000), health and safety issues from re-injections are comparable to normal offshore operations. However, the major environmental concerns are related to mitigation of reinjection wastes to environment.

This technology has the following limitations (UKOOA; 2000):

- Pre treatment is required
- Requires a suitable injection zone.
- Requires high energy to maintain high pump pressure.
- High emissions of greenhouse gases.
- The contaminant may reach into the seabed surface and pollute aquifers.

Stripping Method (Stream Stripping)

A stripping method is suitable for removing dissolved volatile organic compounds from wastewater. The removal is accomplished by passing air or steam through the agitated waste water stream. The primary difference between air stripping and steam stripping is that steam stripping is operated at higher temperatures and the resultant off-gas stream is usually condensed and recovered or incinerated. The off-gas from air stripping contains non-condensable air which must be either passed through an adsorption unit or incinerated in order to prevent transfer of the volatile pollutants to the environment. Hydrocarbons and dissolved volatile organic compounds from PW can be removed on gas platforms by means of steam stripping (Ekins et al., 2005; OSPAR, 2006). The removal is accomplished by passing high volumes of steam through the agitated wastewater stream. The process results in a contaminated off-gas stream which is condensed and recovered. Stripping is performed in tanks or packed towers. Treatment in packed towers is the most efficient application. The packing typically consists of metal rings or saddles. The two types of towers that are commonly used are cross flow and countercurrent, and they differ in design only in the location of the stream inlets. In the cross-flow tower, the stream is drawn through the sides for the total height of the packing.

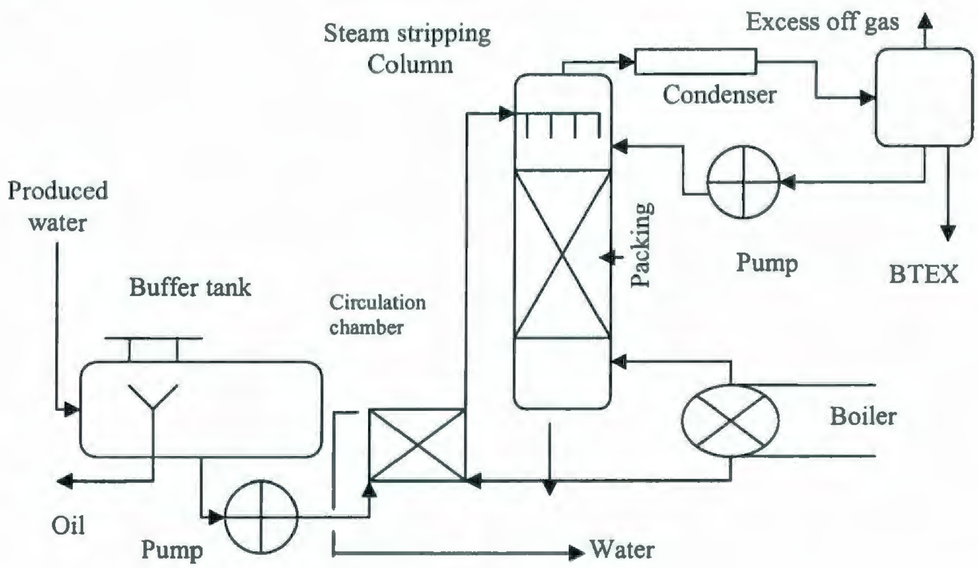

Figure 2.8: Process diagram of steam stripping (modified from OSPAR, 2002)

The countercurrent tower draws the entire steam flow from the bottom. Cross-flow towers have been found to be more susceptible to scaling problems and are less efficient than countercurrent towers. Figure 2.8 shows a countercurrent steam stripper. In stream stripping, mass transfer follows the Henry's Law. When the waste water is fed into a packed column and brought into intense contact with steam flow, the pollutants are transferred from the more concentrated wastewater stream to the less concentrated steam flow until equilibrium is reached.

This technique is suitable for the removal of dissolved oil (BTEX), but will also remove aliphatic hydrocarbons (Ekins et al. 2005, OSPAR 2006). Steam and hydrocarbon off gas are condensed and separated easily. Hydrocarbons that have been separated by steam can be directed to the condensate treatment system and the water can then be discharged. The steam stripping process is adversely affected by low temperatures. For this reason, depending on the location of the tower, it may be necessary to preheat the wastewater. The column and packing materials must be cleaned regularly to ensure that low effluent levels are attained.

Compact Flotation Unit (CFU) Technologies

The CFU is a proven technology in the treatment of PW. The CFU is a vertical pressure vessel, highly efficient in the separation of water, oil and gas to achieve a high standard of treated water. The CFU has a smaller volume with a shorter retention time down to 0.5 minutes (OSPAR 2006, Juliussen 2007). Several combined processes, including gas flotation and induced centrifugal inertia forces, act on the fluid components of different specific gravities (Juliussen 2007). The small oil droplets are made to agglomerate and coalesce, facilitating separation from the water. The separation process is aided by internal devices in the chamber. The technology is flexible, and can be optimized for site specific conditions, and is simple in operation. Several stages can easily be added in series or in parallel to improve treated quality, to account for changes in upstream facilities or to increase capacity according to the flexibility needed on site. Figure 2.9 shows the parallel unit CFU system. Smaller units can be used to treat problematic fluids separately from the bulk fluid. The oil and gas together with a small amount of water is skimmed from the surface by a pipe suspended in the tank. The oil content in the reject fluid varies from 10 to 50 %. Typically, the reject fluid is approximately 1 % of the total flow (OSPAR 2006). Treated water exits to the vessels at the bottom of the outlet for discharge to sea or re-injection. The reject fluid is routed to the closed drain or to a separate treatment stage depending on local requirements. The effectiveness of flotation depends on the amount of residual gas present in the PW.

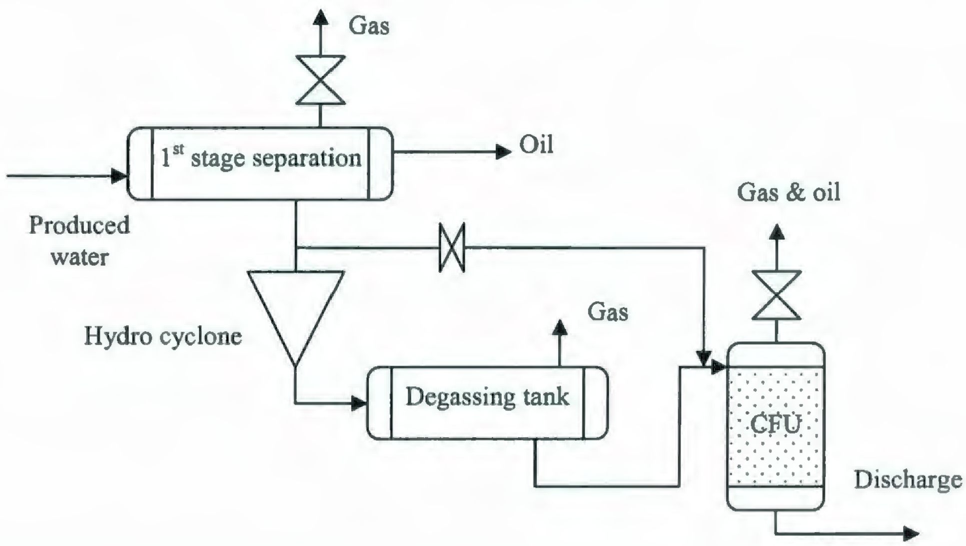

Figure 2.9: Process diagram of CFU technique (modified from OSPAR, 2002)

When limited or no gas is available in the system, the effectiveness of the flotation process is maintained by injecting additional gas (nitrogen or fuel gas) upstream of each CFU vessel (OSPAR, 2006). Normal operation pressure is required from 0.5 bars or upwards (OSPAR, 2006). Flocculants occasionally aid the effectiveness of the separation process.

The CFU treatment technology is suitable for removing hydrocarbons, hydrophobic substances, aromatic compounds and small particles from PW. This technology also reduces depressed oil 80-95%, NPD 45-60%, PAH 60-85%, and BTEX 40-80% depending on the size of oil droplets (OSPAR, 2006). The BTEX removal efficiency depends on the gas rate used and the cleanliness of the gas with respect to BTEX.

2.2.3 Innovative treatment system of produced water

The technologies in this section are new technologies which are currently under development. Some of these technologies have completed lab experiments or trial in offshore for PW treatment. Therefore, these technologies have very high potential for offshore use. However, as the technologies are under development, most information is limited and data regarding field operations is not available.

C-Tour Process

The C-Tour Process enhances the traditional hydrocyclone process by injection of a solvent, i.e., condensate or Natural Gas Liquid (NGL), into upstream water of the hydrocyclone. This process was invented by Rogaland Research Norway in the mid 1990s.The principle of the C-tour Process is rooted in solvent extraction using a condensate hydrocarbon as a solvent. The extraction process is based on thermo dynamical equilibrium between two liquid phases and is thus dependent on the actual composition of the extraction-solvent (OSPAR, 2002). In the C-tour process the extraction solvent is the gas condensate taken from the scrubber. The actual efficiency of the extraction process will therefore depend on the composition of the condensate, which depends on the operating pressure and temperature of the scrubber. The condensate acts as a solvent, and the oil has a high affinity towards the condensate. The condensate and the oil form large, low-density droplets that are easily removed by the downstream hydrocyclone (Henriksen, 2001).

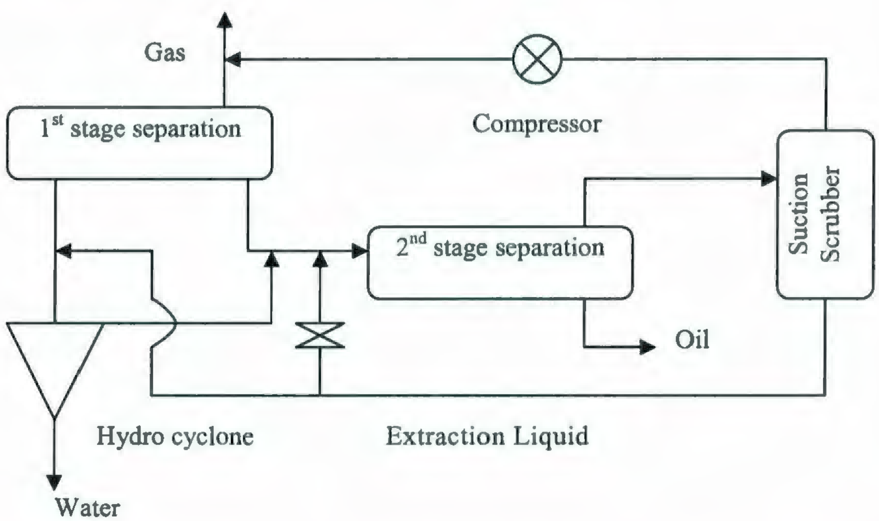

Figure 2.10: Process diagram of C-tour technique (modified from OSPAR, 2002)

The compact test system weighs about four tons and has dimensions of 3.7 m x 1.6 m x 2 m shown in Figure 2.10. It can achieve an oil-in-water content of 1-4 ppm, and also removal efficiencies of 90% (dispersed oil) and 95% (BTX, PAH) have been reported under laboratory and pilot scale conditions (OSPAR 2002). C-tour is not yet generally applicable for reducing the amount of aromatics in PW from offshore installations. However, the test results are promising and it is expected that future development may resolve the current problems. There might be a need for auxiliary equipment in order to reduce the potential transfer of light components (such as BTX components) from the condensate to the discharge stream.

Total Oil Recovery and Remediation (TORR) Technology

Considering the overboard discharge regulations. EARTH (Canada) Corporation has developed alternative technology TORR for the treatment of offshore PW. The new technology is based on the filtration, coalescence and gravity separation processes. The multi-stage separation system is able to remove gas, free floating and emulsified oil from water. To achieve separation, a reusable petroleum adsorbent is used as a filtration medium in the technology which is a unique self-cleaning system. The media being highly oleophillic, allows the absorption of very fine dispersed oil emulsions. Another characteristic of the media lies in its capacity to continue to absorb fine emulsions even when it's fully saturated with oil (Plebon et al. 2005). The media has the ability to adsorb the free-floating and the dispersed oil on its surface. It coalesces the fine emulsions into larger globules. When fully saturated with oil, the drag forces resulting from the flow of water through the media bed promotes the release of the large oil globules while continuing to adsorb the smaller incoming oil emulsions (Plebon et al., 2005). The released coalesced oil is then recovered in the adjacent empty compartments. Here the large oil globules that have been formed are skimmed into a collection header and sent to an oil recovery chamber for quick and easy separation.

This technology recovers dispersed hydrocarbons with a rise velocity of 0.8mm/hr or greater without the additional heat, chemicals or pH adjustment (Plebon et al. 2005).

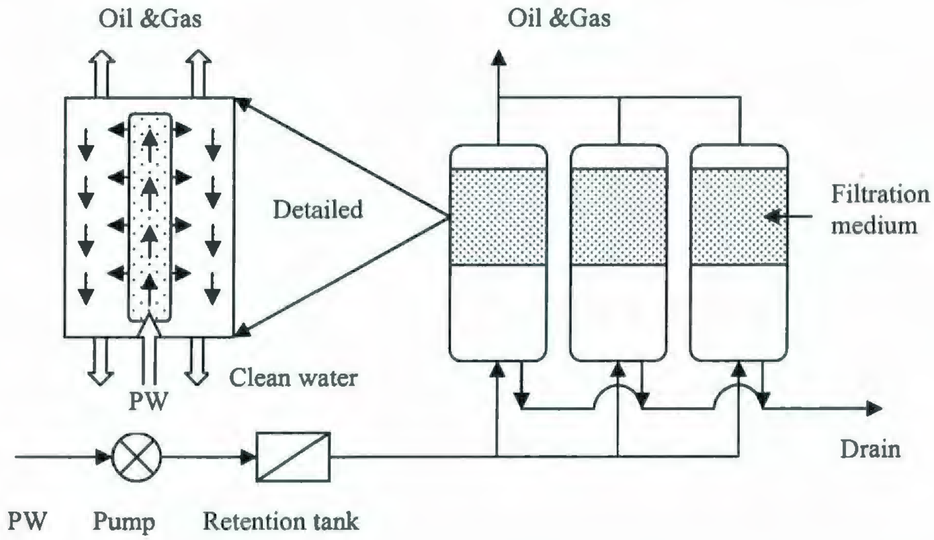

Figure 2.11: Process diagram of TORR technique (modified from Plebon et al., 2005)

The technology has the ability to treat PW with oil concentrations in the range of 150 mg/L down to an average of 3 mg/L, without being affected by sudden flow surges and fluctuations in feed oil concentrations (Plebon et al., 2005). During testing the technology has shown superior control in managing and optimizing PW treatment (Plebon et al., 2005). The volumes of oily water to be treated depend on the transformation of the oil droplets and the recovery of oil. The self-cleaning action of the media (absorption /de-sorption process) allows continuous operation over extensive periods. The treated PW from the demonstration unit is sent to an existing holding tank prior to discharge. Figure 2.11 describes the main components of the technology. An API type separator is generally used to separate oil from the water. The technology has the capacity of performing multi-phase separation by incorporating the physical principles of adsorption, coalescence, desorption and gravity separation in each treatment stage. The technology can treat PW from a wide range of production processes. Crude oil characteristics, PW properties, solids loading, and chemical processes play a major factor in the performance of the technology.

The drawback of the technology is that it requires adequate solids removal systems, to prevent particles larger than 10 microns. The oil coalescing properties should be maintained frequently, increasing the maintenance cost.

2.3 Summary

The management of PW depends on the selection of appropriate technology or system of technologies. Removal of suspended solids, oil and grease is the first step of the treatment process. The primary separation can be accomplished by either mechanical or gravity separation. For offshore installation a mechanical separator like centrifuge/hydrocyclone is more effective than gravitational separation. To meet regulatory discharges several standard integrated systems have been developed which described in the previous section. The summary of integrated systems is reported in Table 2.4. In MPP process the hydrocarbon-contaminated water is passed through a column packed with MPP particles beads, which contain a specific extraction liquid. The main advantage of this process is regeneration of the extraction liquid. It has good pollutants' removal efficiency.

Table 2.4: Summary of PW management systems

PW Management Method	Description	Advantages	Disadvantages
Hydroclone	A device of cylindrical construction that is fitted with one or more tangential inlets which cause the fluid entering the cyclone to follow a circular path around the wall of the process. Rotation of the fluid generates a centripetal acceleration field that separates heavier water and solids.	Capable of reaching low levels of free oil below 10 ppm. Low space requirements.	Highly soluble oil components such as naphthenic acids are not removed. Not permit effluent oil and grease limitations.
CFU	(CFU) is the combination of a hydrocyclone and flotation unit. Several combined processes, including gas flotation and induced centrifugal inertia forces, act on the fluid components of different specific gravities.	The CFU treatment system is especially suitable for removing hydrocarbons, aromatic compounds and small particles from PW.	Large footprint weights.
C-Tour	The C-Tour Process enhances the traditional hydrocyclone process by injection of a solvent, i.e., condensate or Natural Gas Liquid (NGL), into upstream water of the hydrocyclone.	It can achieve an oil-in-water content of 1-4 ppm, and also remove dissolved components such as BTEX, PAH etc.	It is suitable for treating large volumes of PW. High cost
Re-injection of PW	Combination of hydrocyclone and re-injection pumps. In this system PW and sea water are mixed and injected under high pressure to the production aquifers or another suitable zone	Removes BTEX, PAHs, dissolved and dispersed hydrocarbons from PW.	Costly and generates high air emissions.
DOWS	In this system oil and water mix is separated at the bottom of the production well by means of a hydrocyclone.	Reduces PW production, by this way it reduces, depressed oil 50%, BTEX 50%, NPD 50%, and PAH 50%.	DOWS installations are expensive and not cost effective for all wells
Steam Striping	Combination of gravity separation + steam/air stripping. The removal is accomplished by passing air or steam through the agitated waste water stream.	Remove BTEX, PAHs, dissolved and dispersed hydrocarbons from PW.	Highly soluble oil components such as naphthenic acids, are not removed.
MPPE Technology	Developed by Akzo Nobel, is an integral system that makes use of Macro Porous Polymer-Extraction.Used for removal of dissolved and dispersed hydrocarbons at commercial scale from offshore produced water.	Used for removal of dissolved and dispersed hydrocarbons 99.99%.and based on an extraction liquid immobilization in an MPP bed.	Costly for small production

However by-products solids and liquids are toxic. Reinjection of PW is commercially practiced but this system consumes high energy and emissions are noticeable. The stripping system uses gravitational separator to separate suspended solids and oils. Pollutants removal is accomplished by passing air or steam through the agitated waste water stream. The removal efficiency of this system is also high, but packing materials require frequent cleaning that increase operational cost. The C-Tour process utilizes liquid condensate from the gas scrubbers and injects it into the PW upstream of the hydro cyclones. The dispersed and dissolved hydrocarbons, which have higher solubility, are separated by the hydrocyclone. This equipment is in the development stage. The process is very sensitive to the available condensate quality and can be considered as an emerging technology.

TORR is the new technology still under development. This is based on the filtration, coalescence and gravity separation processes. The multi-stage separation system is able to remove gas, and free floating and emulsified oil from PW. The test results of this system have shown good performance in PW cleaning. It can be considered as a future candidate for PW management.

Chapter 3

REVIEW OF MULTI-CRITERIA DECISION MAKING TECHNIQUES

Decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision maker. MCDM analysis is a method widely used in decision making problems that covers most of the economical, industrial, financial or political decisions that are of a multi-criteria nature (Lahdelma et al., 2000). The aim of MCDM analysis is to recommend an action, where the several alternatives can be evaluated in terms of many criteria. This compromised solution depends strongly on the decision maker's personality, on the circumstances of the decision aiding process, on the way the problem is presented and on the method that is used (Vincke, 1992). Two key advantages of MCDM are that it allows greater stakeholder involvement and provides greater transparency to the decisions being made at all levels of appraisal (RPA 2004). This chapter reviews widely used MCDM methods, and selected the most appropriate MCDM methods for the present study.

3.1 Introduction of multi-criteria decision making

According to Lahdelma et al. (2000), MCDM is characterized by methods that support planning and decision processes through collecting, storing and processing different kinds of information to construct a viable idea of how to solve a multi-criteria problem. MCDM is a mathematical model and also a systematic procedure which helps in the comprehensive comparisons between potential actions and provides compromised solutions considering economic, environmental, technological, and socio-cultural related factors. MCDM methods are suitable for a wide variety of decision situations. Furthermore, several weighting techniques have been developed to help decision makers in articulating their preferences. However, certain structural elements are common in the MCDM method.

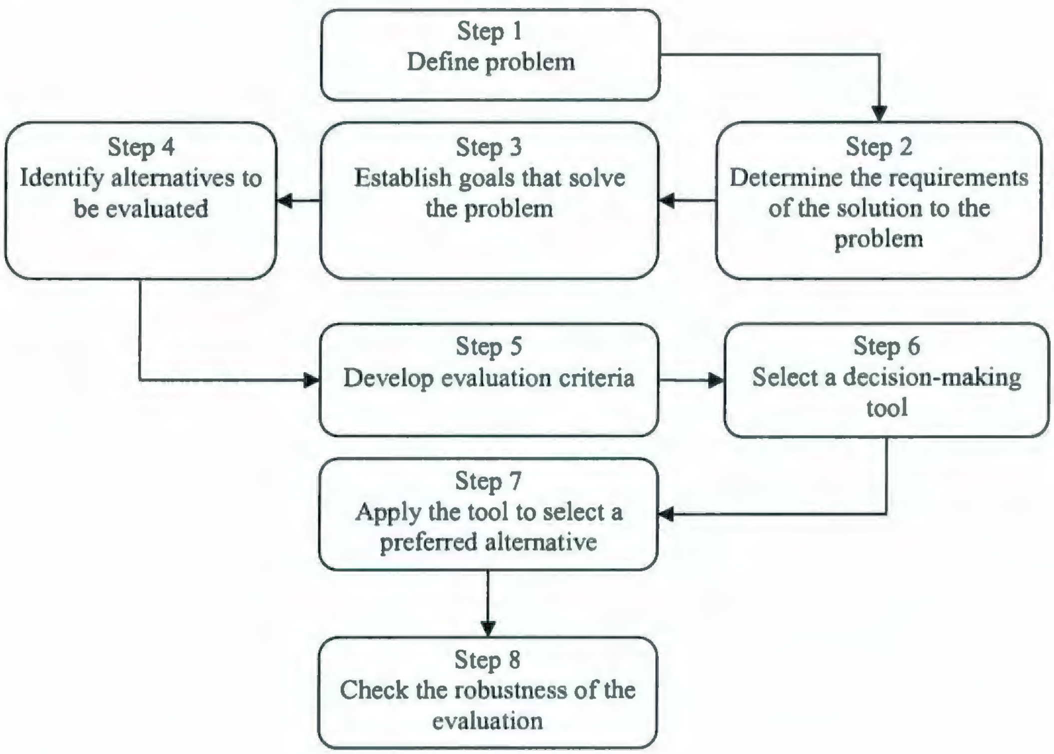

Figure 3.1: General decision making process (Baker et al. 2001)

According to Baker et al. (2001), decision making should start with the problem identification and discussions between decision makers and stakeholders that reduce the possible disagreement about goals and criteria. The core structural elements in the

MCDM problem are the set of alternative actions and their criteria in line with which these actions have to be evaluated.

However, there are a number of structural and external characteristics that go beyond the definition of these basic elements. There are several approaches available to help these characteristics in a consistent and systematic way. According to Baker et al. (2001), a MCDM approach proceeds step-wise, typically with active involvement of decision makers and stakeholders. Figure 3.1 shows the fundamental steps involved in the MCDM process.

Step 1 Define the problem

This process involves defining the problems and goals, limiting assumptions to achieve the goals, system and organizational constraints, and stakeholder issues and involvement. The problem definition must be a concise and unambiguous and agreed upon by all decision makers and stakeholders. It is a crucial and necessary step before proceeding to the next step.

Step 2 Determine requirements

Requirements are conditions that any acceptable solution to the problem must meet. In mathematical form, these requirements are the constraints describing a set of feasible solutions. It is important that even if subjective or judgmental evaluations may occur in the problem, the requirements must be stated in the exact quantitative form.

Step 3 Establish goals

Goals are broad statements of intent and desirable programmatic values (Baker et al. 2001).The goals may be conflicting but this is natural in practical decision-making situations.

Step 4 Identify alternatives

Alternatives offer different approaches for changing the initial condition into the desired condition (Baker et al. 2001). Alternatives must meet the requirements. If there are possible alternatives, these should be screened one by one to check the requirements and to screen out infeasible alternatives from further consideration.

Step 5 Define criteria

Criteria are the controlling factors that represent the decision makers' or other stakeholders' points of view required to establish adequate comparisons of alternatives (Bouyssou, 1986).A consistent set of criteria should avoid redundancy but must be exhaustive and covering issues by all parties. Decision criteria, which will be discriminated from alternatives, must be based on the goals (Baker et al., 2001).It is usual to arrange the groups of criteria, sub-criteria, and sub-sub-criteria in a tree-structure (UK DTLR, 2001). Grouping criteria can help in the process checking; calculating weights in some methods, and facilitating the emergence of higher level views of the issues (UK DTLR, 2001). Keeney and Raiffa (1976), Keeney (1992), and Saaty (1980) suggested a hierarchical way of constructing the criteria structure. The bottom-up and top-down approaches can be used to identify the set of criteria (Lahdelma et al., 2000). The bottom up approach is used to identify the set of criteria in decision aid studies. According to Baker et al. (2001), and Keeney and Raiffa (1976) the criteria should be complete, meaningful, non-redundant, and manageable.

Step 6 Select a decision making tool

The selection of an appropriate tool is not an easy task and depends on the concrete decision problem, as well as on the objectives of the decision makers. According to Lahdelma et al. (2000) the method that suits most of the following objectives should be considered:

- It should be easy to understand
- The approach should be capable to support the necessary number of decision makers
- It should be able to manage the number of alternatives
- The methodology should be able to handle inaccurate and uncertain information
- The methodology should cover the lowest need of preferences from the decision makers.

Step 7 Evaluate alternatives against criteria

To evaluate the alternatives against the criteria requires input data. Depending on the criteria, the assessment may be objective, or it can be subjective (judgmental), reflecting the assessment of the evaluator. The selected decision making tool can be applied to rank the alternatives or to choose a set of most promising alternatives.

Step 8 Validate solutions based on problem statement

The selected alternatives always have to be validated against the requirements and goals of the decision problem. In complex problems the selected alternatives may also call the attention of the decision makers or stakeholders.

3.1.1 Structure of the MCDM problem

A general MCDA problem can be expressed in matrix form as:

$$D = \begin{array}{c c} & \begin{array}{cccc} A_1 & A_2 & \cdots\cdots & A_m \end{array} \\ \begin{array}{c} X_1 \\ X_2 \\ . \\ X_n \end{array} & \begin{bmatrix} C_{11} & C_{12} & \cdots\cdots & C_{1m} \\ C_{21} & C_{22} & \cdots\cdots & C_{2m} \\ . & . & . & . \\ C_{n1} & C_{n2} & \cdots\cdots & C_{nm} \end{bmatrix} \end{array} \tag{3.1}$$

$$w = [w_1, w_2, \ldots\ldots\ldots, w_n]$$

Where

A_i; $i = 1, 2. . . , m$ denote the alternatives;

X_j; $j = 1, 2. . , n$ represent attributes or criteria;

C_{ij} = Crisp or fuzzy values indicating the performance rating of each alternative A_i with respect to each criterion X_j.

w_j; $j = 1, 2, ..., n$ are the weighting factors and represent relative importance of the criteria

The practical assessment of C_{ij} is critical due to unquantifiable, incomplete and non obtainable information and partial ignorance. The unquantifiable information leads to subjective rankings, for examples good, poor, high, low, etc. These subjective rankings lead to vagueness and uncertainty in the decision-maker's judgment. This limitation in

MCDM methods can be addressed through fuzzy based approaches. The strength of the MCDM methodology lies in the dynamic connection of all the steps described in the previous section, however, a formal description of the available MCDM tools that have been broadly used in decision making problems is discussed below.

3.2 Fuzzy multiple criteria decision making

The MCDM tools, which are commonly used in decision making problems, are based on crisps values. The main limitations of these techniques are that, they can not handle the vagueness and uncertainty in the decision-maker's judgment. This limitation in MCDM methods has lead to a fuzzy based approach. The proposed MCDM approach is fuzzy composite programming involving the extension of a analytical hierarchy process called fuzzy analytical hierarchy process (FAHP). The following section describes the details of the proposed approach.

In (1965) Zadeh presented fuzzy sets theory and Bellman and Zadeh (1970) applied this theory to MCDM problems. There has been a great deal of literature and books in this field in the last two decades, such as Chen et al. (1992) and Zimmerman (1985; 1987).

Fuzzy Multiple Criteria Decision Making (FMCDM) basically comprises two phases (Dubois and Prade, 1980) Phase 1 aggregates the performance score with respect to each alternative/strategy, and in Phase 2 all alternatives are ranked according to their synthetic value (or utility value) from Phase 1. The hierarchical process of FMCDM can be summarized as follows:

Step 1 Define the nature of the problem;

Step 2 Construct the hierarchy system for evaluation (Figure, 3.2);

Step 3 Select the appropriate evaluating method;

Step4 Determine the relative weights or performance score of each criterion when necessary.

Step 5 Calculate the synthetic utility values, which are the aggregation value of relative weights and performance scores corresponding to alternatives;

Step 6 Rank the alternatives referring to their synthetic utility values from step. 5.

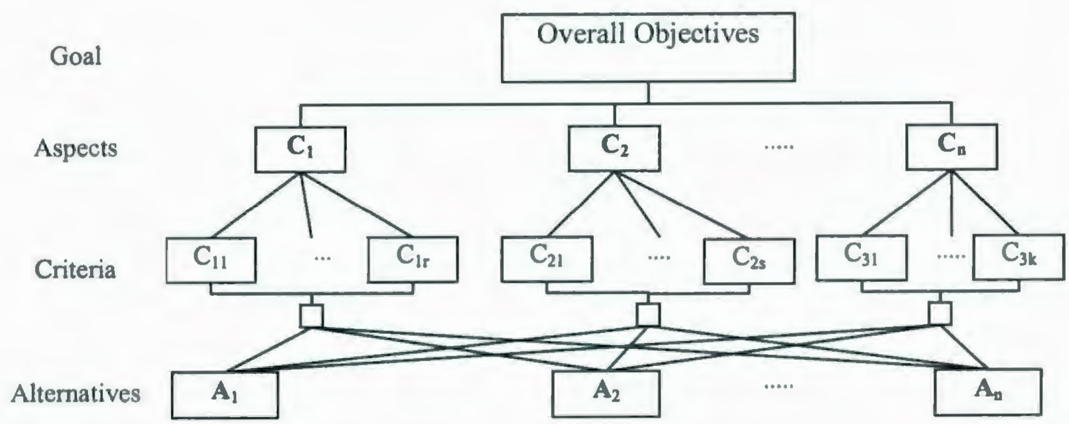

Figure 3.2: Hierarchy system for FMADM

3.2.1 Classification of Fuzzy MCDM Methods

The taxonomy of fuzzy MCDM methods is shown in Figure 3.3. Chen et al. (1992) have classified MCDM models based on the following four stages:

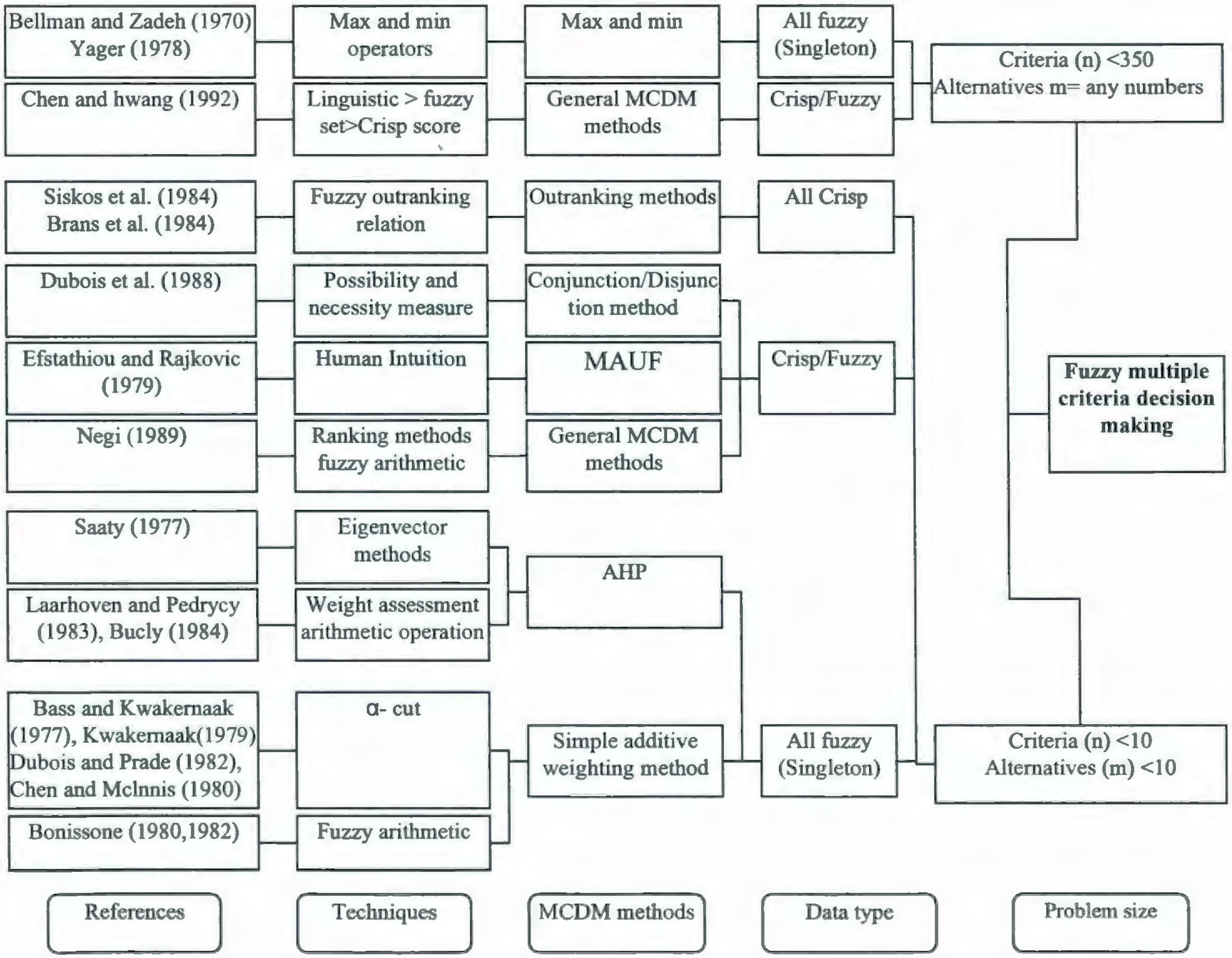

Figure 3.3: Taxonomy of fuzzy MCDM methods adopted from (Chen et al., 1992)

1. Problem size;

2. Data type;

3. MCDM methods; and

4. Techniques

1. According to Chen et al., (1992) fuzzy methods are suitable for alternatives and attributes less than 10, and

2. The data could be in the form of (a) all fuzzy, (b) all fuzzy singletons (single value and its corresponding membership function), (c) all crisp and (d) mixture of fuzzy and crisp.

3. The concepts of fuzzy methods are derived from classical methods of MCDM: simple additive weighting (SAW), analytical hierarchy process (AHP), multiple attribute utility functions (MAUF), etc.

4. The final stage provides the techniques required for applying fuzzy MCDM methods that include the α-cut method, fuzzy arithmetic operations possibility and necessity measures, eigenvector method etc. The details of references and sources of these approaches can be seen in Chen et al. (1992).

3.2.2 Concept of fuzzy set

A major contribution of the fuzzy set theory is its capability of representing vague data. A fuzzy set is a class of objects with a continuum of grades of membership. A fuzzy set is characterized by a membership function which assigns to each object a grade of membership ranging between zero and one (Zadeh, 1965).

Fuzzy Numbers

Fuzzy numbers are the special classes of fuzzy quantities. A fuzzy number is characterized by a given interval of real numbers, with a membership function between 0 and 1 (Deng, 1999).

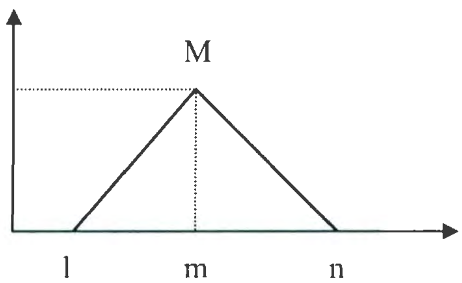

Figure 3.4: Construction of triangular membership function.

Triangular fuzzy numbers (TFN) M, shown in Figure 3.4 are defined by three real numbers, expressed as (l,m,u). The parameters l, m, and u, respectively, indicate the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event. The TFNs can be described as;

$$\mu_a(x) = \begin{cases} (x-l)/(m-l), & x \le m, \\ (u-x)/(u-m), & m \le x \le u, \\ 0, & otherwise \end{cases} \tag{3.2}$$

In applications it is convenient to work with TFNs because of their computational simplicity, and they are useful in promoting representation and information processing in a fuzzy environment. In this study TFNs are applied to calculate the relative importances of criteria.

Algebraic Operations on TFNs

When using fuzzy sets in applications, the algebraic operations deal with fuzzy numbers. There are various operations on TFNs, but only three important operations are used in this study. For example, two TFNs A and B are defined by the triplets $A = (l_1, m_1, u_1)$ and $B = (l_2, m_2, u_2)$, then

- Addition:

$$A + B = (l_1, m_1, u_1) + (l_2, m_2, u_2) \tag{3.3}$$
$$= (l_1 + l_2, m_1 + m_2, u_1 + u_2)$$

- Multiplication:

$$A.B = (l_1, m_1, u_1).(l_2, m_2, u_2) \tag{3.4}$$
$$= (l_1.l_2, m_1.m_2, u_1.u_2)$$

- Inverse:

$$(l_1, m_1, u_1)^{-1} \approx (1/u_1, 1/m_1, 1/l_1) \tag{3.5}$$

3.2.3 Conversion of linguistic variables to fuzzy numbers

Linguistic variables are values that are not numbers but words or sentences in a natural or artificial language (Kickert and Walter, 1978). In environmental and social studies, most of the information is imprecisely defined due to the unquantifiable nature of data or lack of proper knowledge. The experts often use linguistic scales (high, moderate, low or very good, good, and bad etc.) to express the existing scenarios. Chen et al. (1992) has defined eight scales to convert linguistic terms into fuzzy numbers. Three important scales are reported in Figure 3.5 (a), Figure 3.5 (b) and Figure 3.5 (c). The first scale has 3 levels, whereas the second and third scales contain five levels. The linguistic terms for the first scale are "low", medium" and "high". In the second and third scales, two additional degrees - "very low" and "very high" and “medium low” and “medium high” respectively - are introduced. The same linguistic terms contain different meaning at different scales. For example “high” in the first scale means [(0.6, 0), (0.8, 1.0), (1.0, 1.0), (1.0, 0)] i.e. the most likely interval is between 0.8 and 1.0 (when the membership function μ is 1) and the largest likely interval is in between 0.6 and 1.0 (when the membership function μ is 0). But in the second scale the “high” means be [(0.6, 0), (0.70, 1.0), (0.9, 0)]. This reflects the fact that the same linguistic terms may possess different meanings for different occasions.

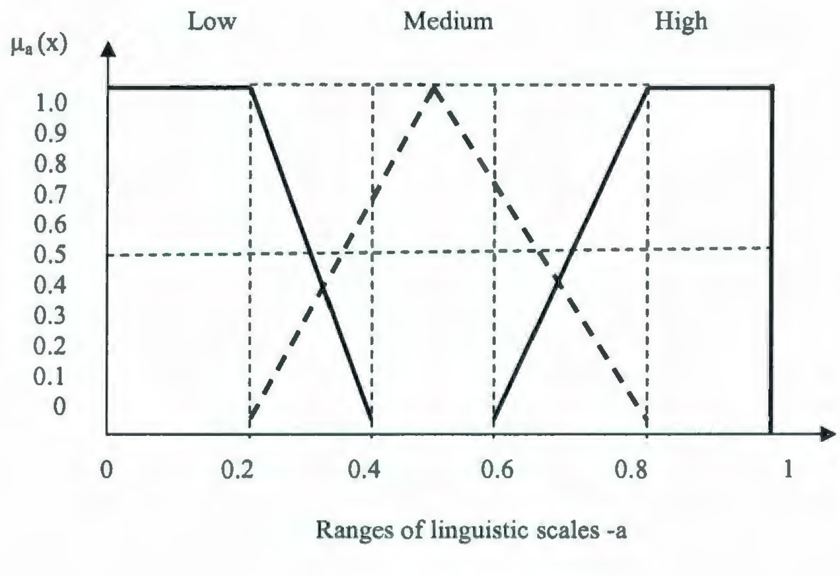

Figure 3.5(a): Conversion scales of linguistic terms into numerical scores

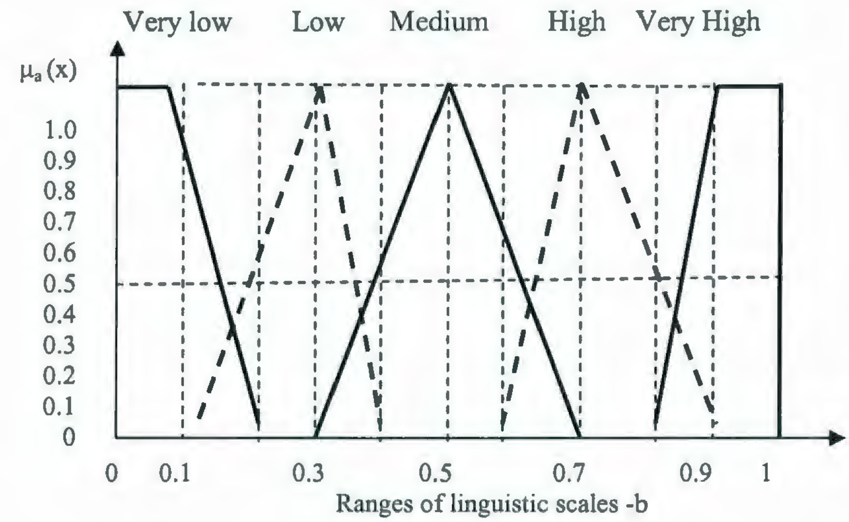

Figure 3.5(b): Conversion scales of linguistic terms into numerical scores

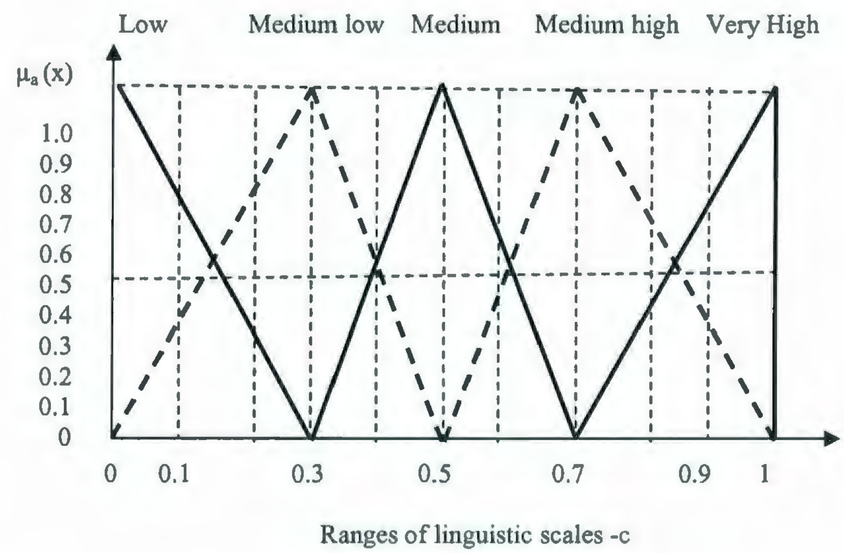

Figure 3.5 (c): Conversion scales of linguistic terms into numerical scores

3.2.4 Fuzzy ranking methods

In general, the MCDM method assumes all performance ratings (C_{ij}) and relative importance of attributes (W_j) are crisp values. A utility function $U(x_1, x_{2,...,}x_m)$ is defined by the C_{ij} and W_j values. For alternatives A_i, the utility function aggregates its performance ratings into a final rating. This final rating determines how well one alternative satisfies the decision-maker's utility. The alternatives with higher final ratings are said to be preferred alternatives.

The alternative performance rating C_{ij} can be crisp, fuzzy, and/or linguistic. When fuzzy data are incorporated into MCDM problems the final ratings are no longer crisp numbers, rather they are fuzzy numbers. It is not straightforward to compare the alternatives with fuzzy numbers. In MCDM applications when the final ratings are fuzzy, different ranking methods can be used to compare these fuzzy utility values. Chen et al. (1992) have classified fuzzy methods into four major groups as shown in Figure 3.3. Fuzzy scoring techniques are the most popular in defining left/right scores of TFN. There are several methods widely used in defining the scores of TNF such as, Chen's ranking method (1985), Yager's (1980, a b) centroid value method, alpha cut methods etc. Details of these methods are given in the next section.

Chen Ranking Method (1985)

The Chen ranking method (1985) is based on left and right scores of the membership function. The left and right scores refer to the intersection of a fuzzy number M with the

Chen fuzzy min and Chen fuzzy max respectively. Figure 3.6 illustrates the details of Chen's fuzzy min and Chen's fuzzy max.

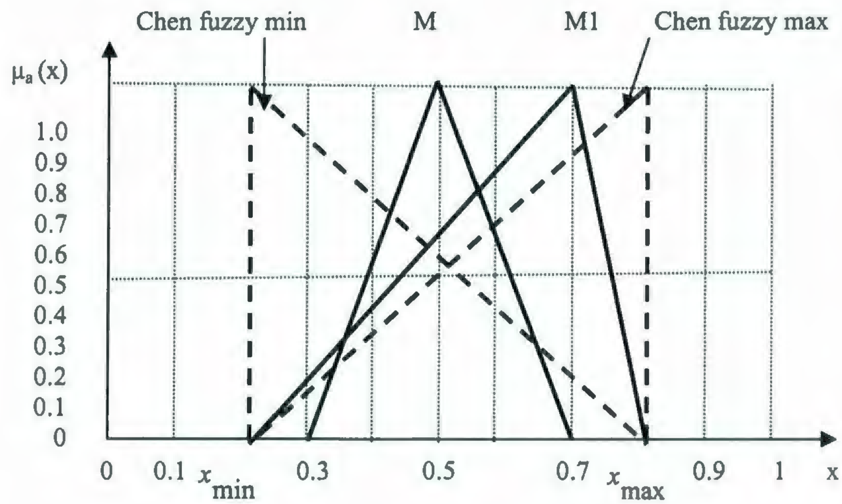

Figure 3.6: Chen ranking method applied to TFNs

The maximizing set is a fuzzy subset with membership function $\mu_{max}(x)$ defined as:

$$\mu_{\max}(x) = \left[\frac{x - x_{\min}}{x_{\max} - x_{\min}}\right]^k, \quad k > 0 \quad x_{\min} \le x \le x_{\max} \tag{3.6}$$

Where k is an integer indicating the decision maker's attitude towards risk; and x_{min} and x_{max} are the minimum and maximum numbers at the supports set of M. Then the right score $\mu_L(R)$ for M is defined as the intersection of a fuzzy number M with the Chen fuzzy max as follows:

$$\mu_L(R) = \frac{\sup}{x}[\mu_a(x)^{\wedge}\mu_{\max}(x)] \tag{3.7}$$

The minimum set is a fuzzy subset with membership function $\mu_{min}(x)$ defined as:

$$\mu_{min}(x) = \left[\frac{x - x_{max}}{x_{min} - x_{max}}\right]^k, \quad x_{min} \leq x \leq x_{max} \tag{3.8}$$

The left side score $\mu_L(L)$ for M is defined as the intersection of a fuzzy number M with the Chen fuzzy min as follows:

$$\mu_L(L) = \frac{\sup}{x}[\mu_a(x)^\wedge \mu_{min}(x)] \tag{3.9}$$

Where, $\frac{\sup}{x}$ = intersection point between two lines and $\mu_a(x)$ = membership value of fuzzy number M.

Finally the total scores are defined as $\mu_L(T)$ and can be computed as:

$$\mu_L(T) = [\mu_L(R) + 1 - \mu_L(L)]/2 \tag{3.10}$$

Chen et al. (1992) Method

To convert fuzzy number to crisp scores, Chen et al. (1992) introduced a numerical approximation conversion scale. This is a modification of the Chen (1985) fuzzy ranking approache. The left and right scores refer to the intersection of a fuzzy number M with the fuzzy min and fuzzy max respectively. Figure 3.7 illustrates the details of the fuzzy min and fuzzy max.

The method can be described as:

The maximizing and minimizing sets are fuzzy subsets with membership functions defined as:

$$\mu_{\max}(x) = \begin{cases} x, & 0 \le x \le 1 \\ 0, & \textit{Otherwise} \end{cases} \tag{3.11}$$

$$\mu_{\min}(x) = \begin{cases} 1-x, & 0 \le x \le 1 \\ 0, & \textit{Otherwise} \end{cases} \tag{3.12}$$

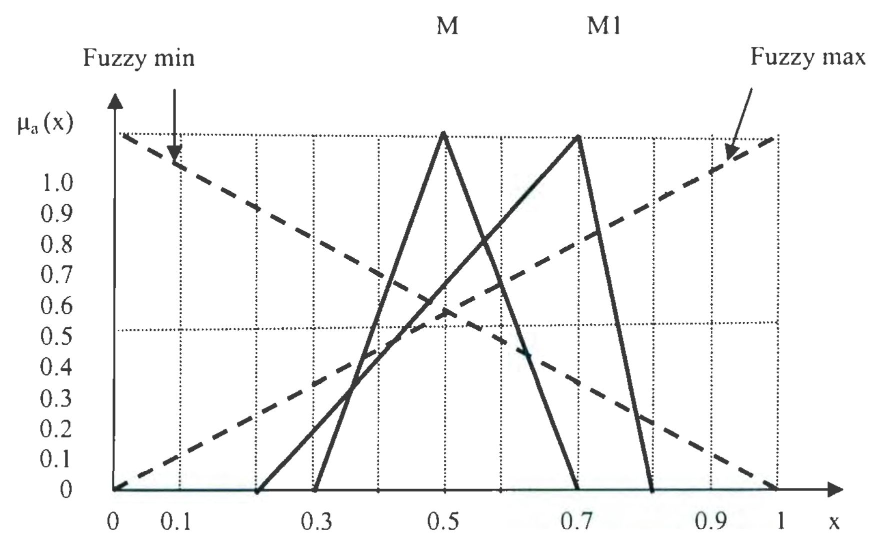

Figure 3.7: Left and right score of Chen et al. (1992) method

The crisp score of fuzzy number M can be obtained by the intersection of M with the fuzzy min $\mu_{\min}(x)$ and fuzzy max $\mu_{\max}(x)$ respectively as follows.

The right leg score of $\mu_L(R)$ can be determined as:

$$\mu_L(R) = \frac{\sup}{x}[\mu_a(x)^{\wedge}\, \mu_{\max}(x)] \tag{3.13}$$

The left leg score of $\mu_L(L)$ can be determine using

$$\mu_L(L) = \frac{\sup}{x}[\mu_a(x)^\wedge \mu_{\min}(x)] \tag{3.14}$$

Finally the total score $\mu_L(T)$ can be computed as:

$$\mu_a(T) = [\mu_L(R) + 1 - \mu_L(L)]/2 \tag{3.15}$$

Yager's Centroid Index Ranking Method (1980b)

This method determines the centroid of the fuzzy number as follows:

$$x_0 = \frac{\int_0^1 g(x)\mu_i(x)dx}{\int_0^1 \mu_i(x)dx} \tag{3.16}$$

Where g(x) is treated as a weight function that measures the importance of the value x. The denominator serves as a normalizing factor whose value is equal to the area under the membership function μ_i. When g(x) = x (linear weight), equation 3.16 gives the x_o, (geometric centre).The value of x_o is the weighted mean value of fuzzy number L(x) and higher x_o values are considered better. Figure 3.8 shows the concept of centroid point of fuzzy numbers M_l and M. Since $X_{Ml} > X_{M;}$ M_l is representing better that M. When both fuzzy numbers have the same centroidal distance, a fuzzy number with a larger mean and smaller spread should be the higher ranked (Lee and Li, 1988).

For example assuming g(x) = x, the crisp values of fuzzy number M shown in Figure 5.8 can be determined as follows:

$$\mu_M(x) = \begin{cases} \dfrac{x-0.2}{0.1}, & 0.2 \le x \le 0.3....(Left \quad leg) \\ \dfrac{0.5-x}{0.2}, & 0.3 \le x \le 0.5....(Right \quad leg) \end{cases}$$

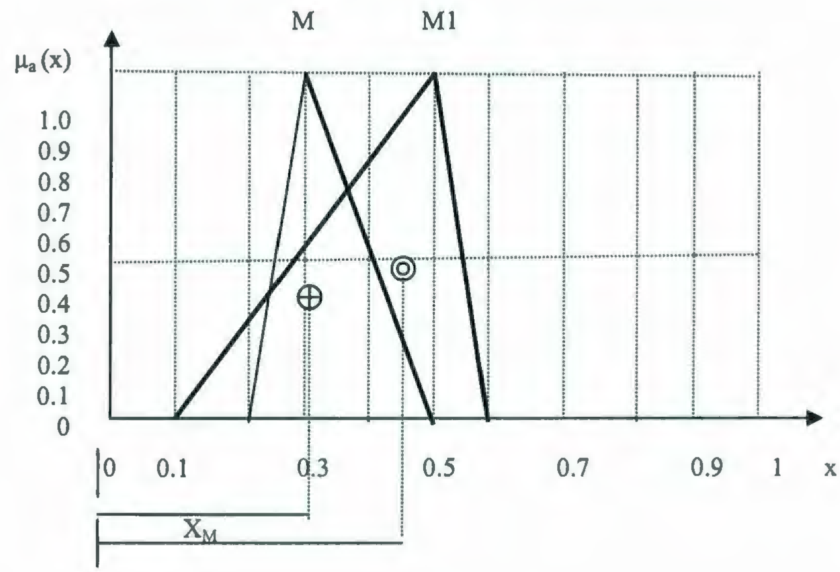

Figure 3.8: Centriod point of fuzzy numbers M and M_1

Ranking using α- cuts

According to Wang (1997), in order to make crisp scores among the alternatives, an α-cuts based method can be used for checking and comparing fuzzy numbers. According to Adamo (1980) the α-cut methods depends on the alpha values which are called α-preference indexes. The decision maker is to specify the minimum acceptable degree of α for a fuzzy set. The fuzzy sets with higher α-cut values are considered better (Chen et al., 1992). Mabuchi (1988) used the α-cut method to derive the degree of dominance of one fuzzy set over another. According to Buckley (1987) the α- cuts method can be stated as:

If A and B be fuzzy numbers with α-cuts, $A_\alpha = [a_1, b_1]$ and $B_\alpha = [a_2, b_2]$ then the ranking order can be determined by the condition;

$A > B$ if $a_1 > b_2$ (3.17)

For example as shown in Figure (3.9) if we set α-cut =0.9 then A_α left and A_α right can be calculated as:

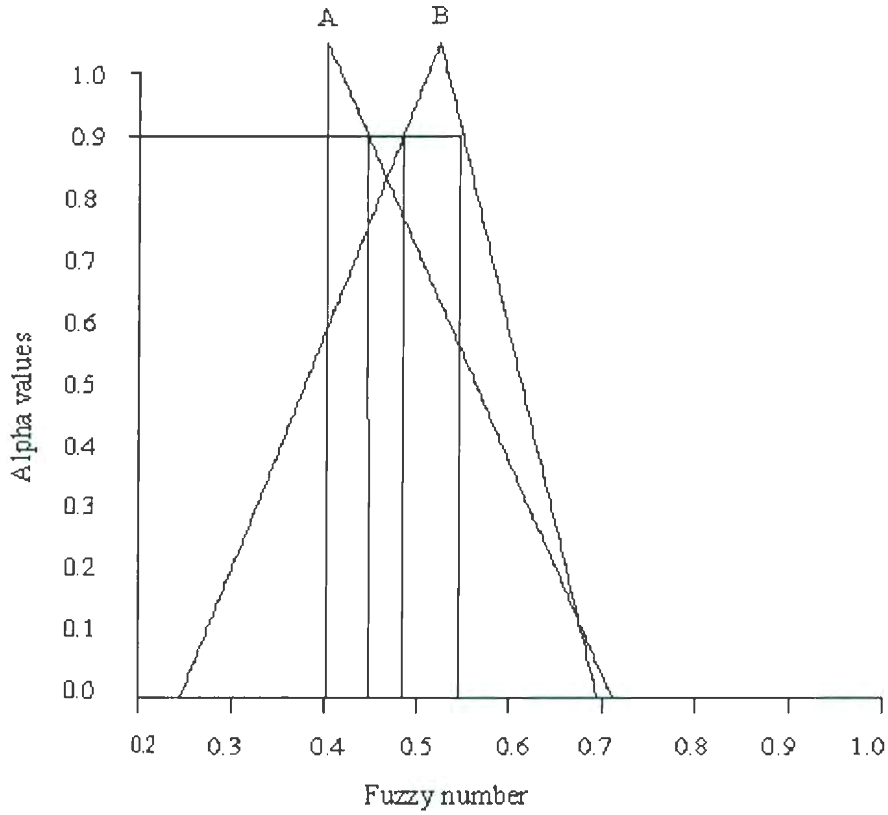

Figure 3.9: Principle of alpha cut method

$A_{0.9}$ = [0.4, 0.44] and similarly at $B_{0.9}$ = [0.48, 0.52]. Based on equation 3.17 B>A, because $a_2 = 0.48 > b_1 = 0.44$.

Jie et al. (2006) applied alpha cut analysis to transform the total weighted performance matrices into interval performance matrices. According to the Jie et al. (2006) the alpha left and alpha right values can be calculated as follows:

$$\alpha_{Left} = [\alpha * (m-1) + 1] \tag{3.18}$$

$$\alpha_{Right} = n - [\alpha * (n-m)] \tag{3.19}$$

Where the parameters l, m, and n, respectively, indicate the smallest possible value (left), the most promising value (middle), and the largest possible value (right) of a fuzzy TFN. The alpha cut analysis introduces two values, namely alpha right (maximum range) and alpha left (minimum range) which need to be converted into crisp values (Jie et al., 2006). It can be done with the lambda function, which represents the attitude of the decision maker. Jie et al. (2006) suggested the range of the lambda (λ) function to be 0 to 1. According to Jie et al. (2006) the attitude of the decision makers may be optimistic, moderate or pessimistic. A decision maker with an optimistic attitude will take the maximum values of the range; the moderate person will take the medium value and the pessimistic person will take the minimum value of the range. After assigning the λ values the crisp scores can be computed by the equation 3.20 (Jie et al., 2006).

$$C_{i\lambda} = \lambda * \alpha_{Right} + \lfloor (1-\lambda) * \alpha_{Left} \rfloor \tag{3.20}$$

Where $C_{i\lambda}$ is the crisp score of i^{th} criteria

The crisp values need to be normalized, because the elements of the pair wise comparison matrix (PCM) do not have the same scale. The normalization can be done by the equation (3.21)

$$C_{i\lambda}^{T} = \frac{C_{i\lambda}}{\sum C_{i\lambda}} \tag{3.21}$$

Where $C_{i\lambda}^{T}$ is the normalized crisp score of i^{th} criteria.

3.2.5 Weighting methods

Assigning weights is an important process as it can make a significant difference in the results (Hobbs and Meier, 2000). According to Hobbs and Meier (2000), weights should be constant with tradeoffs that decision makers are willing to make among criteria. In other words, weights should represent the value that the decision maker willingly trades off one criterion for another or the relative importance of unit changes in the criterion values. Different weighting methods can possibly give different weights and in turn, different results (Hobbs and Meier, 2000). Commonly used weighting methods are described below:

Equal weights

In this method all criteria are considered equally important thus equal weights are assigned to all of them. This method is the simplest; however, it is not quite realistic that all the criteria have the same importance (Hobbs and Meier, 2000).

Direct weighting method

Using this method, the decision makers directly assign weights according to their judgment. This method is simple but requires careful attention. There are various ways to directly assign weights, point allocation, categorization of criteria based on their importance, ranking before assigning weights, defining ratios of importance of each pair of criteria, and rating or scaling the criteria (Hobbs and Meier, 2000). In case of a large number of criteria, a "hierarchical approach" can be applied to help in this process (Hobbs and Meier, 2000). In a hierarchical process, criteria are grouped into major categories and weights are then assigned to each criterion. This method is better than the non-hierarchical method and provides more variable weights. However, the structure of the hierarchy can affect the defined weights (Hobbs and Meier, 2000).

Swing weights Method

The swing method was first introduced by Von and Edwards (1986). Using this method, criteria are compared by considering a hypothetical alternative which has been assigned the worst values for all criteria (Hobbs and Meier, 2000). Another hypothetical alternative is then set up that would be improved. This criterion is then given a swing weight of 100. Team members similarly select the next criterion and determine the relative importance of swinging, and order the first criterion over second one. The process is then repeated until all criteria have been ordered. After ranking the alternatives according to preference, weights are then assigned to alternatives such as 100 are assigned to the most preferred alternative and zero is assigned to the worst (Von and

Edwards, 1986). The weights are then normalized to obtain total weights of one (Baker et al., 2001). This method is not too difficult for decision makers (Hobbs and Meier, 2000).

The Analytic Hierarchy Process (AHP; Saaty, 1980)

The Analytic Hierarchy Process (AHP) is a powerful technique that has proven to be useful in structuring complex MCDM problems in engineering, economics and social sciences. This popular process was introduced by (Saaty 1977, 1980). Since its introduction, the AHP has become one of the most widely used MCDM methods, and has been used to solve unstructured problems in different areas of human needs and interests, such as political, economic, social and management sciences (Modarres 2006). AHP is a quantitative comparison method used to select a preferred alternative by using pair-wise comparisons of the alternatives based on their relative performance against the criteria.

Table 3.1: The pair-wise comparisons preference index scale

How important is *A* relative to *B*?	**Preference index assigned** Adopted (Saaty 1980)
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Overwhelmingly more important	9

The method requires decision maker comparison for every possible pair of criteria and provides their importance ratio (Hobbs and Meier, 2000). The pair-wise comparisons can be made using a nine-point preference index scale as shown in Table 3.1 where "1" represents that two criteria are equally important, while the other extreme "9" represents that one criterion is absolutely more important than the other, the values 2, 4, 6 and 8 are intermediate values that can be used depending on judgement (Saaty 1980). Using the scales of importance, the pair wise comparison for priority of different hierarchy level attributes is performed and the relative matrix is formed. The pair wise comparison matrix (PCM) is developed by defining the weight for each pair denoted by w_i for i^{th} pair and a vector W is defined such that

$$W = (w_1, w_2, w_3 ....w_n)$$

Where

$$\sum_{m=1}^{n} w_m = 1 \qquad (3.22)$$

With n criteria, a 1/2{n (n-1)} comparisons matrix can be conducted. The PCM can be solved by using eigen values (Michael et al., 2000). For example, if the PCM is 'A' then the eigen values can be written as:

$$\overline{A}\,\overline{W} = \lambda\,\overline{W} \qquad (3.23)$$

Where $\overline{A}$ = the binary importance matrix,

$\overline{W}$ = weight vectors and

λ = eigen values. The equation 3.23, can be written in the following general form

$$\begin{bmatrix} 1 & 1/c_{12} & .... & 1/c_{n1} \\ c_{12} & 1 & .... & 1/c_{n2} \\ . & . & . & . \\ c_{n1} & c_{n2} & .... & 1 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ . \\ W_n \end{bmatrix} = \lambda_{max} \begin{bmatrix} W_1 \\ W_2 \\ . \\ W_n \end{bmatrix} \tag{3.24}$$

Where, c_{ij} is the pair wise comparison of the criteria. Each element of the lower triangle in the matrix is reciprocal to the upper triangle (Saaty, 1980). The solution to equation (3.24) yields the eigenvector matrix $\overline{W}$, which represents the normalized weights for the criteria.

It is necessary to estimate the consistency of the judgment matrix. To do this, it is necessary to find its consistency index (CI), average CI and consistency ratio (CR), which can be defined (Saaty, 1980) as:

$$C.I = \frac{\lambda_{max} - n}{n-1} \tag{3.25}$$

$$C.R = \frac{C.I}{R.I} \tag{3.26}$$

Where C.I = consistency index, C.R = consistency ratio, λ_{max} = maximum eigen value, n = number of parameters in the matrix, and R.I = random index. Saaty (1980) suggested the R.I values given in Table 3.2.

Table 3.2: Random index (Saaty, 1980)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I	0.0	0.0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

When CR $\leq$ 0.10, the judgment matrix can be considered as having a satisfactory consistency (Saaty, 1977; 1980) that is, the weight vector is reliable. Otherwise, we must reconstruct the judgment matrix.

Fuzzy Analytical Hierarchy Process

Fuzzy AHP is an efficient tool and is widely used to handle the fuzziness of the data involving vagueness and uncertainty in the decision-maker's judgment. In general the AHP use of crisp values to obtain the PCM may introduce subjective uncertainty, which can be addressed through assignment of fuzzy data in the PCM. Kahraman et al. (2003) used the fuzzy AHP for comparing supplier selection for a firm. Triangular fuzzy numbers were used in that case. So et al. (2006) used the fuzzy AHP for service quality assessment. Lee et al (2008) used the fuzzy AHP for performance evaluation of an IT department in the manufacturing industry. Many studies have been done with the application of fuzzy AHP, and different fuzzy AHP models have been developed (Cheng, 1996; Cheng, 1999; Lee et al., 2006). To calculate the relative weights of each criterion, this study used extent fuzzy AHP analysis (Lee et al. 2006) which is based on fuzzy algebraic operations. Triangular fuzzy numbers are used for the fuzzification of a decision maker's judgment. The crisp values raging from 1/9 to 9, suggested by Saaty (1980) are fuzzified using the triangular fuzzy number f = (l, m, u) where the parameters l, m, and u, respectively, indicate the smallest possible value, the most promising value, and the largest possible value and that represent the uncertain range (Lee et al., 2006). The fuzzified numbers are reported in the Table 3.3.

Table 3.3: Conversion of Crisp PCM to Fuzzy PCM

How important is *A* relative to *B*?	Preference index (Saaty 1988)	Fuzzy value (Lee et al. 2006)
Equally important	1	(1, 1, 1)
Moderately more important	3	(1,3,5)
Strongly more important	5	(3,5,7)
Very strongly more important	7	(5,7,9)
Overwhelmingly more important	9	(7,9,11)
Intermediate values (Need to judge two)	2	(1,2,4)
	4	(2,4,6)
	6	(4,6,8)
	8	(6,8,10)

A simple example is considered to demonstrate the fuzzy AHP analysis. Consider three criteria C_1, C_2 and C_3. Each element of the lower triangle in the PCM is reciprocal to the upper triangle ($I_{jk}=1/I_{jk}$). The fuzzy pair wise comparison matrix with respect to this goal is shown in Table 3.4

Table 3.4: Fuzzy PCM with respect to goal

	C1	C2	C3
C1	1, 1, 1	1/5,1/3,1	1, 1, 1
C2	1, 3, 5	1, 1, 1	1/3,1/2,1
C3	1, 1, 1	1, 2, 3	1, 1, 1

After constructing the fuzzy pair wise comparison matrices, the Fuzzy extent analysis is applied as follows:

Total sum of the whole fuzzy PCM:-

Left = 1+1/5+1+1+1/3+1+1+1+1 =7.5 (a_1)

Middle = 1+1/3+1+3+1+1/2+1+2+1 =10.83 (b_1)

Right = 1+1+1+5+1+1+1+3+1 =15.0 (c_1)

The first row sum (for C_1)

Left = 1+1/5+1 = 2.20 (α_1)

Middle = 1+1/3+1 = 2.33 (α_2)

Right = 1+1+1 = 3.0 (α_3)

First row sum / Total sum

Left $= \alpha_1/ c$ = 2.2/15.0 = 0.147

Middle $= \alpha_2/ b_1$ = 2.33/ 10.83 = 0.215

Right $= \alpha_3/ a$ = 3/7.50 = 0.40

The same calculation above applies to criteria C_2, and C_3 and the results are summarized in Table 3.5.

Table 3.5: Criterion Weights (after Fuzzy Extent Analysis)

Criteria	Overall weights		
	left	Middle	Right
C1	0.147	0.215	0.40
C2	0.155	0.416	0.934
C3	0.200	0.369	0.667

The principle criteria weights from the fuzzy extent analysis are also fuzzy data. To obtain crisp values any fuzzy ranking methods described previously can be used. In this study the ranking method described by Yager (1980b) is used to calculate the crisps scores.

3.2.6 Other multi-criteria decision making methods

Beside the previously mentioned MCDM methods, there are other techniques frequently using in decision making problems, as discussed in this section:

TOPSIS Method

Hwang and Yoon (1981) have developed the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method based on the concept that the chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution. There are many applications of fuzzy TOPSIS in the literature. For instance, Triantaphyllou and Lin (1996) developed a fuzzy version of the TOPSIS method based on fuzzy arithmetic operations, which leads to a fuzzy relative closeness for each alternative. Chen (2000) extended the TOPSIS to the fuzzy environment and used it for selecting a systems analysis engineer for a software company. Tsaur et al. (2002) applied fuzzy set theory to evaluate the service quality of an airline. Chu (2002) presented a fuzzy TOPSIS model involving a group decision for solving a plant location selection problem. Chu and Lin (2003) proposed the fuzzy TOPSIS method for robot selection. Lai et al. (1994) applied this compromised solution concept in multiple objective mathematic programming. When using TOPSIS to deal with a MCDM problem, the process includes six steps (Chen et al. 1992; Olson, 2004, Mahmoodzadeh et al., 2007) as follows:

Step 1 Construct a decision matrix for the ranking.

Step 2 Calculate the normalized decision matrix

Step 3 Calculate the weighted normalized decision matrix by multiplying the normalized decision matrix by its associated weights.

Step 4 Calculate the positive ideal (PIS) and negative ideal (NIS) solutions

Step 5 Calculate the separation measures

Step 6 Rank the preference order.

The detailed procedure of this method can be found elsewhere like (Chen et al. 1992; Olson, 2004, Mahmoodzadeh, 2007). The application of this method can be illustrated in as follows:

Construction of decision matrix: A decision matrix is basically an array, presenting on one axis a list of alternatives, and on the other axis, a list of criteria. The decision matrix for a problem can be established presenting alternatives on the X axis and criteria values on the Y axis. To form a normalized decision matrix, the equation 3.27 can be used.

$$r_{ij} = \frac{C_{ij}}{\sqrt{\sum_{j=1}^{n} C_{ij}^{2}}} \tag{3.27}$$

Where C_{ij} is a crisp value indicating the performance rating of each alternative Ai with respect to each criterion Xj

The positive ideal solution (PIS) and negative ideal (NIS) solution are determined by equation 3.28 and equation 3.29 as:

$$V^{+} = \{v_1^{+} \ldots\ldots v_n^{+}\} = [(Max \quad v_{ij} \left| j \in J),(Min \quad v_{ij} \right| j \in J')] \qquad (328)$$

$$V^{-} = \{v_1^{-} \ldots\ldots v_n^{-}\} = [(Min \quad v_{ij} \left| j \in J),(Max \quad v_{ij} \right| j \in J')] \qquad (3.29)$$

Where V associated with the positive sign indicates benefit criteria and V associated with the negative sign indicates loss criteria. J = 1, 2... n are associated benefit criteria and J' = 1, 2... n are associated loss criteria.

The separation measures between each alternative can be measured by, using the 'm' dimensional euclidean distance. The separation measure D_i^{+} of each alternative can be calculated by equation 3.30 as:

$$D_i^{+} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{+}\right)^2}, \qquad i = 1, \ldots\ldots, m \qquad (3.30)$$

Similarly, the separation measure D_i^{-} of each alternative can be calculated by equation 3.31 as:

$$D_i^{-} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{-}\right)^2}, \qquad i = 1, \ldots\ldots, m \qquad (3.31)$$

The relative closeness of the alternative Ai with respect to PIS/NIS is expressed by equation 3.32 as:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, \qquad i = 1,........m \tag{3.32}$$

Where the index value of C_i lies between 0 and 1, with the larger index values indicating the better performance of the alternatives.

Overall value model

Overall value models are mathematical models which are used to evaluate alternatives consistently with the preferences of the decision maker (Clemen, 1996). Some of the models, such as the additive value function, provide a single index which enables the decision maker to rank alternatives. The additive value function is the most commonly used function as it is simple and easily understood. This function is basically a weighted average of scoring functions. The evaluation measures for each criterion were linearly averaged to provide a single number or index, which represents the decision maker's preferences. The overall preference score for each option is simply the weighted average of its scores on all the criteria. The preference score for option i with criterion j is represented by x_{ij} and the weight for each criterion is represented by w_j, and for n criteria the overall score for each option, V_i, is given by equation 3.33.

$$V_i = x_{i1}w_1 + x_{i2}w_2 + ... + x_{in}w_n = \sum_{i}^{n} w_i x_{ij} \tag{3.33}$$

Where, x_i represents the score under the i^{th} criterion, and w_i is the corresponding weight factor.

Simple additive weighting method (Hwang and Yoon, 1981)

This method is a very widely used method which involves weighting attributes, scaling attribute values, and then calculating the total score, which is the sum of the products of weights and scores for all the attributes. The option attaining the highest score is to be selected. According to Hwang and Yoon (1981), the most preferred option (A*) is selected such that:

$$A^* = \left\{ A_i \middle| \max \sum_{j=1}^{n} w_j x_{ij} / \sum_{j=1}^{n} w_j \right\} \tag{3.34}$$

$$\sum_{j=1}^{n} w_j = 1$$

Where x_{ij} is the level of the i^{th} option attained for the j^{th} criterion on a numerically comparable scale. The weights (w_j) normally add up to 1 (Hwang and Yoon, 1981). This method may be extended to include hierarchical consideration of criteria as in the method called the Hierarchical Additive Weighting Method (Hwang and Yoon, 1981) where the criteria are classified into levels and the weights of criteria in the lower levels are assigned based on the weights of the criteria in the higher levels.

Multi-Attribute Utility Theory (MAUT)

MAUT is a quantitative comparison method used to combine dissimilar measures of costs, risks, and benefits, along with individual and stakeholder preferences, into high-level, aggregated preferences. The foundation of MAUT is the use of utility functions. Utility functions transform different criteria to one common, dimensionless scale (0 to 1) known as the multi-attribute utility (Michael et al. 2000, Baker et al. 2001). Once utility functions are created, the objective or subjective data of an alternative can be converted to utility scores. As with the other methods, the criteria are weighted according to importance. To identify the preferred alternative, each normalized alternative's utility score results are multiplied by criteria weights. The preferred alternative will have the highest total score. MAUT comparisons are typically used when quantitative information is known about each alternative, which can result in firmer estimates of the alternative performance. The MAUT evaluation method is suitable for complex decisions with multiple criteria and many alternatives.

3.3 The selection of MCDM techniques for this study

The present chapter describes the different MCDM techniques, and their advantages and limitations. After careful review of the MCDM techniques, the most suitable methods were selected for the present study. The MCDM framework of this study is divided into two groups, the traditional method, which integrated the AHP with an overall value model and the fuzzy based method that combines the FAHP and TOPSIS techniques. The advantage of the selected methods can be addressed as:

The AHP method was found to be the most appropriate, for its simplicity, transparency, consistency, and adaptability to the varying number of criteria and its sensitivity to the impact range. The AHP was integrated with an overall value model to solve the decision matrix. The overall value model was found to be the best suited technique for this study, because it can handle large numbers of criteria, and it is simple and easy to understand

To compare the results, this study also conducted another set of MCDM operations; in this case, FAHP was added up the TOPSIS algorithm. The advantage of this MCDM set is that it will be able to handle the uncertainties associated with the assignment of weights and subjective scoring. The advantage of the proposed approach is that it will validate the final evaluation. The results from two different frameworks will make the final evaluation more reliable. This approach has a few basic and required steps which are generally used in MCDM problems. The proposed approach can be extended depending on the preferences of the problems in a variety of directions such as, financial, social, and environmental decision making problems.

Chapter 4

METHODOLOGY OF ECOLOGICAL RISK ASSESSMENT FOR PRODUCED WATER

4.1 Introduction

The term ecological risk assessment (ERA) can be defined as a process that evaluates the likelihood of adverse ecological effects, which may occur or are occurring as a result of exposure to one or more stressors (USEPA, 1998; CCME, 1999). The purpose of ERA is to contribute to the protection and management of the environment through scientifically credible evaluation of the ecological effects of human activities (Suter, 1993). Once PW is discharged into the ocean, it starts mixing with ambient water and becomes diluted. The mixing of the pollutant in the recipient water may be expressed through a dilution factor (Rye et al., 1996). Various factors like ambient current, discharge depth and velocity, discharge direction, and density of PW affect the dilution (Huang et al., 1996; Mukhtasor, 2001). The risk associated with the PW is strongly related to contaminants fate and distribution in the ambient seawater (Karman and Reerink, 1998), which mainly depends on the hydrodynamic characteristics, discharge geometry, and the ambient water flow characteristics. To assess contaminants' concentrations for risk assessment purposes hydrodynamic modeling plays an important role (Lee and Cheung, 1991; Huang et al. 1996; Mukhtasor, 2001). This chapter reviews dilution and dispersion modeling which has been widely used for ocean outfalls. An ERA frame work for PW discharges from offshore petroleum operations is also introduced in this chapter.

4.2 Dilution and dispersion modeling for ocean outfalls

PW from oil and gas industries contains significant amounts of pollutants including the PAHs, NPD, volatile BTEX components, heavy metals, non-volatile and semi-volatile chemicals, and the process chemicals; some of these are highly toxic and may pose risk to ecological entities and health hazards to humans through food chains. Factors that govern the toxicity of the pollutant when mixed into the recipient water should be considered carefully. The mixing of the release in the recipient water may be expressed through a dilution factor (Rye et al. 1996). The field studies and dispersion modeling of the fate of PW in the North Sea shows a typical initial dilution of 1000 folds within 50 to 100 m of the discharge point (Furuholt, 1996). According to the Rye et al. (1996), the initial dilution can be considered 1:1000 at a distance of 500 meters. Several factors affect the mixing and dilution, such as discharge velocity, ambient water velocity, wind direction etc. The outfall discharge velocity is much higher than the ambient velocity and the point of discharge is located at sufficient depth below the water surface to enhance the dilution (Mukhtssor, 2001). The plume trajectory and turbulent diffusion, in addition to initial dilution, is also an important measure for hydrodynamic modeling (Mukhtssor, 2001). According to USEPA (1991) "a mixing zone is an area where an effluent discharge undergoes initial dilution and is extended to cover the secondary mixing in the ambient waterbody." A mixing zone is an allocated impact zone where acute and chronic water quality criteria may be exceeded a higher number of time than the protection areas (Huang et al., 1996). Developing hydrodynamic models, the mixing of PW has been conceptualized as two separate regions (Lee and Cheung, 1991; Mukhtasor, 2001, Jirka et al. 1996). In the first region, the initial jet characteristics such as momentum flux, buoyancy flux, and outfall geometry influence the jet trajectory and mixing. This region is known as near-field (NF). On the other hand when the plume travels away from the source, the source characteristics become less important, and this region is known as far-field (FF), in which ambient conditions such as strength and direction of sea water currents, buoyant spreading motions and passive diffusion control trajectory and dilution of the turbulent plume (Jirka et al. 1996).

4.2.1 Various dilution models

Numerous dilution models are available for initial dilution prediction. The available models, and their scope and applications are discussed in this section.

Dilution model by Lee and Cheung (1991): This model is basically an asymptotic solution in the two limits flow regime; buoyancy dominated near field (BFNF) and buoyancy dominated far field (BFFF). The BDNF and BDFF can be classified by the ratio of the depth above discharge, H (m) to the plume/cross length flow scale l_b. The length scale is defined by $l_b = B/u^3$ where u = average ambient current speed (m/s) and B is the effluent buoyancy defined as Qg', where Q is the discharged flow rate (m^3/s) and equal to $u_e \pi d^2 / 4$, where u_e is the exit velocity (m/s) of the jet and d is the diameter (m) of the exit pipe, and g' is the reduced gravitational acceleration defined by $g' = (\rho_a - \rho_o) * g / \rho_a$, where ρa and ρ_o = densities of ambient sea water and effluent water, and g = gravitational acceleration . The jet behavior for a buoyancy dominated discharge is governed by the dimensionless depth Hu^3/B. According to Lee and Cheung (1991) and Wood et al. (1993) the BDNF is the regime where $H / l_b << 1$ and the BDFF is the regime where $H/ l_b >> 1$. The transition between the BDNF and BDFF can be considered $H/ l_b =0(1)$. Two length scales are used in the Lee and Cheung (1991) model in which l_q is the measure of direct effect of jet geometry on the flow characteristics and l_m is the measure of the distance where buoyancy becomes more effective than the jet momentum. The mathematical expression of this model can be expressed as:

$$l_q = d\left(\frac{\pi}{4}\right)^{1/2} \tag{4.1}$$

$$l_m = \frac{m^{3/4}}{B^{1/2}} \tag{4.2}$$

For $H / l_q >> 1$ the volume flux is not important, so the dilution changes to

$$S = f(H / l_b) \tag{4.3}$$

Where, S = the centerline dilution (dimensionless)

For $H / l_q << 1$ the dilution equation for the BDNF is given as

$$\frac{SQ}{ul_b^2} = C_1\left(\frac{H}{l_b}\right)^{5/3} \tag{4.4}$$

For $H / l_q >> 1$ the dilution equation for the BDFF is given as

$$\frac{SQ}{ul_b^2} = C_2\left(\frac{H}{l_b}\right)^{5/3} \tag{4.5}$$

The average values for C_1 and C_2 were suggested to be 0.1 and 0.51 respectively. The dilution characteristics with this model can represent the BDNF and BDFF. No specific solution was incorporated to predict the dilution in the transition zone.

Dilution model by Lee and Neville - Jones (1987): During the study of a number of United Kingdom outfalls, Lee and Neville - Jones (1987) developed dilution models for the minimum surface dilution based on field data for horizontal buoyant jets. These models can be expressed as:

$$\frac{S_m Q}{u l_b^2} = 0.31\left(\frac{H}{l_b}\right)^{5/3} \quad \text{for BDNF, } H / l_q < 5 \tag{4.6}$$

and

$$\frac{S_m Q}{u l_b^2} = 0.32\left(\frac{H}{l_b}\right)^{2} \quad \text{for BDFF, } H / l_q \geq 5 \tag{4.7}$$

Where, S_m = minimum dilution in the surface boil generated by the discharge and H = water depth above the discharge. In this model there is a discontinuity in the predictions at ($H / l_q = 5$).

Dilution model developed by Huang et al. (1998): Huang et al. (1998) developed a dilution model for both centerline and minimum surface dilution that covers all the regimes, from the buoyancy dominated near field (BDNF) through the intermediate regime to the buoyancy dominated far field (BDFF) with a single equation. The model equation used to represents the centerline dilution is as follows:

$$\frac{S_c Q}{uH} = C_1\left(\frac{H}{l_b}\right)^{-1\ 3} + \frac{C_2}{1 + a_1\left(\frac{H}{l_b}\right)^{-a_2}} \tag{4.8}$$

Where S_c = centerline dilution, H = water depth above the discharge, and C_1, C_2, a_1, and a_2 are model constants. The constants C_1 and C_2 are 0.1 and 0.51 as given by Lee and Cheung (1991) in equations 4.4 and 4.5, and the constants a_1 and a_2 are selected as 0.1 and 2 respectively.

The single equation used to represents the minimum surface dilution is as follows:

$$\frac{S_m Q}{uH} = C_3\left(\frac{H}{l_b}\right)^{-1\ 3} + \frac{C_4}{1 + a_3\left(\frac{H}{l_b}\right)^{-a_4}} \tag{4.9}$$

where S_m = centerline dilution (dimensionless), H = water depth above the discharge (m), and C_3, C_4, a_3, and a_4 are model constants. The constants C_3 and C_4 are 0.08 and 0.32 and the constants a_1 and a_2 are as 0.2 and 0.5 respectively.

Dilution model proposed by Rye et al. (1996): Rye et al. (1996) proposed an analytical method for initial dilution. The mixing of the release in the recipient water is expressed through dilution factor. The model equation used to represents the dilution is as follows

$$Dilution = \frac{C_o}{C} = \frac{ULH}{Q_o} = \frac{V}{Q_o}\sqrt{96K_z\frac{x^3}{U}} \tag{4.10}$$

where, x = distance from the source (m), V = horizontal diffusion velocity (m/s), K_z = vertical diffusion coefficient (m^2/s), U = average ambient current velocity (m^2/s), L = width of the plume diluted in the sea water (m), C = concentration of pollutants measured in the recipient water (g/m^3), C_o = concentration of pollutants measured in the outlet opening (g/m^3), Q_o = the release rate through the outlet opening (m^3/s) and H = height of the plume diluted in the sea water (m).

4.2.2 Parameters for the selected model

From the review of several initial dilution models, the model presented by Rye et al. (1996) was found to be more realistic, and has been used for predicting PW initial dilution. Because this model simplest among the others and data for this model were found from a practical application in the Ocean outfalls dilution analysis Rye et al. (1996). For the Rye et al. (1996) model the required parameters are discussed briefly in the following section.

Distance from the source (x)

For PW discharged, based upon worst-case platform characteristics Karman and Reerink, (1998) used a default values at 500 m from the platform, to calculate the concentration of a chemical in the water. The same values were used to calculate the concentration of pollutants measured in this study.

Vertical diffusion coefficient (K_z)

The vertical diffusion coefficient (K_z) is about 0.01 m^2/s for a wind velocity 10 m/s (Rye et al., 1996) . The vertical diffusion coefficient may be affected by the plume depth. A plume depth of more than 25 m tends to form vertical turbulence; in this case a lower vertical diffusion coefficient may be considered given (Rye et al., 1996). For the present study K_z was 0.01 m^2/s.

Effluent discharge rate (Q_o)

The release rate through the outlet opening is an important parameter used in the outfall modeling. The average PW discharge from one platform is 0.0174 m^3/sec (GESAMP, 1993). Studies from 30 oilfields have shown the range of PW discharge to be 3.68×10^{-6} m^3/sec to 0.276 m^3/sec (USEPA, 1993). Rye et al. (1996) used an effluent discharge rate 0.007 m3/sec for his study, and a same value was used in this study.

Ambient water velocity (U)

Ambient water velocity at the offshore platform location varied between 0.03 and 0.3 m/s (Brandsma and Smith, 1996).The USEPA (1995) used an ambient velocity of 0.05 m/sec for the open bay in Louisiana, and the same value was used for this study.

Horizontal diffusion velocity (V)

Rye et al. (1996) used lateral diffusion velocity 0.013 m/sec during the application of his model, and the same value was used for this study.

4.3 Framework for ecological risk assessment for produced water

The comprehensive framework for ecological risk assessment (ERA) developed by USEPA (1998) is presented in Figure 4.1.

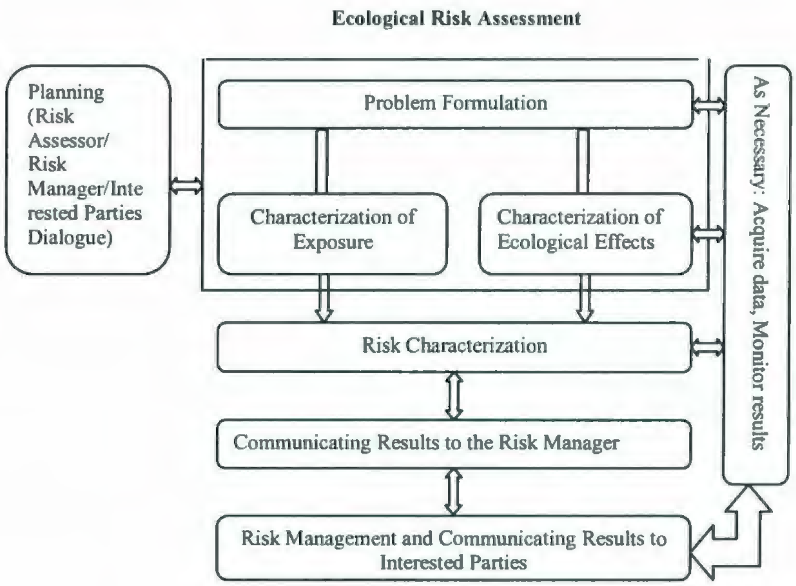

Figure 4.1: Ecological Risk Assessment Framework (USEPA 1998)

This framework consists of the following four basic steps:

- Problem Formulation;
- Analysis;
- Risk Characterization; and
- Risk Management and Communication.

4.3.1 Problem formulation

Problem formulation is a process for generating and evaluating preliminary hypotheses about the occurrence of ecological effects from human activities. It provides the foundation for the entire ERA. Problem formulation is the outcome of three components: (a) assessment endpoints that adequately reflect management goals and the ecosystem they represent, (b) conceptual models that describe key relationships between a stressor and an assessment endpoint and (c) an analysis plan.

Conceptual models

A conceptual model in the problem formulation phase is a description and representation of relationships between ecological entities and stressors. It may describe primary, secondary and tertiary exposure pathways, or co-occurrence among exposure pathways, ecological effects and receptors. Conceptual models for ecological risk assessments can be developed from information about stressors, potential exposure, and predicted effects on an ecological entity. Figure 4.2 describes a conceptual model for potential risk from PW discharged. There are several potential stressors present in the PW. For this study only two types of stressors are considered to calculate the ecological risk, namely, organic PAHs, and inorganic metals, like cadmium (Cd), copper (Cu), and zinc (Zn). The metal compounds were chosen due to there toxicity and high concentration in PW, and since PAH compound have rarely been used to represent ecological risk from PW, they were selected for this study. PAHs could bioaccumulate due to accumulation in sediments or particulate matter.

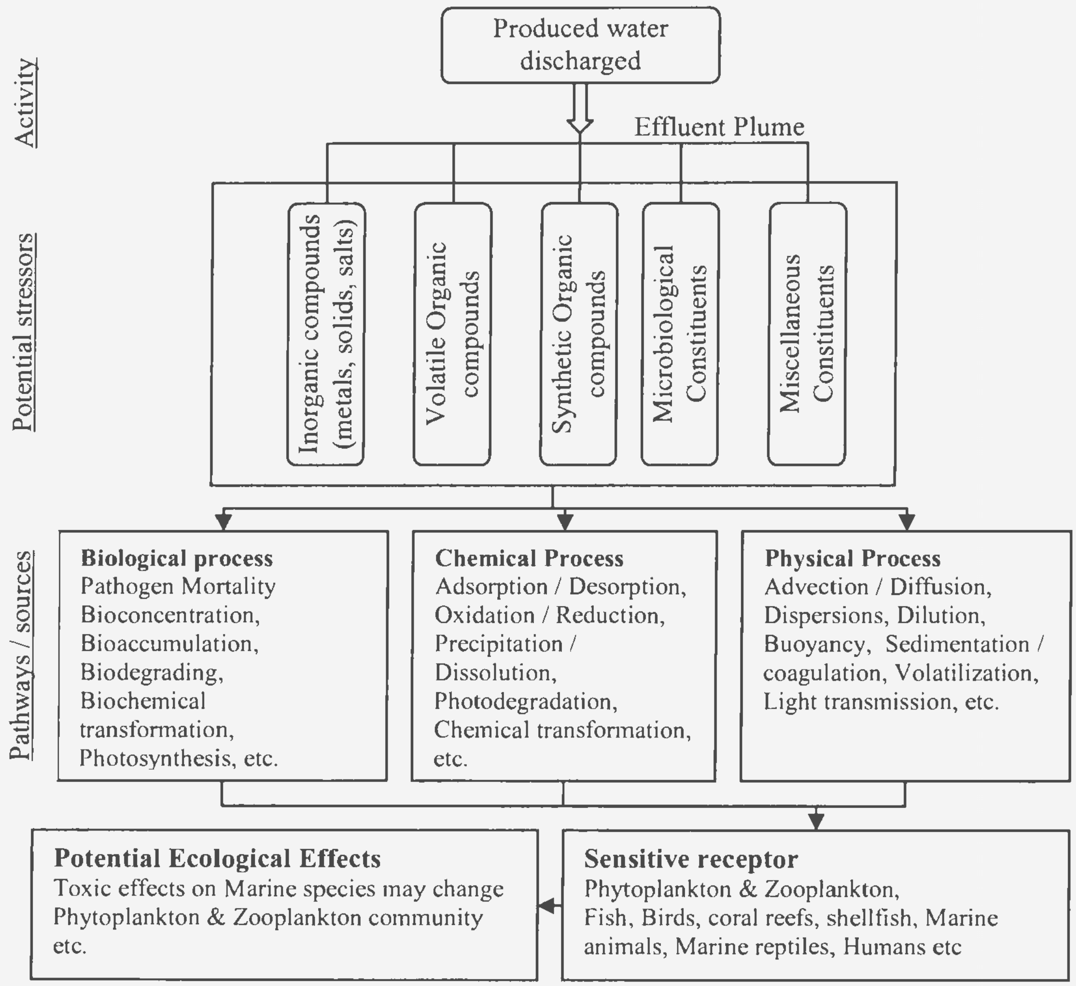

Figure 4.2: Conceptual model of potential risks for produced water discharged (From NAS 1984)

The acute stressors data are generally expressed as EC_{50} (for aquatic plants) or LC_{50} (for aquatic animals). The EC_{50} or LC_{50} is the measure of the lethal concentration at mortality of 50% of exposed organisms during the specified time. For this study the acute toxicity data were collected from different sources and tabulated in Appendix-B. According to Neff et al. (2006), 2-ring and 3-ring PAHs are the main contributors to the ecological risk of PW discharges. These compounds are relatively more soluble in water than the higher molecular weight PAHs (Neff et al., 2006). From the literature it has been found that acute toxicity data for PAHs in estuarine and marine environments is related to the lower molecular weight PAHs, containing 3 or less benzene rings in their structure. The acute and lethal toxicity data for the lower molecular weight PAHs are collected from different sources and reported in Appendix-B. The PAH concentrations causing lethal effects in marine organisms vary widely, with the lowest 96-h LC_{50} of 40 μg/L was recorded for juvenile mysid shrimp (Mysidopsis bahia) exposed to fluoranthene (USEPA, 1978). For this study, it was hypothesized that the data available (Appendix-B) are representative of the ecological entities in the marine environment.

The toxicity data in Appendix- B are at various exposure times. To use this data for further analysis, the following assumptions were made which are described with the help of a flowchart in Figure 4.3.

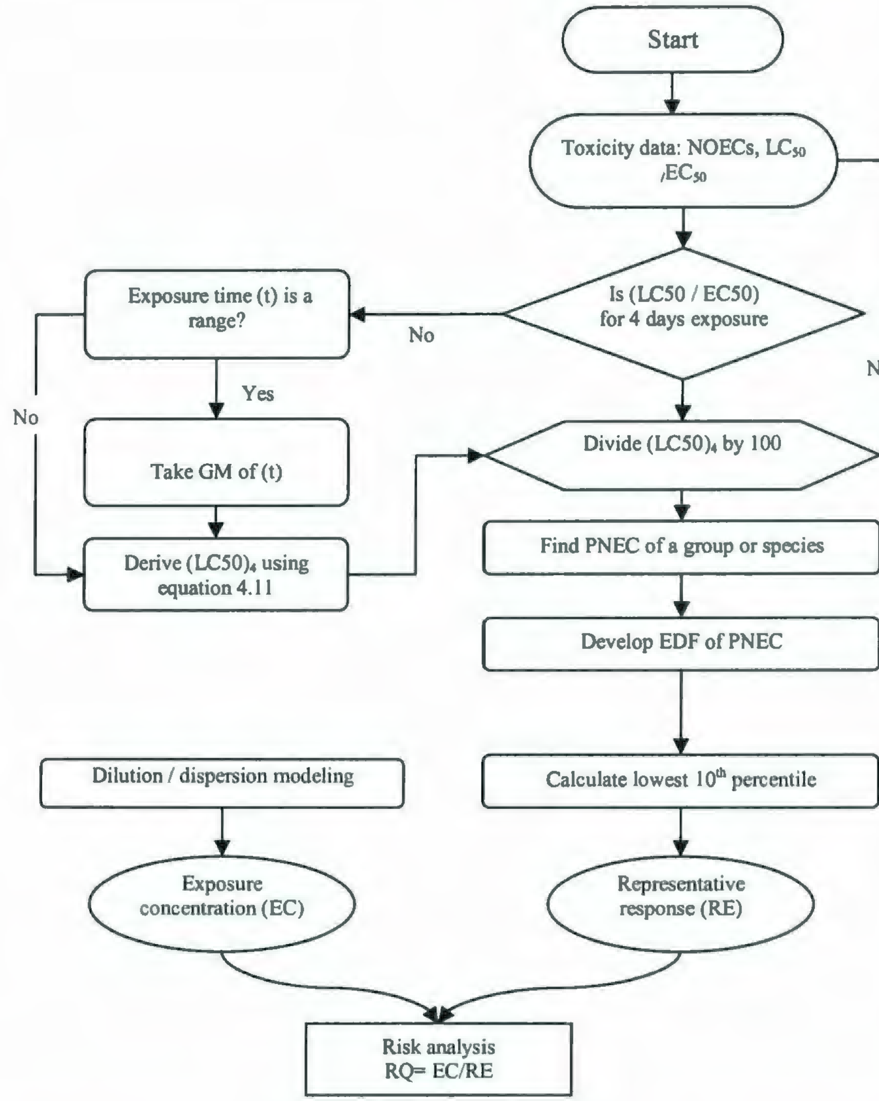

Figure 4.3: Structure of ecological risk calculation (modified from Sadiq et al., 2003)

1. If the range of LC_{50} or EC_{50} data were given, the data were converted into their geometric mean ($GM = \sqrt{lowest \times Highest}$) using lowest and highest values (French and French, 1989).

2. The exposure time for this study was assumed 4 days (96 hrs), and when the exposure time was other than 4 days then the relationship in equation 4.11 was used to convert LC_{50} to 96hrs (French and French, 1989).

$$(LC_{50})_4 = (LC_{50})_t \left(\frac{t}{4} \right)^{0.817} \qquad (4.11)$$

where $(LC_{50})_t = LC_{50}$ at any time t

3. The PNEC values were calculated from $(LC_{50})_4$ data by dividing an uncertainty factor of 100 as suggested by Thatcher et al. (1999).
4. NOEC values were directly used as a PNEC. In case of ranged data the GM of NOEC values were as PNEC.
5. If NOEC values were given other than 96 hours exposure, it was assumed as 96 hours exposure time.

The analyzing plan was the final component in the problem formulation which included a description of the assessment design, data needs, measures, and methods for conducting the analysis phase of the risk assessment. The analysis plan included pathways and relationships identified during the problem formulation that would be pursued during the analysis phase.

4.3.2 Analysis phase

The second phase of the risk assessment process examines two primary components such as, exposure and effects, and their relationships with each other and the ecosystem characteristics. There are three steps to be considered during analysis phase:

- Selecting the data and models to be used in the analysis
- Analyzing and characterizing the exposure by examining the sources of stressors.
- Characterization of ecological effects

At the beginning of the analysis phase, it is necessary to evaluate the data and model to be used for analysis. For this study the toxicity data for PW were collected from published sources and reported in Appendix- B. The models, like dilution/dispersion or a conceptual model for ERA, have been discussed in the previous section.

Characterization of exposure describes potential or actual contact of stressors with receptors. It is based on measures of exposure, and also on receptor characteristics and their distribution in the environment. It analyzes sources of pollution, distribution of contaminants, and modes of contact between stressors and receptors. This stage also focuses on the identification of pollutant sources, the exposure pathways, and the intensity and distribution of stressors spatially and temporally.

Source identification is the first objective of exposure analysis. There are two types of sources, and the first one is the original source of the stressors or location from where PW is discharged. The other source is the present location of stressors, e.g. the location where the receptors are exposed (USEPA, 1998). The second objective of exposure analysis is to describe the spatial and temporal distribution of stressors in the environment, which may be defined as the predicted environmental concentration (PEC). The PEC is an estimate of the expected concentration of a chemical to which the environment will be exposed after discharge. The actual exposure will depend upon the fundamental properties of the chemical such as the partition coefficient, degradation and bioconcentration factor, the concentration in the discharge stream, and the dilution in the receiving environment. For this research the PEC was calculated from the pollutants' concentration in the PW (Appendix-D) with the help of Equation 4.10. The geometric mean (GM) values were used when the concentration was as a given range of values. In the case where the individual pollutant concentration was not found, the total concentration was used. For example if the concentration of an individual PAH was not found then the total PAHs concentration in PW was used to calculate the PEC. The organisms do not necessarily stay close to the impact zone as they can move within the whole area or beyond the area under study (Sadiq, 2001). Stansbury (1991) considered the mitigation rate of finfish and shellfish to determine the exposure probability (p) for characterization of ecological risk. The US EPA (2000) calculated exposure probability as the ratio of the impact zone to the area under study. For simplicity this study used 100% exposure probability.

Bioavailability of the stressors is another factor and although the solubility of PAHs and other organics very widely, all contaminants in PW except metals were assumed to be completely dissolved in water and thus 100% bioavailable to the marine species (USEPA, 2000). The USEPA (2000) used a leaching factor (LF) to determine the bioavailable fraction (BF) of metals in the pore water. The USEPA (1996) introduced conversion factor (CF) factor to determine the bioavailable fraction (BF) of metals in the drilling waste discharge. Table 4.1 provides a summary of USEPA leaching factors (LF) and conversion factors (CF). To calculate the exposure concentration (EC), the PEC is adjusted as follows:

$$EC = PEC \times p \times BF \tag{4.12}$$

Where, EC = exposure concentration; PEC = predicted environmental concentration; (calculated from equation 4.10); P = exposure probability, (assumed for this study to be 100%); and BF = bioavailable fraction (100% for organics and CF in Table 4.1 for metals were used for this study)

Table 4.1: Factors to determine bioavailability fraction of contaminants

Metals	Leaching factor (LF) USEPA (2000)	Conversion factor (CF) USEPA (1996)
As	0.005	1.00
Cd	0.110	0.994
Cr	0.034	0.993
Cu	0.0063	0.830
Hg	0.018	0.850
Ni	0.043	0.990
Pb	0.020	0.951
Zn	0.0041	0.946

The PEC values and then EC were calculated for different locations from the discharged point and are reported in Table 4.2. The predicted no effect concentration (PNEC) is an estimate of the highest concentration of a chemical in a particular environmental media at which no adverse effects are expected. In general the PNEC represents a toxicity threshold, derived from standard toxicity data such as NOECs, LC_{50} and EC_{50}. For this study the toxicity data were collected from different sources (Appendix - B).

According to Husain et al. (2002) selection of a PNEC value, which is representative of the whole community, is a difficult task from a management goals and risk assessment point of view. Lenwood et al. (1998) have recommended the lowest 10^{th} percentile of PNEC values of response as the representative values (RE).

Table 4.2: Calculated PEC and EC (μg/l)

	50 m from discharge point		100 m from discharge point		500 m from discharge point	
Toxicant	PEC	EC	PEC	EC	PEC	EC
NA	0.05484	0.05484	0.01939	0.01939	0.00173	0.00173
1-MNA	0.03932	0.03932	0.01390	0.01390	0.00124	0.00124
2-MNA	0.01572	0.01572	0.00556	0.00556	0.00050	0.00050
d-MNA	0.00853	0.00853	0.00302	0.00302	0.00027	0.00027
ANA	0.00005	0.00005	0.00002	0.00002	0.00000	0.00000
FL	0.00123	0.00123	0.00044	0.00044	0.00004	0.00004
PH	0.00014	0.00014	0.00005	0.00005	0.00000	0.00000
FLAN	0.00004	0.00004	0.00002	0.00002	0.00000	0.00000
Cd	0.00055	0.00055	0.00019	0.00019	0.00002	0.00002
Cu	0.01476	0.01225	0.00522	0.00433	0.00047	0.00039
Zn	0.88615	0.83830	0.31330	0.29638	0.02802	0.02651
	0.05484	0.05484	0.01939	0.01939	0.00173	0.00173

The RE values are also highly uncertain and change (increasing or decreasing) with the availability of data. For this study the PNEC values were fitted to different statistical distributions. A lognormal distribution was found to be the best fit for defining the response variability among the candidates. The PNEC fitted lognormal distribution is shown in Figure 4.4. A safety level at the lowest 10^{th} percentile on the response distribution was selected to save 90% of the ecological community.

To calculate the 10^{th} percentile response and associated uncertainty, 1000 times bootstrap re-sampling was performed on the PNEC data. The use of re-sampling methods in ecological risk assessment has been discussed in Suter (1993).

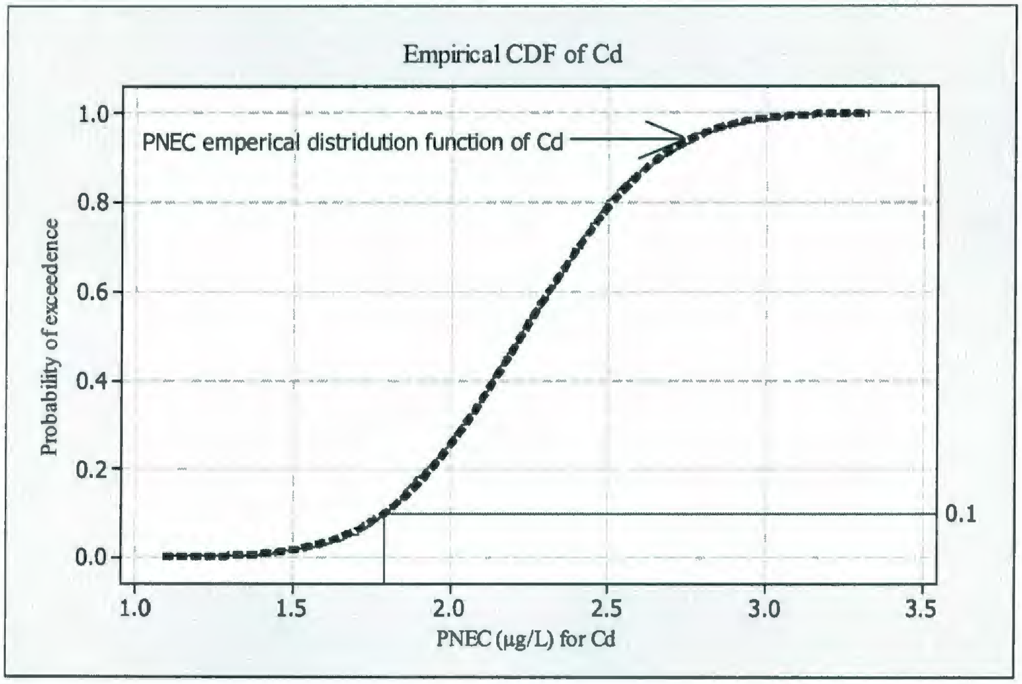

Figure 4.4: Lognormal distribution fit to the PNEC empirical CDF of (Cd).

To demonstrate bootstrapping it was asummed that the available PNEC data was a statistically random sample. Bootstrapping is quite accurate, with an adequate re-sampling size and enough iteration (Manly, 1991). This method has the advantage of mathematical simplicity and ease of implementation with a computer. The greatest advantage of bootstrapping, however, is that no special distribution of data values is required, and the uncertainty of the estimate can be calculated easily (Manly, 1991). For this study a bootstrapping macro was written in MINITAB version 15 notepad (Appendix -C) to develop cumulative distribution function (CDF) of the PNEC values. A set of equation 4.13 was used in the bootstrapping macro to calculate lowest 10th percentile of values. The calculated representative (RE) value is reported in Table 4.4.

$$\left.\begin{aligned}
&Y_i = \log(X_i)\\
&\mu_Y = mean(Y_i)\\
&\sigma_Y = Std.(Y_i)\\
&X_p = e(\mu_Y - z\sigma_Y)\\
&\mu_{10} = \sum X_{10} / B\\
&\sigma_{10} = \sum (X_{10} - \mu_{10})^2 /(B-1)
\end{aligned}\right\} \tag{4.13}$$

Where, Xi = PNEC values; P = percentile values (in this case 10th percentile); Z = values from standard normal table corresponding to the percentile, in this case Z = 1.282; B= No. of bootstrap runs (1000); μ_{10} = mean of lowest 10th percentile values of PNEC (RE) and σ_{10} = standard deviation of lowest 10th percentile values of PNEC. The toxicants data and their PNEC values are reported in Tables 4.3.

The lowest 10th percentile values for all toxicants (or protection level of 90%) were determined and were compared with the U.S federal water quality criteria (USEPA, 2000 and CCME, 1999) as shown in Table 4.4.

Characterization of the ecological effects describes the effects induced by a stressor, links them to the assessment endpoints, and evaluates how they change with varying stressor levels (USEPA 1998). The ecological effects from the PW may be acute or chronic. The primary focus of this study is to characterize the acute effects on the marine species from PW. Associated uncertainties for the evaluation were determined by bootstrapping.

Table 4.3: Data statistics of PNEC

Toxicant	Data Point	Mean PNEC (μg/L)	Stdev. of PNEC (μg/L)
Cadmium (Cd)	23	34	65.2
Copper (Cu)	23	11.37	22.33
Zinc (Zn)	23	50	75.5
PAHs Compounds			
NA	15	162	507
1-MNA	5	19.5	16.92
2-MNA	7	10.23	8.82
d-MNA	8	9.6	9.43
ANA	6	14.0	9.89
FL	4	9.00	5.90
PH	3	3.40	2.430
FLAN	5	2331	2990

***Notes**: NA = naphthalene; 1-MNA = 1-methylnaphthalene; 2-MNA = 2-methylnaphthalenes; d-MNA = dimethylnaphthalenes; ANA = acenaphthene; FL = fluorine; PH = phenanthrene; FLAN = fluoranthene.*

4.3.3 Risk characterization

Risk characterization is the final step in ERA and is the combination of planning, problem formulation, and analysis of predicted or adverse effects related to assessment endpoints. The conclusions explained in the characterization provide information for environmental decision making. The associated uncertainties in the models are also discussed in this section. The hazard quotient (HQ) represents the ratio of the exposure concentration (EC) and the representative response values (RE). The HQ is a single number that represents the likelihood that a chemical will cause harm when the environment is exposed to it. The HQ of each contaminant can be calculated by the equation 4.14 as follows:

$$HQ = \frac{EC}{RE} \tag{4.14}$$

Where, EC = exposure concentration calculated by equation (4.12) and RE = representative values.

Table 4.4: Comparison of RE values with standard water quality criteria (μg/L)

Toxicant	Lower 10^{th} percentile PNEC (RE) (μg/L)	Stdv. of RE (μg/L)	(USEPA, 2000) FWQA	(CCME, 1999)
Cadmium (Cd)	1.324	0.564	9.30	0.12
Copper (Cu)	0.029	0.021	2.4	4.0
Zinc (Zn)	1.203	0.19	81.0	30.0
NA	4.30		-	1.4
1-MNA	2.63	1.4	-	-
2-MNA	3.02	1.40	-	-
d-MNA	0.753	0.568	-	-
ANA	6.558	0.435	-	-
FL	3.49	1.010	-	-
PH	1.210	0.570	-	-
FLAN	1.72	0.20	-	-

For risk management purposes it may be interesting to know the risk of a group of chemicals. The toxicities of individual hydrocarbons or hydrocarbon fractions are approximately additive in nature (Warne et al., 1989 and Van Wezel et al., 1996). HQs for all the target organic chemicals in receiving waters can be summed which is equivalent to the total hazard of the target hydrocarbons.

The assumption of an independent mode of action enables the use of statistical calculation rules for combining the independent probabilities (Jooste, 2000). For example, for the mixture of three chemicals, the total risk can be calculated by the following equations:

$$Risk(A+B) = Risk(A) + Risk(B) - Risk(A) \times Risk(B) \tag{4.15}$$

$$Risk(A+B+C) = Risk(A+B) + Risk(C) - Risk(A+B) \times Risk(C) \tag{4.16}$$

Where, A, B, C = risks of contaminants A, B, and C respectively. Similar relation can be applied for more pollutants.

4.3.4 Risk description

The ecological risk is characterized by calculating the HQ. The HQ for exposure concentrations were calculated for selected stressors at different locations (Table 4.5).

Table 4.5: Calculated risk from PW discharged in to a marine environment

Toxicant	HQ (50 m from discharge point)	HQ (100 m from discharge point)	HQ (500 m from discharge point)
Cadmium (Cd)	0.00041	0.00015	0.00001
Copper (Cu)	0.42252	0.14938	0.01336
Zinc (Zn)	0.69684	0.24637	0.02204
NA	0.01275	0.00451	0.00040
1-MNA	0.01495	0.00529	0.00047
2-MNA	0.00521	0.00184	0.00016
d-MNA	0.01133	0.00401	0.00036
ANA	0.00001	0.00000	0.00000
FL	0.00035	0.00012	0.00001
PH	0.00012	0.00004	0.00000
FLAN	0.00003	0.00001	0.00000

The HQs of individual PAH compounds were added together to obtained the combined risk. Figure 4.5 shows the ecological risks for different pollutants. The ecological safety level in the marine system is defined by HQ< 1. The HQ> 1 represents a level, at which marine ecological entities are in danger.

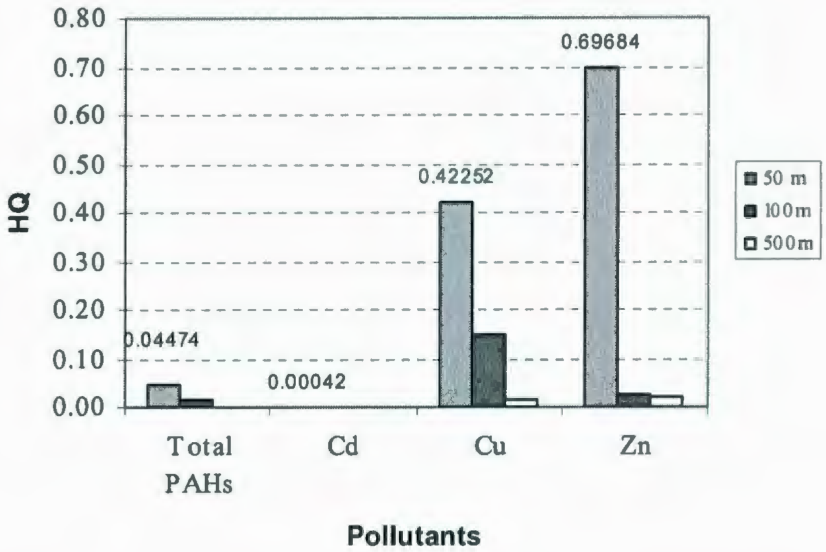

Figure 4.5: Acute risks from PW discharged in different scenarios

4.4 Summary

This chapter develops a methodology for ecological risk calculation from PW discharged to the ocean. Acute toxicity data of Cd, Cu, Zn and PAHs were used to characterize the risk. Based on the acute toxicity data PNEC values were derived. A safe level at the lowest 10^{th} percentile of PNEC was selected to save 90% of the ecological community. The lowest 10^{th} percentile values were assumed to the representative values (RE) for the whole ecosystem. The REs for Cd, Cu, Zn and PAHs were calculated and are reported in Table 4.4. The GMs of different discharge scenario were used to calculate exposure concentrations (ECs). The risk is characterized by HQ, which is the ratio of EC and RE. HQs less than one assumed the ecosystem was safe from acute toxicity. From this study even though the calculated acute risk seemed to show that the ecological community was safe, but PW contained some carcinogenic pollutants like arsenic, PAHs with higher benzene ring (4-6), etc. These highly toxic pollutants at even very low concentrations can change the ecological balance. They have high bioaccumulation capability and they can easily enter to the human body through food chains. Detailed study is necessary to know the accurate risk from PW.

The hazard quotients (HQ) for different PW management options were calculated and these values were used in the MCDM model to evaluate the PW management options.

Chapter 5

EVALUATION METHODOLOGY FOR PRODUCED WATER MANAGEMENT

This chapter deals with the various steps involved in the development of decision making tools for PW management. Unlike simple decision making problems in the real world this framework is designed for more than one criterion and alternative. With this consideration, the decision making tool can be considered as the MCDM technique (Turban and Meredith, 1991). Two separate analyses were conducted for this study, one with crisp values and another used fuzzy data. A crisp value is a less complex deterministic MCDM approach which uses single estimates of decision variables (Stansbury et al., 1999), but it leads to uncertainty, and so fuzzy analysis was conducted to handle the uncertainty of the evaluation. Finally, comparing both results, the best management system was outlined.

5.1 Structure of the methodology

The organization of the methodology is shown in Figure 5.1. The evaluation of produced water management techniques is the major objective of this study.

5.1.1 MCDM models for this study

The MCDM models for this study can be divided into two groups; The AHP technique that is integrated with the overall value model to develop the first model, and the FAHP method that is combined with the TOPSIS technique. Figure 5.2 shows the detailed MCDM models used in this study.

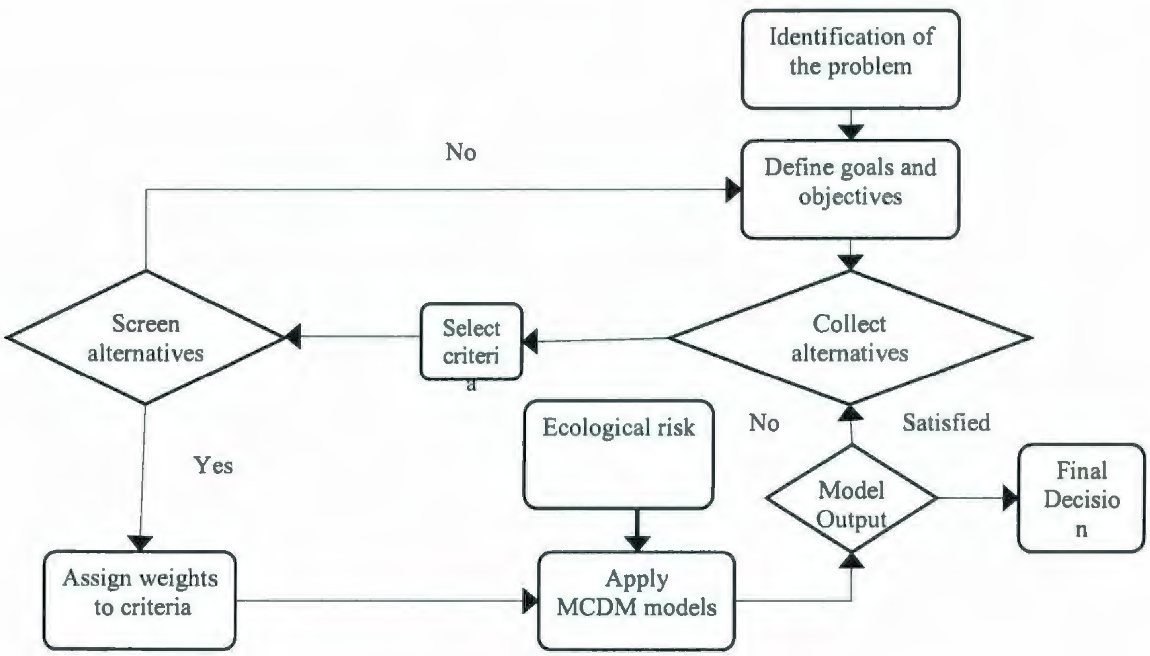

Figure 5.1: Structure of the methodology

5.2 Scoring schemes and criteria evaluation

The first step of MCDM is to identify the evaluation criteria. The criteria are the controlling factors in which PW management options will be scored in the evaluation. Therefore, the criteria must be chosen in such a way, so that they accurately reflect the issues with respect to PW management. The system that achieves the maximum objectives with the minimum cost is desirable. According to Gladwell and Loucks (1999) the selection of a PW management system should identify a set of evaluation criteria considering all the beneficial and adverse environmental, economical and social environmental effects. Haq et al. (2001) recommended independent technology assessments in the decision making process to identify the potential technology to meet regulatory standards and innovation competitiveness.

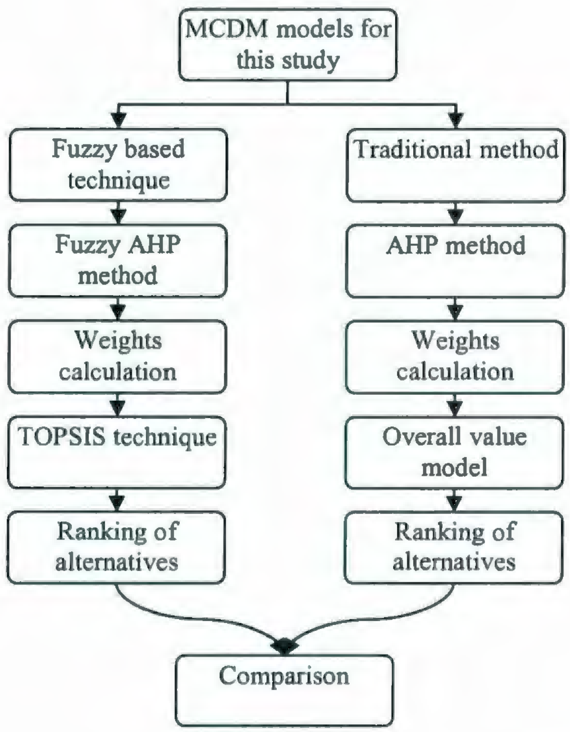

Figure 5.2: MCDM models for the study

5.2.1 Scoring scheme

Scores are assigned numbers which represent the options' properties under each criterion. The scoring schemes used in the evaluation are divided into two types, subjective and quantitative. The first type of data provides qualitative information and linguistic variables are used to convert the scores, and the second type provides quantitative data. These scoring schemes are described below:

Quantitative scheme

Quantitative data such as the weight, footprint etc. are normalized to unit interval scaled values before being used in the evaluation. The normalization was conducted using linear value functions as shown in equation 5.1. As this type of data may have either increasing or decreasing values, two ranges of normalized scores were used. Positive scores with a range of 0 to 1 were given to those with increasing values and negative scores with a range of -1 to 0 were given to those with decreasing values.

$$r_i = \pm \frac{C_i}{\sum_{i=1}^{n} C_i} \tag{5.1}$$

Where r_i is the normalized value of the criteria C_i.

An example of a quantitative scoring scheme and its calculation are given here for the 'weights' criterion which are considered loss criteria (the less weight, more preferable for an option). It is then assumed that the weights of the three alternatives A, B, and C are 15 ton, 18 ton, and 12 ton. Therefore, using equation 5.1, the normalized scores for option 'A' having weights 15 ton can be calculated as below.

Normalized scores for A = -15/ (15+18+12)

= -0.334 (negative sign indicating loss criteria)

Calculation of unknown data

In the case, where authentic quantitative data for an alternative were not found, the mean value of that criterion was calculated. The criteria mean values were assumed, and the alternative value and associated uncertainties were assigned 20% for that criteria score. The mean values of a criterion can be calculated by equation 5.2 as:

Mean values $\bar{x} = \frac{\sum C_{ij}}{n}$ and (5.2)

Where, $\bar{x}$ = Mean unknown values; C_{ij} = criterion values for the corresponding alternatives and n = number of data point

Subjective rankings

Where quantitative data is not available, subjective rankings are used to measure the option. The subjective rankings are then converted into numbers with the help of a conversion scale. The conversion scale is divided and marked with the numbers of 0 to 1. Scores are then directly obtained by comparing the characteristics of each option with the conversion scale. Linguistic terms are used to capture the subjective ranking.

Linguistic terms are not numbers but words or sentences in natural or artificial language (Kickert and Walter, 1978). In environmental and social studies, most of the information is imprecisely defined due to the unquantifiable nature of data or lack of proper knowledge. The experts often use linguistic scales (high, moderate, low or very good, good, and bad etc.) to express the existing scenarios. In this study, four linguistic terms: low (L), moderate (M), high (H) and extremely high (E), have been used. Too many linguistic terms make the evaluation process complex (Lee, 1996). Figure 5.3 shows the linguistic scales for this particular case.

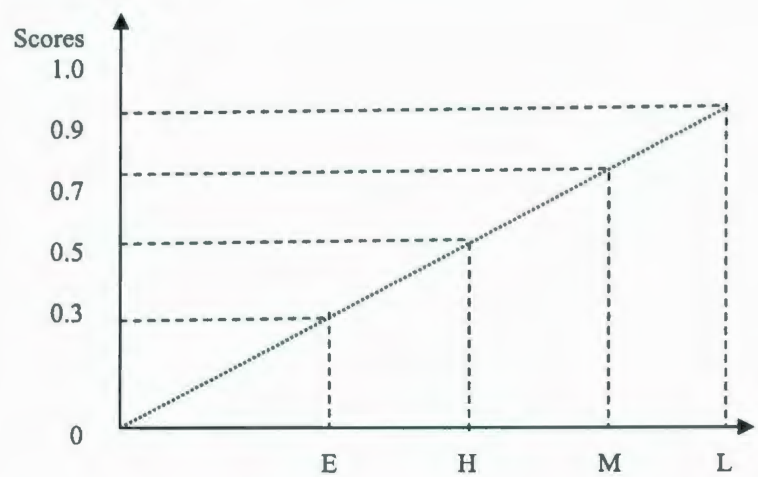

Figure 5.3: The conversion scale of linguistic variables

To capture the subjective scores, the conversion scale as shown in Figure 5.3 is used unless otherwise mentioned.

5.2.2 Criteria evaluation

In this study, criteria were divided into two distinct groups, threshold criterion and decision making criterion.

Threshold Criterion

The threshold criterion is used to screen out inappropriate options which are not likely to be selected as the optimum option at the end of the evaluation. The options that were unable to meet the regulatory oil and grease discharge standard limit described in Chapter 2 (Table 2.2) were rejected and not considered for further evaluation.

Decision Making Criteria

The criteria which were used to evaluate and compare options are called decision making criteria. To compare PW management options, the decision making criteria were divided into four major categories. These are technical feasibility, environmental effects, cost, and health & safety. The detailed criteria hierarchy is shown in Figure 5.4. For the criteria hierarchy figure number in the bracket, the first digit represents the principle criteria and other digits are indicating the sub-criteria. The criteria used in this evaluation are briefly described below:

Technical feasibility (C_1)

Technical characteristics play an important role within the evaluation of any management system. Technical feasibility is a criteria category used to assess the options in terms of their technical performance. These criteria were sub-divided into lower level criteria as shown below (Modified from Worakanok, 2003).

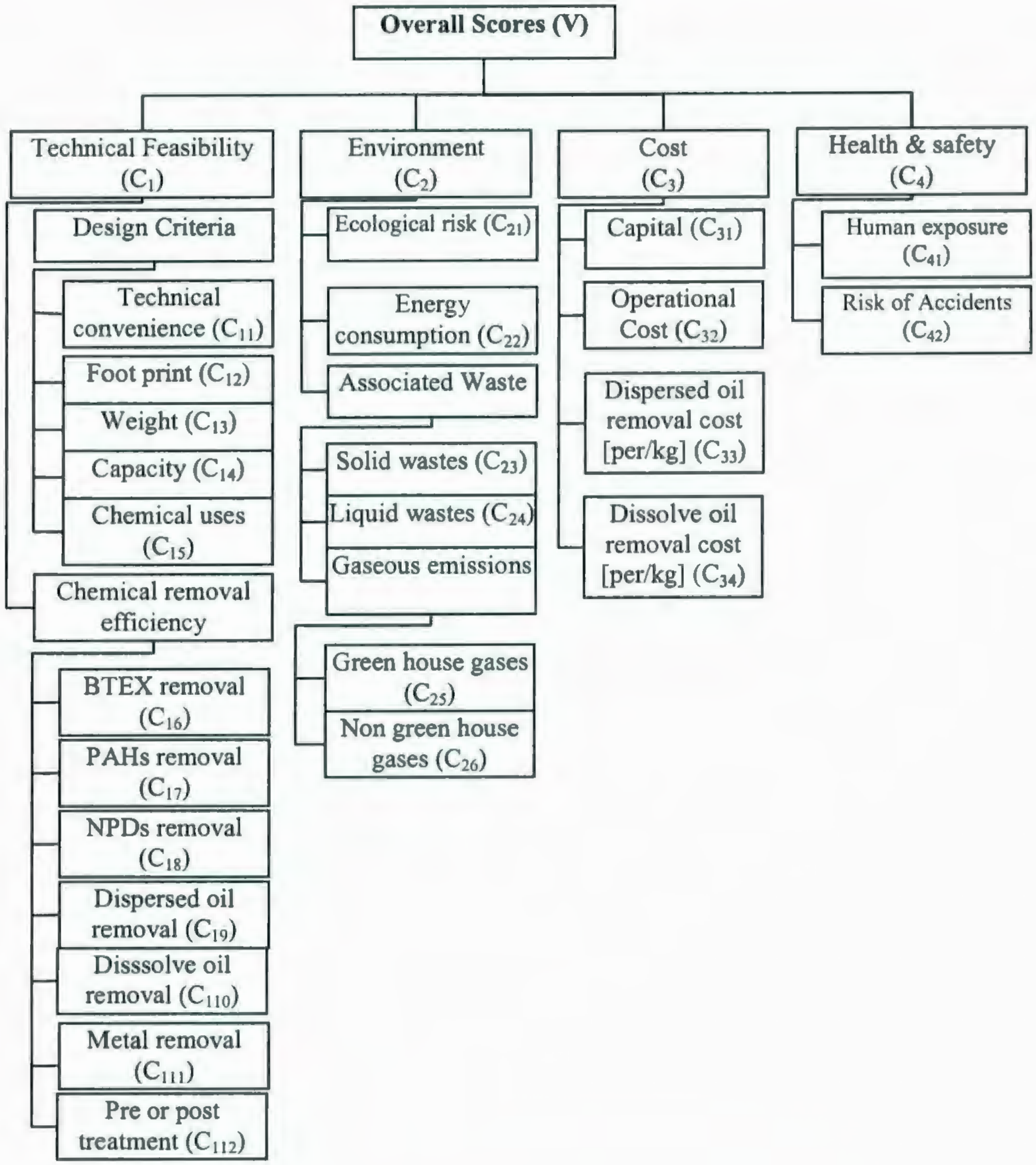

Figure 5.4: Criteria hierarchy structure

Technical convenience (C_{11})

The technical convenience is an important criterion in evaluation of the technology. The technical convenience can include the minimum number of moving parts, easy access for inspection and minimum sensitivity to other activities on the platform. Impacts might be effect when the technology is under operation or idle. For example, other activities that might be affected by the technology are vessel movement particularly in offshore operations. This criterion was evaluated subjectively, considering the levels of convenience and positive values were used for the assigned scores. To calculate the score the conversion scale shown in Figure 5.5 was used.

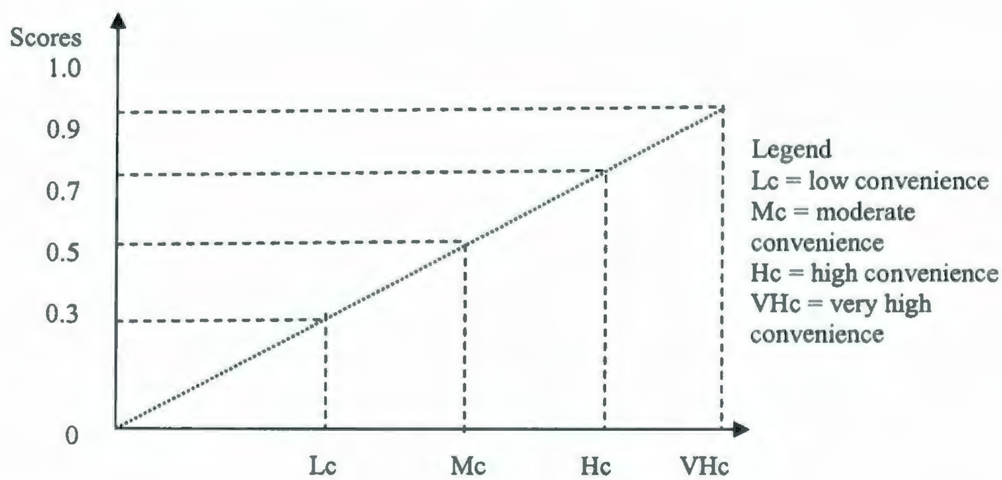

Figure 5.5: Conversion scale for technical convenience criteria

Foot print (C_{12})

As offshore platforms normally have area constraints, the total area of a management system is also important for the offshore application. This criterion was evaluated quantitatively and negative values were used for the assigned scores.

Weight (C_{13})

As offshore platforms normally have weight constraints, the total weight of a management system is also important for the offshore application. This criterion was evaluated quantitatively and negative values were used for the assigned scores.

Capacity (C_{14})

This option was scored and the criterion was evaluated based on the designed PW handling capacity by the technology. The capacity of the system is desirable hence positive values were used for its scores.

Chemical usage (C_{15})

According to the (UKDTLR, 2001), a considerable amount of chemicals are used for treatment of PW that are entering the marine waters (Henderson et al; 1999). The amount of chemicals required for the implementation of a management system was a criterion for this evaluation. During the separation process of PW, several chemicals are added at various stages to aid the oil and water separation and to mitigate operational problems such as corrosion and scale formation. With an increasing water production the amount of chemicals is increased, that has a significant environmental effect (Hendersson et al, 1999). The most commonly used production chemicals are flocculants, emulsion breakers, corrosion inhibitors, scale inhibitors and antifoam where injection chemicals include biocide, antifoam, oxygen scavenger and scale inhibitor and most of these chemicals are toxic (Hendersson et al, 1999). The use of chemicals totally depends on PW quality which may change from field to field and depending on the well life and property of drilling fluids. The criterion was evaluated subjectively by considering the quantity of chemicals used by the technology. The scores can be obtained directly by comparing the technology with Figure 5.3. Positive values were used for this score.

Chemical removal efficiency

BTEX removal efficiency (C_{16})

BTEX (benzene, toluene, ethylbenzene and xylenes) compounds are highly volatile aromatic compounds found in PW. BTEX compounds are moderately soluble in seawater and biodegrade rapidly in the water column (OGP 2005). BTEX compounds have a moderate affinity for partitioning into lipid tissues of aquatic organisms and sorption to organic matter (OGP 2005). Exposure to BTEX can occur by ingestion (consuming water contaminated with BTEX), inhalation (exposure to BTEX present in the air) or absorption through the skin. Absorption of these chemicals may be by spilling PW onto one's skin. There is sufficient evidence to believe that benzene is a human carcinogen. Workers exposed to high levels of benzene were found to have an increased incidence of leukemia. Considering the environmental impact, BTEX removal efficiency by the system is included as decision criteria in the evaluation. This criterion was evaluated quantitatively. The BTEX removal efficiency of the technology is considered with positive scores.

PAHs removal efficiency (C_{17})

PAHs are hydrocarbon molecules with several cyclic rings present in PW. They are relatively insoluble and their potential for bioaccumulation increases with increasing molecular weight (OGP, 2005). PAHs increase biological oxygen demand, and are highly toxic to aquatic organisms. Some of the PAH compounds are carcinogenic to man and animals (Veil et al., 2004). PAHs are potentially hazardous substances in the environment. They may have acute and chronic toxic effects on survival, feeding, reproduction and behavior of organisms (Bispo et al., 1999). The concentration of higher molecular weight PAHs with four rings or more in crude oil are low and are usually present at very low concentrations in PW (OGP, 2005). They bind strongly to organic matter contributing to their persistency (Neff, 2002). Considering the environmental impact of PAHs, they are included as a decision criterion in the evaluation of PW treatment technology. This criterion was evaluated quantitatively. PAH compounds should be as low as possible in the environment, and hence the PAH removal efficiency of the technology is considered positive scores.

NPD removal efficiency (C_{18})

Some treatment systems can remove NPD (naphthalene, phenanthrene and dibenzothiophene), 2-3 ring aromatic compounds, including their C1-C3 alkyl homologues. The percentages of removal efficiency were used as scoring values. For those treatment systems that can not remove NPD, this study used 0%. This criterion was evaluated quantitatively in the same way as PAHs.

Dispersed Oil removal efficiency (C_{19})

Oil is an important discharge contaminant, because it can create potentially toxic effects near the discharge point. Dispersed oil consists of small droplets suspended in the aqueous phase. If the dispersed oil contacts the ocean floor, contamination and accumulation of oil on ocean sediments may occur, which can disturb the benthic community (Veil et al., 2004). Dispersed oils can also rise to the surface and spread, causing sheening and increased biological oxygen demand near the mixing zone (Stephenson, 1992). Factors that affect the concentration of dispersed oil in PW include oil density, interfacial tension between oil and water phases, type and efficiency of chemical treatment, and type, size, and efficiency of the physical separation equipment (Stephenson, 1992; OGP, 2005). This criterion was evaluated quantitatively and positive values were assigned to scores.

Dissolved Oil removal efficiency (C_{110})

Dissolved Oil are likely contributors to PW toxicity, and their toxicities are additive, although individually the toxicities are insignificant, when combined, aquatic toxicity may occur (Stephenson, 1992). Reduction of dissolved oil is essential before being discharged. This criterion was evaluated quantitatively depending on the percentage removal efficiency by the management system, and positive values were assigned to criterion scores.

Metals removal efficiency (C_{111})

There are scientific concerns about the significant amount of heavy metals introduced into the marine environment by the petroleum industry during the exploration and production phases. The concentration of metals in PW depends on the field, particularly with respect to the age and geology of the formation from which the oil and gas are produced (Veil et al. 2004). Metal typically found in PW include zinc, lead, manganese, iron, mercury and barium. Metals concentrations in PW are often higher than those in the seawater (OGP 2005). However, potential impacts on marine organisms may be low, because dilution reduces the concentration (Stephenson, 1992). Many trace metals are found in PW and a few have been shown to accumulate in marine organisms significantly (Neff, 2002). Besides toxicity, metals can cause production problems. For example, iron in PW can react with oxygen in the air to produce solids, which can interfere with processing equipment, such as hydrocyclones, and can plug formations during injection. This criterion was evaluated quantitatively and scored positively.

Requirement of pre- or post-treatment (C_{112})

Most of the treatment technologies require pre- or post-treatments to improve efficiency, to achieve better quality, to handle byproducts, etc. The extent of such requirements significantly contributes to the overall performance but also adds to the cost, facilities, and technological complexity. This criterion was evaluated subjectively by the five categories shown in Table 5.1 and scored positively.

Table 5.1: Subjective scoring of pre- or post-treatment requirement criteria

Pre/Post treatment requirement	Scores
Basic: cooling, heating, settling, impoundment, etc.	0.9
Primary: pH adjustment, softening, de-oiling, suspended solids removal, + technologies	0.7
Primary: pH adjustment, softening, chemical addition, de-oiling, suspended solids removal, sand filtration, etc. + technologies	0.5
Moderate: regeneration, fouling prevention, trickling filter, constructed wetlands, ionization and removal, UF, Nano – Filtration, low pressure RO, etc. + technologies	0.3
Significant: high pressure filtration, high pressure RO, NORM treatment, etc. + technologies	0.1

Environment (C_2)

Ecological risk (C_{21})

One objective of the water treatment technology regarding the environmental impact is to minimize negative effects in the immediate marine environment. Concerning the treatment of PW, the effects to the marine environment can be determined by the concentration of the constituents discharged to the ocean by technology. Ecological risk assessment is an important tool used to determine the ecological impact. For this ecological risk assessment a tool was used to determine the ecological risk in the marine environment posed by the management systems. The hazard quotient (HQ) is the ratio of the predicted environmental concentration (PEC) and the predicted non-effect concentration (PNEC). The PEC/PNEC ratio is used to characterize the maximum environmental risk for the ecosystems. This criterion was evaluated quantitatively based on the calculated risk and negative values were used for the assigned scores.

Energy consumption (C_{22})

The energy consumption of each technology was considered the total energy used in the treatment process to treat a specific amount of PW. Due to lack of proper information linguistic terms like low, moderate, high etc. are used to express the energy consumption by the technology. Figure 5.3 in previous section was used to calculate the scores.

Solid wastes (C_{23})

During the treatment of PW, some treatment processes or other associated processes generate solid wastes. These wastes are, for example, process sludge and filter media which require further treatment or appropriate disposal. This criterion was evaluated subjectively based on the quantity and toxicity of solid wastes. The linguistic terms were directly mapped with Figure 5.3 in previous section to calculate criterion scores. Positive values were used for the assigned scores.

Liquid wastes (C_{24})

Some treatment processes or other associated processes generate liquid wastes, such as washing liquid and solvents used to extract contaminants from the PW or gas stream. These liquid wastes may or may not require appropriate treatment or disposal. This criterion was subjectively measured similarly to the solid wastes but in this study only the toxicity of the wastes was considered.

Gaseous emissions

The reduction of the total emission into the air has a high priority and is one of the most important environmental challenges connected to the oil and gas industry. At the PW treatment technology, the main greenhouse gas emissions are methane and carbon dioxide. Each greenhouse gas molecule adsorbs different quantities of radiation and has different life spans in the atmosphere. Therefore, different greenhouse gases have different contributions to the greenhouse effect. According to Hendriksen (2001), the global warming potential and acid air emission could be included as a decision criterion in the evaluation of PW treatment technology. This criterion is further divided as follows:

Green house gases emissions (C_{25})

This criterion considers the amounts of greenhouse gases generated from the treatment process. This criterion was evaluated subjectively based on the quantity of greenhouse gas emissions by treatment process. Linguistic terms like low, moderate, high etc. were used to express the quantity of gases emitted. Figure 5.3 (in previous section) was used to calculate the scores. Positive values were used for the assigned scores.

Non green house gases emissions (C_{26})

This criterion was evaluated subjectively based on the quantity of non greenhouse gases (particulate matter (PM), ammonia, and total hydrocarbons) generated from the treatment process. Linguistic terms like low, moderate, high etc. are used to express the quantity of gases generated by the technology. Figure 5.3 was used to calculate the scores. Positive values were used for the assigned scores.

Costs (C_3)

Under the costs category, capital and operational costs of the options were considered.

Capital costs (C_{31})

The rental or purchase cost in using a technology is considered under this criterion. This criterion was evaluated quantitatively by considering the actual cost required by the technology. Negative values were used for the assigning the criterion scores.

Operational costs (C_{32})

Operational costs for PW treatment systems consist of the costs involved in running the plant. These include costs for chemicals, electrical power, operation, control and maintenance. The operational cost is one of the most important factors of any treatment plant and for this reason the operational costs criteria was considered as the decision making criteria .The operational cost of a treatment system was considered based on the cost of handling a specific amount of PW. This criterion was evaluated quantitatively by considering the actual cost required by the systems. Negative values were used for the assigning the criterion scores.

Per kilogram (kg) dispersed oil removal costs (C_{33})

This cost of a technology was considered based on the actual amount of money required to remove per kg of dispersed oil from PW. This criterion was evaluated quantitatively by considering the actual cost required by the technology and negative values were used for the assigned scores.

Per kilogram (kg) dissolved oil removal costs (C_{34})

This cost of a technology was considered based on the actual amount of money required to remove per kg of dissolved oil from PW. This criterion was evaluated quantitatively by considering the actual cost required by the technology and negative values were used for the assigned scores.

Health and Safety (C_4)

In industrial operations health and safety factors should be taken care of in a special way. The possible safety impacts shall be reduced as low as possible in a reasonable manner. For a safer design the management principle should be the elimination and minimization of hazards (UKOOA, 1999). The safety and risk is dealt with a design and operational parameter in the same way as economy, production capacity and functionality (Skramstad et al. 1998). Safety aspects are of high importance in the decision of the selection of the main layout and arrangements, operational aspects and structural elements. In PW treatment, the objective is to ensure that accident and hazardous incidents such as fires, leaks or material damage have a minimum frequency of occurrence (Vinnem, 1999).

From the literature it is clear that any accident can destroy the environment and ecosystem. Considering its importance, the health and safety criterion is considered as a decision criterion in selecting the PW management system. This criterion is divided into human exposure and risks from accident as described below.

Human exposure (C_{41})

The evaluation measure for this criterion was human risks associated with handling and operating the PW treatment process. For example, the systems whose parts are covered and do not require close control by humans were assigned high scores as they prevent operators from direct contact with wastes or inhalation of volatile contaminants. This criterion was evaluated subjectively by considering the risk levels of operators. Linguistic terms such as low, moderate, high etc. were used to express the risk level by the technology, with low meaning the level of risk for an operator was minimal. Figure 5.3 was used to calculate the scores. Positive values were used for the assigned scores.

Risks of accident (C_{42})

Under this criterion, accidents which were associated with the PW management system were considered. This included fires, leaks or material damage, and spills etc. This criterion was evaluated subjectively by considering the levels of accident; Linguistic terms such as low, moderate, high etc. were used to express the accident levels by the technology, with low mean the level of accidents was minimal. Figure 5.3 was used to calculate the scores. Positive values were used for the assigned scores.

5.2.3 Evaluation measure

The evaluation measure is an important tool uses in decision problems, and it describes the performance of an action with respect to criteria, scenarios and decision makers (Beroggi, 1999). In this study evaluation measures were used to measure alternatives under the corresponding criteria, and divided into two groups. The first group included those providing quantitative values while the other provided qualitative values. The quantitative values were then normalized using single value functions, and the qualitative values were subjectively ranked and converted into numbers by conversion scales. The evaluation measures of the 24 criteria used in this study are summarized in Table 5.2.

5.3 Selection of alternatives

Alternatives are distinct potential solutions, which convert the initial state to the desired state. Alternatives should differ from each other. Alternatives can be discovered in many ways such as through brainstorming, by examination or because of requirements (Baker et al., 2001). Alternatives must be defined at a level that enables comparative analysis. This may take a good written description or diagram of the specific functions performed by the alternatives. The diagram should be adequately detailed to describe the differences between the alternatives. Generally, the alternatives should have the ability to meet the requirements and goals.

Table 5.2: Criteria and evaluation measures

No	Criteria	Measures	Scores sign
	Technical feasibility (C_1)		
1	Technical convenience (C_{11})	Subjective ranking: Considering the levels of convenience	(+)
2	Foot print (C_{12})	Quantitatively: Total area (m2)	(-)
3	Weight (C_{13})	Quantitatively: Total weight (ton)	(-)
4	Capacity (C_{14})	Quantitatively: Design capacity (M3/hr)	(+)
5	Chemical usage (C_{15})	Subjective ranking: Level of acceptance depending amount and type of chemicals use.	(+)
6	BTEX removal efficiency (C_{16})	Quantitatively: Removal Efficiency (%)	(+)
7	PAHs removal efficiency (C_{17})	Quantitatively: Removal Efficiency (%)	(+)
8	NPD removal efficiency (C_{18})	Quantitatively: Removal Efficiency (%)	(+)
9	Dispersed Oil removal efficiency (C_{19})	Quantitatively: Removal Efficiency (%)	(+)
10	Dissolved Oil removal efficiency (C_{110})	Quantitatively: Removal Efficiency (%)	(+)
11	Metals removal efficiency (C_{111})	Quantitatively: Removal Efficiency (%)	(+)
12	Requirement of pre- or post-treatment (C_{112})	Subjective ranking:	(+)
	Environment (C_2)		
13	Ecological risk (C_{21})	Quantitatively: Calculated risk	(-)
14	Energy consumption (C_{22})	Quantitatively: Total energy consume per m3 of PW (KJ/M3)	(+)
15	Solid wastes (C_{23})	Subjective ranking: Quantity and toxicity.	(+)
16	Liquid wastes (C_{24})	Subjective ranking: Volume and toxicity.	(+)
17	Green house gases emissions (C_{25})	Subjective ranking: GHG emitted	(+)
18	Non green house gases emissions (C_{26})	Subjective ranking: Non GHG emitted	(+)
	Costs (C_3)		
19	Capital costs (C_{31})	Quantitatively: Rental or purchased cost (Euro)	(-)
20	Operational costs (C_{32})	Quantitatively: Operational cost (Euro/yr)	(-)
21	Per kilogram (kg) dispersed oil removal costs (C_{33})	Quantitatively: per kg removal cost (Euro/kg)	(-)
22	Per kilogram (kg) dissolved oil removal costs (C_{34})	Quantitatively: per kg removal cost (Euro/kg)	(-)
	Health and Safety (C_4)		
23	Human exposure (C_{41})	Subjective ranking: Type and level of exposure	(+)
24	Risks of accident (C_{42})	Subjective ranking: Type and level of accident.	(+)

The PW management options which were unable to meet the regulatory oil and grease discharge standard described in Chapter 2 were not considered for further consideration.

5.3.1 Screening

Generally, the screening of selected alternatives focuses more on potential alternatives. However, as one of the purposes of this study was to provide a general idea of the PW management options suitable for offshore platform, screening the offshore applicability and regulations was given more preference.

5.4 Data Acquisition

The data required to perform the evaluation were collected from sources such as journal papers and reports. The quantitative data were collected from literature sources and qualitative data were generated through subjective judgment by a questionnaires format in Appendix-E.

5.4.1 Data Modifications

The data, which were collected from various sources, have mixed characteristics. Therefore, some modifications were needed to be made in order to use the data in this study. Some assumptions were also made in order to score the options, where data was missing. Some necessary assumptions and calculations of data for the evaluation are presented in detail in the case study in Chapter 6.

5.5 Assignment of Weights

Among many weighting methods described in Chapter 2, the AHP was selected for this evaluation when dealing with traditional methods, and the AHP weighting method, the pair wise comparison for priority of different hierarchy level was performed and the relative matrix was formed. An eigenvalue problem is considered to solve the pair-wise comparison matrix. On the other hand, when dealing with the fuzzy based approach, the FAHP was used to calculate the weighting factors. Details of this process were described in Chapter 3.

5.6 Overall Scoring

Overall scores are numbers used to represent the final ranking of the management system. Higher overall values indicate the better performance of the management system. Due to their simplicity, easily understood additive mathematical models were used to calculate overall scores, when the traditional AHP method was used. However, when the fuzzy based approach was considered, the TOPSIS technique was used for the overall scores calculation. Details of these approaches were discussed in Chapter 3.

5.7 Uncertainty analysis

In order to identify the reliability of the final results, the study also conducted uncertainty analysis. The general equation 5.3 for uncertainty analysis (Coleman and Steele, 1989) was used for this purpose, where, r is the overall value as shown in equation 5.4. After determining the values of r the simplified from of equation 5.3 is equation 5.4, was used to calculate the uncertainty.

$$U_r = \left[\left(\frac{\partial r}{\partial x_1} U_{x_1} \right)^2 + \left(\frac{\partial r}{\partial x_2} U_{x_2} \right)^2 + \dots + \left(\frac{\partial r}{\partial x_j} U_{x_j} \right)^2 \right]^{1/2} \tag{5.3}$$

$$r = \sum_{i=1}^{n} C_{ij} W_i$$

$$\text{Uncertainty (U)} = \left[\sum_{i=1}^{n} (C_{ij} W_i)^2 \right]^{1/2} \tag{5.4}$$

Where, r = data reduction factor, n is equal to number of criterion, and U_i is equal to uncertainty under the r_{ij}^{th} criteria. In this study, it is assumed that the uncertainties follow a normal distribution function with a variance of 20%. According to this assumption, the uncertainties for any mean value Ci will be 0.2Ci. From equation 5.4 substituting the values of Ci with 0.2Ci will give the final uncertainties. Where Ci = the criterion scores.

5.8 Sensitivity analysis

To determine the sensitivity of the evaluation results, this study varied the criteria weights to observe new overall values and alternative ranks. In addition this analysis assured that the weights used in the evaluation were well defined among the criteria.

Table 5.3: Alternative weights structure

Case	Criteria	Change in criteria weights
1	Technical Feasibility	30% increase others decreased
2	Environment	30% increase others decreased
3	Health & safety	30% increase others decreased
4	Cost	30% increase others decreased

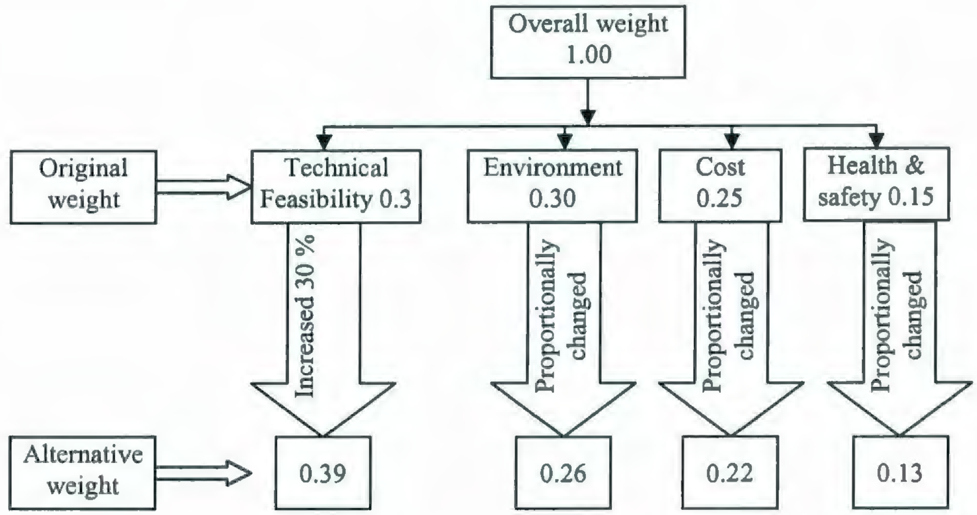

Figure 5.6: Alternative weights calculation for the criteria

Four sets of analyses (Table 5.3) were conducted by specifying new weights for one criterion or a group of criteria and adjusting the weights of the other criteria proportionally. In all cases, the total weights sumed to one. Therefore, once one criterion weight was increased, the others were decreased. For example, as shown in Figure 5.6, the weight of technical feasibility criteria 0.30 was increased by 30% and other criteria were decreased proportionally in order to make the sum of the total weights equal to one.

5.9 Summary

This chapter has discussed the evaluation methodology for the PW management system. To develop the MCDM methodology two MCDM approaches, the traditional method and the fuzzy based technique were used. Each criteria and relation to this study was discussed in detail. To determine the uncertainty it was assumed that the variance of the mean values were 20%. Sensitivity analysis was done by changing the criteria weights. In this methodology the original criteria weights were changed by 30%. Once a criterion weight was increased by 30%, others criteria weights were decreased proportionally so that the sum of all criteria weights remained one.

Chapter 6

APPLICATION OF THE PROPOSED METHODOLOGY: A HYPOTHETICAL CASE STUDY

6.1 Introduction

To demonstrate the proposed methodology a simple hypothetical case study applicable for PW management in offshore oil and gas industries was introduced. Depending on the data availability six PW treatment technologies, namely macro porous polymer extraction (A_1), steam stripping (A_2), produced water reinjection (A_3), compact flotation unit (A_4), C- tour process (A_5), and downhole oil water separation (A_6) were evaluated using 24 selected criteria. The details of these technologies were discussed in Chapter 2. Two MCDM models described in Chapter 3 were applied to rank the selected alternatives according to their performance in the oil and gas field. The following section discusses the detailed steps involved in both methodologies.

6.2 Application of traditional method

In traditional frameworks an additive value model was integrated with the AHP to enhance the decision making process. The linguistic approach was applied to capture the subjective judgment of decision makers in the absence of quantitative data. This framework is the combination of the following steps.

6.2.1 Defining criteria

The criteria were the controlling factors under which the options were scored during the evaluation. This study used four major criteria namely, technical feasibility, environmental, costs effects, and health and safety.

Table 6.1: The criteria hierarchical structure of the case study

No	Criteria	Criteria symbol
	Technical feasibility	**C_1**
1	Technical convenience	C_{11}
2	Foot print	C_{12}
3	Weight	C_{13}
4	Capacity	C_{14}
5	Chemical usage	C_{15}
6	BTEX removal efficiency	C_{16}
7	PAHs removal efficiency	C_{17}
8	NPD removal efficiency	C_{18}
9	Dispersed Oil removal efficiency	C_{19}
10	Dissolved Oil removal efficiency	C_{110}
11	Metals removal efficiency	C_{111}
12	pre- or post-treatment	C_{112}
	Environment	**C_2**
13	Ecological risk	C_{21}
14	Energy consumption	C_{22}
15	Solid wastes	C_{23}
16	Liquid wastes	C_{24}
17	Green house gases emissions	C_{25}
18	Non green house gases emissions	C_{26}
19	**Costs**	**C_3**
	Capital costs	C_{31}
20	Operational costs	C_{32}
21	Per kilogram (kg) dispersed oil removal costs	C_{33}
22	Per kilogram (kg) dissolved oil removal costs	C_{34}
23	**Health and Safety**	**C_4**
	Human exposure	C_{41}
24	Risks of accident	C_{42}

The criteria were selected based on the literature review and experience. Table 6.1 shows the criteria structure for this study. The criteria were evaluated both quantitatively and subjectively. The criteria C_{12}, C_{13}, C_{14}, C_{15}, C_{16}, C_{17}, C_{18}, C_{19}, C_{110}, C_{111}, C_{21}, C_{31}, C_{32}, C_{33}, and C_{34} were considered quantitative and the other criteria were treated subjectively. Depending on the course of action the criteria were given positive (+) or negative (-) scores. For positive (+) scores it was assumed that the high values for the criteria were preferable, on the other hand negative (-) signs indicated low values of the criteria, less desirable. For example weight criteria, for offshore installations should be as low as possible and low values were preferred for the criteria.

6.2.2 Data Acquisition

Two types of data were used in this study; quantitative and qualitative. Quantitative data are measurable numerical values which can be expressed by a unit such as ton, meter, etc and the qualitative data are non measurable and represent the quality of the products. Linguistic terms like very good, good, bad, very bad etc were used to represent the qualitative data. The linguistic judgement was converted to numeric values by the appropriate conversion scale.

Quantitative data

Quantitative data such as the weight and size were collected from different sources including OSPAR (2002, 2006) and Ekins et al. (2005) and reported in Appendix-A. In the case where authentic quantitative data for an alternative was not found the criteria mean values were calculated with equation 5.2 and used as alternative values, and at the same time the associated uncertainties were assigned 20% for these criteria. The data were then normalized to unity with the equation 5.1. Normalized values for different alternatives are reported in Table 6.2.

Table 6.2: Aalternatives' normalized scores for quantitative criteria

		Normalized scores					
C_1	Technical Feasibility	A1	A2	A3	A4	A5	A6
C_{12}	Foot print	-0.248	-0.331	-0.265	-0.113	-0.044	0.000
C_{13}	Weight	-0.268	-0.244	-0.244	-0.195	-0.049	0.000
C_{14}	Capacity	0.011	0.007	0.007	0.592	0.192	0.192
C_{16}	BTEX removal efficiency	0.248	0.226	0.251	0.150	0.000	0.125
C_{17}	PAHs removal efficiency	0.237	0.215	0.239	0.094	0.094	0.120
C_{18}	NPD removal efficiency	0.232	0.211	0.235	0.040	0.164	0.117
C_{19}	Dispersed Oil removal efficiency	0.217	0.186	0.219	0.137	0.131	0.110
C_{110}	Dissolved Oil removal efficiency	0.292	0.265	0.295	0.000	0.000	0.147
C_{111}	Metals removal efficiency	0.000	0.000	0.667	0.000	0.000	0.333
C_2	**Environment**	-	-	-	-	-	-
C_{21}	Ecological risk	-0.217	-0.218	-0.002	-0.224	-0.224	-0.114
C_3	**Costs**	-	-	-	-	-	-
C_{31}	Capital costs	-0.039	-0.064	-0.465	-0.167	-0.167	-0.098
C_{32}	Operational costs	-0.048	-0.075	-0.402	-0.167	-0.167	-0.142
C_{33}	Per kilogram (kg) dispersed oil removal costs	-0.035	-0.055	-0.383	-0.167	-0.167	-0.193
C_{34}	Per kilogram (kg) dissolved oil removal costs	-0.110	-0.018	-0.534	-0.167	-0.167	-0.004

Qualitative /Subjective data

For this study the subjective criteria were judged according to questionnaires in Appendix E. Details of subjective rankings were discussed in Chapter 5. Three expert's judgments were proposed to eliminate the judgment ambiguity. The linguistic terms described in Chapter 5 were used to assign the subjective judgments. The detailed judgments are reported in Table 6.3. To calculate the crisp scores the linguistic terms are directly mapped with the respective conversion scales described in Chapter 5.

Table 6.3: Subjective judgment of alternatives

	Alternatives	C_{11}	C_{15}	C_{112}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{41}	C_{42}
Expert -1	A_1	MC	L	B	L	M	M	L	M	M	L
	A_2	HC	L	B	L	L	L	L	M	M	L
	A3	MC	M	C	H	M	M	H	H	M	M
	A4	HC	M	B	L	M	M	L	M	M	M
	A5	HC	M	B	M	L	L	M	M	M	M
	A6	LC	M	D	H	M	M	H	H	M	M
Expert -2	A_1	HC	M	B	L	M	M	M	M	L	M
	A_2	MC	M	B	L	L	L	M	L	L	M
	A3	LC	M	C	H	M	M	M	M	M	M
	A4	HC	L	B	L	L	L	M	M	M	L
	A5	MC	M	B	M	M	M	M	M	L	M
	A6	LC	M	D	H	M	M	H	M	M	M
Expert -3	A_1	MC	M	B	M	L	L	M	M	M	M
	A_2	HC	L	B	M	L	L	M	L	M	M
	A3	LC	M	C	M	L	L	M	M	M	M
	A4	MC	L	B	L	L	L	M	M	M	L
	A5	HC	M	B	M	M	M	M	M	M	M
	A6	MC	L	C	M	M	M	M	M	M	M

The average crisp score was considered the criteria score. For example the subjective scores for criteria C_{11} for alternative A_1 were calculated as:

Score C_{15} = - (L+M+M)/3 = (0.9+0.7+0.7)/3 = 0.767.

Similarly all subjective judgments were scores for different criteria and are reported in Table 6.4.

Table 6.4: Alternatives scores for subjective criteria

Alternatives	C_{11}	C_{15}	C_{112}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{41}	C_{42}
A_1	0.633	0.833	0.700	0.833	0.767	0.767	0.767	0.767	0.767	0.767
A_2	0.633	0.833	0.700	0.833	0.900	0.900	0.767	0.833	0.767	0.767
A3	0.367	0.700	0.500	0.567	0.767	0.767	0.633	0.633	0.700	0.700
A4	0.633	0.833	0.700	0.900	0.833	0.833	0.767	0.700	0.700	0.833
A5	0.633	0.700	0.700	0.700	0.767	0.767	0.700	0.700	0.767	0.700
A6	0.367	0.767	0.367	0.567	0.700	0.700	0.567	0.633	0.700	0.700

6.2.3 Weights calculation

Once the decision hierarchy was constructed, the next important task was the weight calculation for the criteria. When dealing with the traditional method, the AHP mentioned in Chapter 3 was used to calculate criteria weights. Pair-wise comparisons were made between the elements at each level of the hierarchy with respect to the connected element in the level above. In order to make comparisons between the elements at each level of the hierarchy, the pair-wise comparisons matrix (PCM) was judged for different hierarchy levels as matrixes A_G for the top level, and matrix A_{C1}, A_{C2}, and A_{C3} represented the PCM under criteria C_1, C_2, and C_3 respectively. It was assumed that the sub-criteria under criterion C_4 were equally important. The individual PCM with consistency ratios of less than 0.1 were aggregated using the geometric mean method discussed in Chapter 3. The matrix A_G represents the PCM with respect to a goal. The maximum eigenvalue of

A_G was found to be $\lambda_{max} = 4.29$ and the corresponding eigenvectors are shown in Table 6.5.

Matrix A_G

	C1	C2	C3	C4
C1	1	1.0	4	2
C2	1.0	1	2	3
C3	0.25	0.5	1	5
C4	0.5	0.333	0.2	1

Table 6.5: Eigenvector of PCM A_G

C_1	C_2	C_3	C_4
0.40	0.32	0.20	0.08

Matrix A_{C1}

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{110}	C_{111}	C_{112}
C_{11}	1	1.27	0.91	1.04	0.96	0.96	0.97	0.98	0.99	0.97	0.98	0.99
C_{12}	0.79	1	0.79	1.09	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
C_{13}	1.09	1.27	1	1.27	1.04	1.01	1.01	1.01	1.01	1.01	1.01	1.01
C_{14}	0.97	0.92	0.79	1	0.86	0.96	0.97	0.98	0.99	0.97	0.98	0.99
C_{15}	1.04	1.00	0.97	1.16	1	1.01	1.01	1.01	1.01	1.01	1.01	1.01
C_{16}	1.04	1.00	1.00	1.04	1.00	1	1.27	0.91	1.04	1.27	0.91	1.04
C_{17}	1.03	0.99	0.99	1.03	0.99	0.79	1	0.79	1.09	1.27	0.91	1.04
C_{18}	1.02	0.99	0.99	1.02	0.99	1.09	1.27	1	1.27	1.27	0.91	1.04
C_{19}	1.01	1.00	1.00	1.01	1.00	0.97	0.92	0.79	1	1.27	0.91	1.04
C_{110}	1.03	0.99	0.99	1.03	0.99	0.79	0.79	0.79	0.79	1	0.91	1.04
C_{111}	1.02	0.99	0.99	1.02	0.99	1.09	1.09	1.09	1.09	1.09	1	1.04
C_{112}	1.01	1.00	1.00	1.01	1.00	0.97	0.97	0.97	0.97	0.97	0.97	1

Matrix A_{C2}

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}
C_{21}	1	1.267	0.915	1.036	0.962	0.962
C_{22}	0.789	1	0.790	1.087	1.005	1.005
C_{23}	1.093	1.266	1	1.272	1.036	1.005
C_{24}	0.965	0.920	0.786	1	0.859	0.962
C_{25}	1.04	0.995	0.965	1.164	1	1.005
C_{26}	1.04	0.995	0.995	1.040	0.995	1

The consistency ratio (CR) was calculated with equations 3.25 and 3.26 and found for matrix A_G to be 0.080, which is less than 0.1, so the matrix A_G with respect to the goal can be considered to be consistent. The eigenvector of the PCM was considered to be the normalized weight factors of the corresponding criteria. Similarly the maximum eigenvalue (λ_{max}) of the remaining PCM A_{C1}, A_{C2}, and A_{C3}, were found to be 12.035, 6.012 and 4.029 respectively.

Matrix A_{C3}

	C_{31}	C_{32}	C_{33}	C_{34}
C_{31}	1	1.267	1.093	1.036
C_{32}	0.789	1	1.266	1.088
C_{33}	0.915	0.79	1	1.272
C_{34}	0.965	0.92	0.786	1

The weighting factors of these matrixes were calculated from the corresponding eigenvector and normalized to the upper level weight factors. A simple example is given here to show the weighting calculation procedure. For the matrix AC_3 the eigenvectors were found to be 1.09, 1.019, 0.979 and 0.911 for the criteria C_{31}, C_{32}, C_{33} and C_{34} respectively, and then the weighting factors were calculated as shown in Table 6.6.

Table 6.6: Example for weight factors calculation

Criteria	eigenvector	Weights factors
C_{31}	1.090	= (1.090*0.2)/4.0 = 0.055
C_{32}	1.019	= (1.019*0.2)/4.0 = 0.051
C_{33}	0.979	= (0.979*0.2)/4.0 = 0.049
C_{34}	0.911	= (0.911*0.2)/4.0 = 0.046
Sum=	4.000	

Similarly all weighting factors were calculated and reported in Table 6.7. The CR of the PCM A_{C1}, A_{C2}, and A_{C3}, were found to be 0.002, 0.01 and 0.003 respectively which indicates that the PCMs A_{C1}, A_{C2}, and A_{C3}, have adequate consistency.

Table 6.7: Weighting factors of criteria and subcriteria

Criteria	Criteria symbol	Weights
Technical feasibility	**C_1 (0.40)**	
Technical convenience	C_{11}	0.033
Foot print	C_{12}	0.032
Weight	C_{13}	0.035
Capacity	C_{14}	0.031
Chemical usage	C_{15}	0.034
BTEX removal efficiency	C_{16}	0.035
PAHs removal efficiency	C_{17}	0.033
NPD removal efficiency	C_{18}	0.036
Dispersed Oil removal efficiency	C_{19}	0.033
Dissolved Oil removal efficiency	C_{110}	0.031
Metals removal efficiency	C_{111}	0.035
pre- or post-treatment	C_{112}	0.033
Environment	**C_2 (0.32)**	
Ecological risk	C_{21}	0.054
Energy consumption	C_{22}	0.050
Solid wastes	C_{23}	0.059
Liquid wastes	C_{24}	0.049
Green house gases emissions	C_{25}	0.055
Non green house gases emissions	C_{26}	0.054
Costs	**C_3 (0.2)**	
Capital costs	C_{31}	0.055
Operational costs	C_{32}	0.051
Per kilogram (kg) dispersed oil removal costs	C_{33}	0.049
Per kilogram (kg) dissolved oil removal costs	C_{34}	0.046
Health and Safety	**C_4 (0.08)**	
Human exposure	C_{41}	0.04
Risks of accident	C_{42}	0.04

6.2.4 Determining the overall score for each alternative

The overall scores V_i are dimensionless numbers, where higher V_i values indicate better performance of the alternatives. By comparing V_i's the decision maker can directly identify the best alternatives. For the traditional method, V_i for each alternative was computed by using equation 3.33 and they are reported in Figure 6.1.

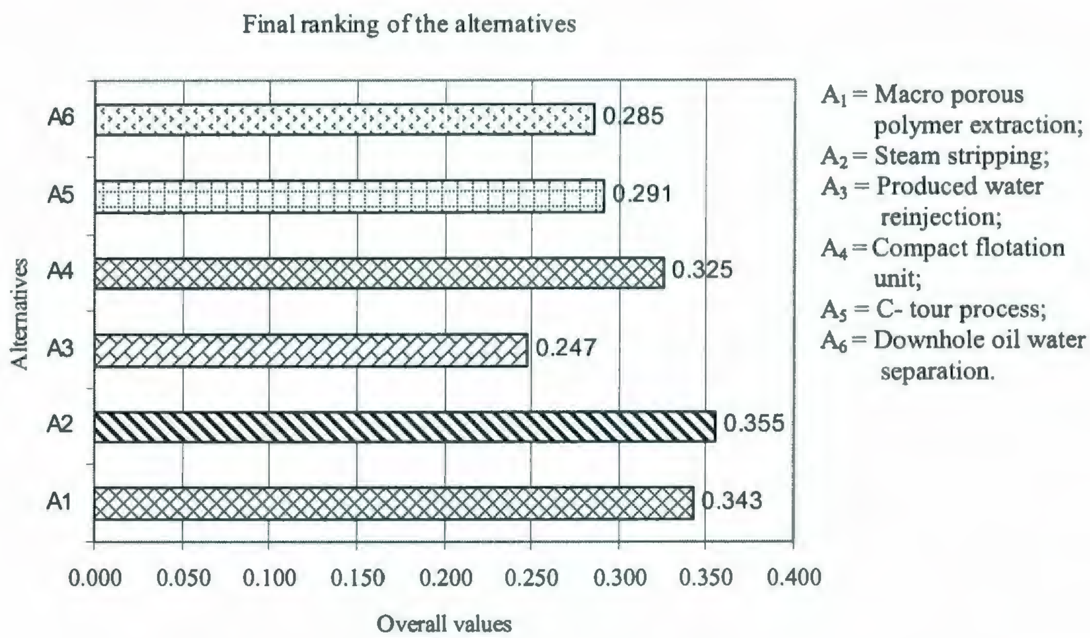

Figure 6.1: Final overall scores and ranking of the alternatives

According to the calculated overall scores for each PW management option presented in Figure 6-1, the three best alternatives were A_2, A_1 and A_4. The technologies attained the overall values of 0.355, 0.343, and 0.325 respectively. Therefore, based on the overall values alone, these three options can be considered the optimum alternatives for PW management under the established set of criteria. The alternative A_5, which ranks fourth in this evaluation, obtained slightly lower overall scores than alternative A_4. This option is in the development stage, so only a few pilot tests have been conducted on offshore platforms, so alternative A_5 can be considered the most promising option for future offshore applications. To determine the dominating criteria the overall scores for the each principle criteria were calculated as shown in Figure 6.2.

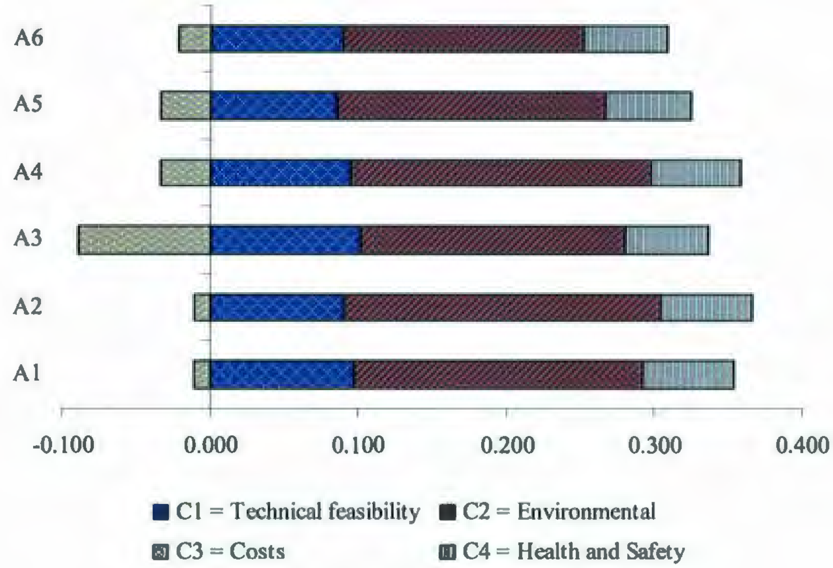

Figure 6.2: Criteria scores of each alternative

Analyzing Figure 6.2 it is found that the loss criteria scores for the alternative A_3 are the highest which indicated the alternative A_3 is more costly than the other alternatives. The higher loss scores also indicated alternative A_3 occupies the largest footprint and has more weights than the other alternatives. For the criteria C_2, the reverse scenario is found as, in this case alternative A_3 has gained the maximum overall scores meaning the alternative A_3 is technically better than the other alternatives. The overall scores of criteria C_3 indicated that alternative A_2 had gained the maximum values, which means alternative A_2 is the most environmental friendly alternative. In this case alternative A_3

had the least overall scores because A_3 generated large volumes of waste and the air emission from this technology was also more than the other alternatives, because it consumed high quantities of energy during operations. For criteria C_4 all alternatives gained approximately the same overall values meaning the health and safety issues for all alternatives were almost equal.

6.2.5 Uncertainty analysis

Uncertainty of this study could have arisen due to subjective judgments and unknown data. According to Modarres (2006) the variance (σ_{Ai}) of the data distribution can be considered as the uncertainty. In this study it wsa assumed that the uncertainties followed a normal distribution. By this assumption the uncertainties were considered 20% for all unknown data scores and the mean criteria scores were used to calculate uncertainty. Table 6.8 provides a simple example of an uncertainty calculation.

Table 6.8: Variance of criteria

	Alternatives (A_1)	
Criteria	Mean scores (μ_{A1})	Criteria uncertainty (C_u)= 20% of μ_{A1}
C_{41}	0.76	0.15
C_{42}	0.76	0.15

The uncertainties for the overall values were calculated by using equation 5.4 and replacing Ci with C_u and W_i by weighting factors of the corresponding criteria. The estimated uncertainty values for the alternatives are listed in Table 6.9. These values are relative uncertainties because in this study the uncertainty was assumed to be 20% for unknown data and the subjective scoring these values might have varied depending on the data availability and subjective judgements. The calculated uncertainties for different alternatives were added and subtracted with the overall scores to find the variations of the overall scores. Figure 6.3 is re presents the variation of overall scores.

Table 6.9: Associated uncertainties of evaluation options

Alternatives	Uncertainty
A_1	0.027
A_2	0.027
A_3	0.022
A_4	0.033
A_5	0.032
A_6	0.021

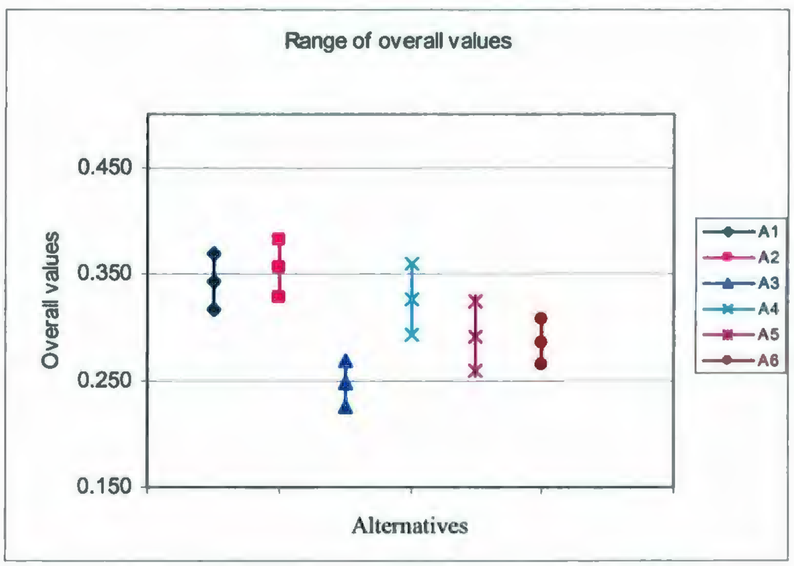

Figure 6.3: Variation of the overall scores

According to Figure 6.3, the alternatives A_1 and A_2 provided the highest overall values with the same uncertainty. Though the overall scores for alternatives A_6 were slightly lower than forth ranked alternative A_5 it had the lowest uncertainty. Considering uncertainty, the alternative A_6 was the forth ranked option.

6.2.6 Sensitivity analysis

To determine the sensitivity of the evaluation, the criteria weights were varied and new overall values and alternative ranks were determined. According to the principle described in Chapter 5 (Table 5.3) four sets of analyses were conducted by increasing the weight for one criterion or a group of criteria and proportionally decreasing the weights of the other criteria. In all cases, the total weight remained constant. In this case, the criteria weights were increased by 30% and other criteria weights were decreased proportionally. The results of the sensitivity analysis are shown Figure 6.4.

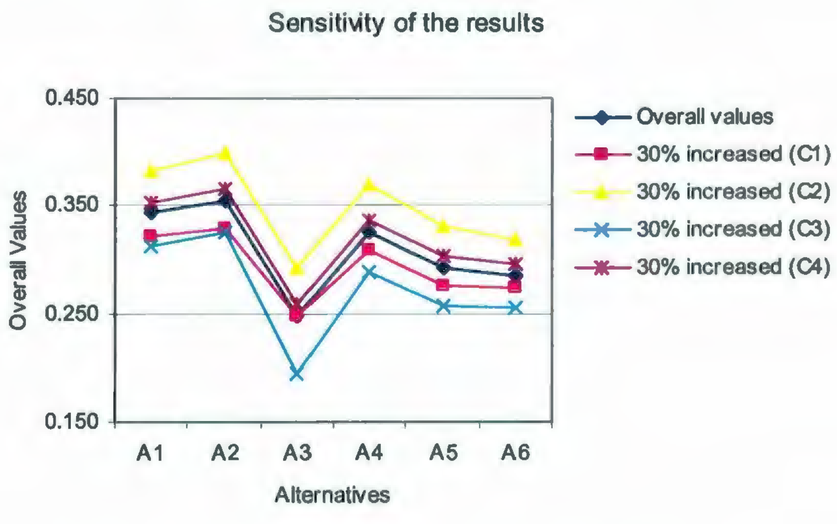

Figure 6.4: Sensitivity analysis of the overall values

6.3 Application of the fuzzy based concept

The traditional AHP was modified to give a fuzzy AHP. This methodology integrated the TOPSIS algorithm with the fuzzy AHP to solve the decision matrix. The essential steps of this framework can be described as follows:

6.3.1 Collection and ranking of the subjective data

The fuzzy scores were generated according to the subjective judgments shown in Table 6.3. The triangular fuzzy numbers (TFNs) shown in Figure 6.5 were used to generate fuzzy data from the subjective judgments. The linguistic terms used in the subjective judgments were directly converted to fuzzy scoring with the help of conversion scales shown in Figure 6.5. The average values of the judgments (shown in Table 6.3) were used to form fuzzy data. The detailed fuzzy data for the alternatives are reported in Table 6.10.

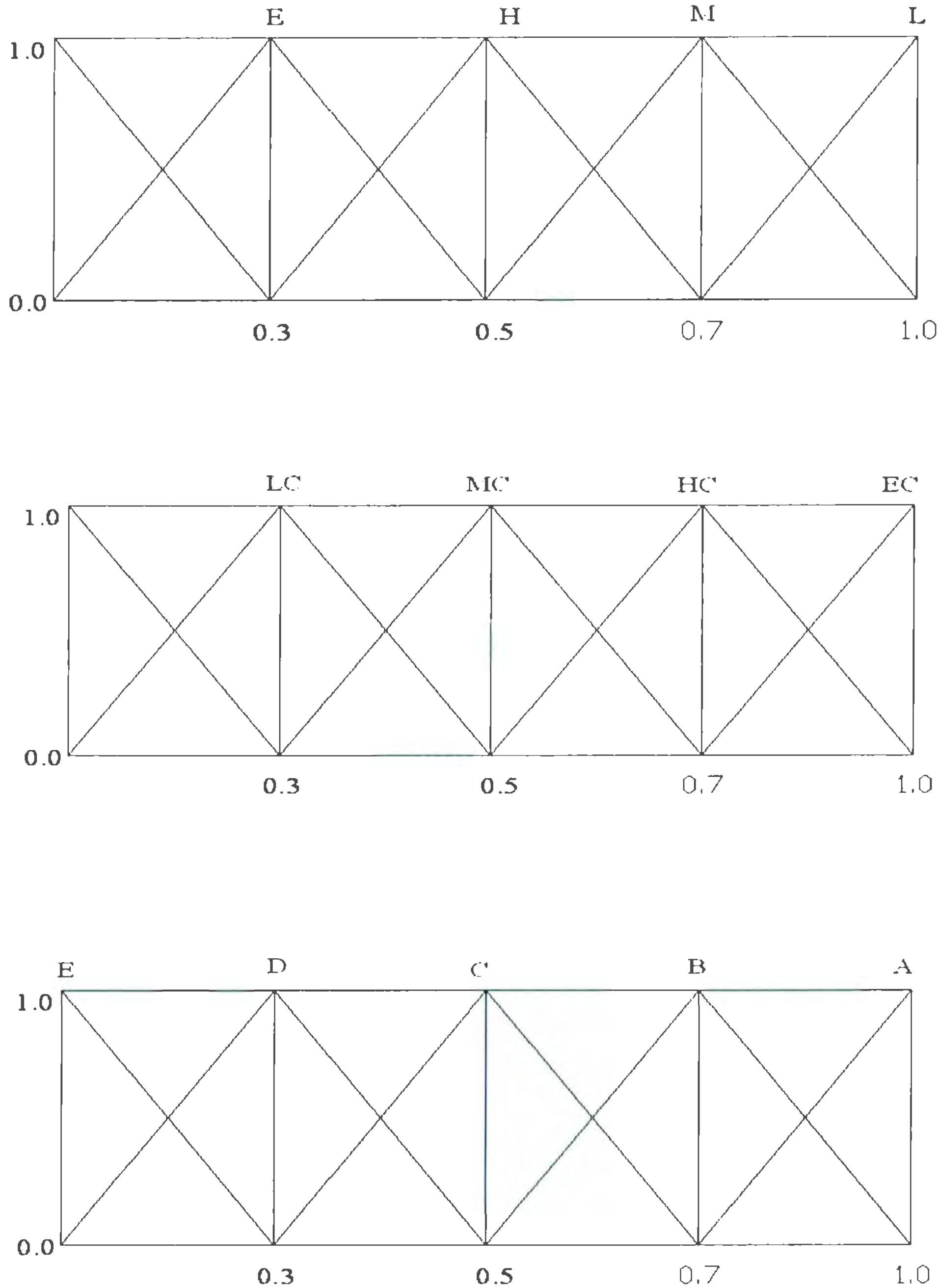

Figure 6.5: Linguistic variable conversion scales for the fuzzy method

Table 6.10: Fuzzy average data values

Alternatives / Criteria	A_1	A_2	A3	A4	A5	A6
C_{11}	0.43 0.63 1.0	0.43 0.63 1.0	0.1 0.37 0.57	0.43 0.63 0.90	0.43 0.63 0.90	0.1 0.37 0.57
C_{15}	0.63 0..90 1.0	0.43 0.63 1.0	0.5 0.7 1.0	0.63 0..90 1.0	0.5 0.7 1.0	0.57 0.8 1.0
C_{112}	0.5 0.7 1.0	0.5 0.7 1.0	0.3 0.5 0.7	0.5 0.7 1.0	0.5 0.7 1.0	0.1 0.37 0.57
C_{22}	0.63 0.90 1.0	0.63 0.90 1.0	0.37 0.57 0.80	0.7 1.0 1.0	0.5 0.7 1.0	0.37 0.57 0.80
C_{23}	0.57 0.8 1.0	0.7 1.0 1.0	0.57 0.8 1.0	0.63 0.90 1.0	0.57 0.8 1.0	0.5 0.7 1.0
C_{24}	0.57 0.8 1.0	0.7 1.0 1.0	0.57 0.8 1.0	0.63 0.90 1.0	0.57 0.8 1.0	0.5 0.7 1.0
C_{25}	0.57 0.8 1.0	0.57 0.8 1.0	0.43 0.63 1.0	0.57 0.8 1.0	0.5 0.7 1.0	0.37 0.57 0.80
C_{26}	0.57 0.8 1.0	0.63 0..90 1.0	0.43 0.63 1.0	0.5 0.7 1.0	0.5 0.7 1.0	0.43 0.63 0.90
C_{41}	0.57 0.8 1.0	0.57 0.8 1.0	0.5 0.7 1.0	0.5 0.7 1.0	0.57 0.8 1.0	0.5 0.7 1.0
C_{42}	0.57 0.8 1.0	0.57 0.8 1.0	0.5 0.7 1.0	0.63 0..90 1.0	0.5 0.7 1.0	0.5 0.7 1.0

6.3.2 Ranking of fuzzy data

The data shown in Table 6.10 are also fuzzy; the straight forward addition is not applicable. Crisp values are necessary to compare the criteria. The crisp values for fuzzy data were calculated by Yager's Centroid Index Ranking Method (1980b) described in Chapter 3. A sample example is given here to demonstrate this method. Consider the fuzzy numbers 0.43, 0.63, and 1.0 from Table 6.10, which can be characterized by the membership function as:

$$\mu_M(x) = \begin{cases} \dfrac{x-0.43}{0.20}, & 0.43 \le x \le 0.63....(Left \quad leg) \\ \dfrac{1.0-x}{0.37}, & 0.63 \le x \le 1.0....(Right \quad leg) \end{cases}$$

The crisp value X_M can be computed by equation 3.16 as:

$$X_M = \frac{\int_{0.43}^{0.63} (x * \frac{x-0.43}{0.20})dx + \int_{0.63}^{1.0} (x * \frac{1-x}{0.37})dx}{\int_{0.43}^{0.63} (\frac{x-0.43}{0.20})dx + \int_{0.63}^{1} (\frac{1.0-x}{0.37})dx}$$

$$X_M = \frac{0.196}{0.285} = 0.687$$

Similarly the crisps scores for all fuzzy data (in Table 6.10) were calculated and they are reported in Table 6.11

Table 6.11: Crisp scores of fuzzy average data

Alternatives / Criteria	A_1	A_2	A3	A4	A5	A6
C_{11}	0.687	0.687	0.347	0.653	0.653	0.347
C_{15}	0.843	0.687	0.733	0.843	0.733	0.790
C_{112}	0.733	0.733	0.500	0.733	0.733	0.347
C_{22}	0.843	0.843	0.580	0.850	0.733	0.580
C_{23}	0.790	0.850	0.790	0.843	0.790	0.733
C_{24}	0.790	0.850	0.790	0.843	0.790	0.733
C_{25}	0.790	0.790	0.687	0.790	0.733	0.580
C_{26}	0.790	0.843	0.687	0.733	0.733	0.653
C_{41}	0.790	0.790	0.733	0.733	0.790	0.733
C_{42}	0.790	0.790	0.733	0.843	0.733	0.733

6.3.3 Weight calculation using the fuzzy AHP

To form the fuzzy pair wise comparison matrix (FPCM), the original PCM A_G was fuzzified according to the TFNs described in Chapter 3 (Table 3.3), and formed the FPCM A_{FG}. Fuzzy extent analysis described Chapter 3 was applied on the A_{FG} to calculate fuzzy weight factors. The following section describes the detailed steps involved in the fuzzy extent analysis.

Matrix A_{FG}

	C1	C2	C3	C4
C1	1 1 1	1 1 1	2 4 6	1 2 4
C2	1 1 1	1 1 1	1 2 4	1 3 5
C3	0.17 0.25 0.5	0.25 0.5 1	1 1 1	3 5 7
C4	0.25 0.5 1	0.2 0.34 1	0.14 0.2 0.34	1 1 1

Calculating element wise and row summing of the FPCM A_{FG}:

Left = 1+1+2+1+1+1+1+1+0.17+0.25+1+3+0.25+0.2+0.14+1 =15.04

Middle = 1+1+4+2+1+1+2+3+0.25+0.5+1+5+0.5+0.34+.02+1 =23.79

Right = 1+1+6+4+1+1+4+5+0.5+1+1+7+1+1+0.34+1 =35.84

Row sum of the FPCM A_{FG}:

	Left	Middle	right
first row	5.00	8.00	12.00
2nd row	4.00	7.00	11.00
3rd row	4.45	6.75	9.50
4th row	1.59	2.04	3.34

The lower values of the weighting factors for C1= 5.0/35.84 = 0.14

The middle values of the weighting factors for C1= 8.0/23.79 = 0.336

The right values of the weighting factors for C_1= 12.0/15.04 = 0.798. Similarly weighting factors C_2, C_3, and C_4 were calculated and they are reported in Table 6.12.

Table 6.12: Fuzzy weighting factors for PCM A_{FG}

Criteria	Left	Middle	right
C1	0.140	0.336	0.798
C2	0.112	0.294	0.731
C3	0.124	0.284	0.632
C4	0.044	0.086	0.222

The calculated weights are also fuzzy. To obtain crisp values equation 3.16 was used. The crisp values W were than normalized to unity to get the final normalized weighted values.

$$W = \begin{bmatrix} 0.425 \\ 0.379 \\ 0.347 \\ 0.117 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} \qquad W^T = \begin{bmatrix} 0.335 \\ 0.299 \\ 0.274 \\ 0.092 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} \tag{6.1}$$

Where, W^T are the normalized weights for the criteria. To calculate the subcriteria weights the PCM A_{C1}, A_{C2} and A_{C3} were used and normalized to the corresponding upper level weights. It was assumed, the sub criteria under C_4 were of equal importance. Table 6.13 is shows the calculated weights from the fuzzy analysis.

Table 6.13: Criteria weights for fuzzy analysis

Criteria	Criteria symbol	Weights
Technical feasibility	**C_1 (0.335)**	
Technical convenience	C_{11}	0.028
Foot print	C_{12}	0.027
Weight	C_{13}	0.029
Capacity	C_{14}	0.026
Chemical usage	C_{15}	0.028
BTEX removal efficiency	C_{16}	0.029
PAHs removal efficiency	C_{17}	0.028
NPD removal efficiency	C_{18}	0.030
Dispersed Oil removal efficiency	C_{19}	0.027
Dissolved Oil removal efficiency	C_{110}	0.026
Metals removal efficiency	C_{111}	0.029
pre- or post-treatment	C_{112}	0.027
Environment	**C_2 (0.299)**	
Ecological risk	C_{21}	0.051
Energy consumption	C_{22}	0.047
Solid wastes	C_{23}	0.055
Liquid wastes	C_{24}	0.045
Green house gases emissions	C_{25}	0.051
Non green house gases emissions	C_{26}	0.050
Costs	**C_3 (0.274)**	
Capital costs	C_{31}	0.075
Operational costs	C_{32}	0.070
Per kilogram (kg) dispersed oil removal costs	C_{33}	0.067
Per kilogram (kg) dissolved oil removal costs	C_{34}	0.062
Health and Safety	**C_4 (0.092)**	
Human exposure	C_{41}	0.046
Risks of accident	C_{42}	0.046

6.3.4 Application of the TOPSIS

The decision matrix (DM) for this problem was established presenting alternatives on the X axis and criteria values on Y axis. To form the DM the values in Table 6.11 and Appendix - A were used. The DM was then normalized by equation 3.27. The normalized matrix (Table 6.14) was than multiplied by the weighting factors (in Table 6.13) to form the weighted normalized decision matrix as shown in Table 6.15. After constructing the weighted normalized DM the positive ideal solution (PIS) and negative ideal (NIS) solution values were determined with equations 3.28 and equation 3.29 and they are reported in Table 6.16. The separation measure D_1^+ and D_1^- were calculated by using equations 3.30 and equation 3.31 and they are reported in Table 6.17.

Table 6.14: Normalized decision matrix for the problem

Alternatives / Criteria	A_1	A_2	A3	A4	A5	A6
C_{11}	0.687	0.687	0.347	0.653	0.653	0.347
*C_{12}	0.248	0.331	0.265	0.113	0.044	0.000
*C_{13}	0.268	0.244	0.244	0.195	0.049	0.000
C_{14}	0.011	0.007	0.007	0.592	0.192	0.192
C_{15}	0.843	0.687	0.733	0.843	0.733	0.790
C_{16}	0.248	0.226	0.251	0.150	0.000	0.125
C_{17}	0.237	0.215	0.239	0.094	0.094	0.120
C_{18}	0.232	0.211	0.235	0.040	0.164	0.117
C_{19}	0.217	0.186	0.219	0.137	0.131	0.110
C_{110}	0.292	0.265	0.295	0.000	0.000	0.147
C_{111}	0.000	0.000	0.667	0.000	0.000	0.333
C_{112}	0.733	0.733	0.500	0.733	0.733	0.347
*C_{21}	0.217	0.218	0.002	0.224	0.224	0.114
C_{22}	0.843	0.843	0.580	0.850	0.733	0.580
C_{23}	0.790	0.850	0.790	0.843	0.790	0.733
C_{24}	0.790	0.850	0.790	0.843	0.790	0.733
C_{25}	0.790	0.790	0.687	0.790	0.733	0.580
C_{26}	0.790	0.843	0.687	0.733	0.733	0.653
*C_{31}	0.039	0.064	0.465	0.167	0.167	0.098
*C_{32}	0.048	0.075	0.402	0.167	0.167	0.142
*C_{33}	0.035	0.055	0.383	0.167	0.167	0.193
*C_{34}	0.110	0.018	0.534	0.167	0.167	0.004
C_{41}	0.790	0.790	0.733	0.733	0.790	0.733
C_{42}	0.790	0.790	0.733	0.843	0.733	0.733

* indicate loss criteria

Table 6.15: Weighted normalized decision matrix for the problem

Alternatives / Criteria	A_1	A_2	A3	A4	A5	A6
C_{11}	0.019	0.019	0.010	0.018	0.018	0.010
*C_{12}	0.007	0.009	0.007	0.003	0.001	0.000
*C_{13}	0.008	0.007	0.007	0.006	0.001	0.000
C_{14}	0.000	0.000	0.000	0.015	0.005	0.005
C_{15}	0.024	0.019	0.021	0.024	0.021	0.022
C_{16}	0.007	0.007	0.007	0.004	0.000	0.004
C_{17}	0.007	0.006	0.007	0.003	0.003	0.003
C_{18}	0.007	0.006	0.007	0.001	0.005	0.004
C_{19}	0.006	0.005	0.006	0.004	0.004	0.003
C_{110}	0.008	0.007	0.008	0.000	0.000	0.004
C_{111}	0.000	0.000	0.019	0.000	0.000	0.010
C_{112}	0.020	0.020	0.014	0.020	0.020	0.009
C_{21}	0.011	0.011	0.000	0.011	0.011	0.006
C_{22}	0.040	0.040	0.027	0.040	0.034	0.027
C_{23}	0.043	0.047	0.043	0.046	0.043	0.040
C_{24}	0.036	0.038	0.036	0.038	0.036	0.033
C_{25}	0.040	0.040	0.035	0.040	0.037	0.030
C_{26}	0.040	0.042	0.034	0.037	0.037	0.033
*C_{31}	0.003	0.005	0.035	0.013	0.013	0.007
*C_{32}	0.003	0.005	0.028	0.012	0.012	0.010
*C_{33}	0.002	0.004	0.026	0.011	0.011	0.013
*C_{34}	0.007	0.001	0.033	0.010	0.010	0.000
C_{41}	0.036	0.036	0.034	0.034	0.036	0.034
C_{42}	0.036	0.036	0.034	0.039	0.034	0.034

The final scores of each alternative were obtained using equation 3.32. For example the final score of alternative A_1 can be calculated as:

$$A_1 = \frac{0.024}{(0.077 + 0.024)} = 0.240$$

The final scores of all the alternatives were similarly calculated and they are shown in Figure 6.6.

Table 6.16: Determination of positive and negative ideal solutions

Criteria	V^{+}	V^{-}
C_{11}	0.019	0.010
*C_{12}	0.000	0.009
*C_{13}	0.000	0.008
C_{14}	0.015	0.000
C_{15}	0.024	0.019
C_{16}	0.007	0.000
C_{17}	0.007	0.003
C_{18}	0.007	0.001
C_{19}	0.006	0.003
C_{110}	0.008	0.000
C_{111}	0.019	0.000
C_{112}	0.020	0.009
C_{21}	0.000	0.011
C_{22}	0.040	0.027
C_{23}	0.047	0.040
C_{24}	0.038	0.033
C_{25}	0.040	0.030
C_{26}	0.042	0.033
*C_{31}	0.003	0.035
*C_{32}	0.003	0.028
*C_{33}	0.002	0.026
*C_{34}	0.000	0.033
C_{41}	0.036	0.034
C_{42}	0.039	0.034

Table 6.17. Separation measure D_i^{+} of each alternative

Alternatives	separation measure D_i^{+}	separation measure D_i^{-}
A_1	0.077	0.024
A_2	0.087	0.028
A_3	0.131	0.075
A_4	0.102	0.043
A_5	0.099	0.042
A_6	0.092	0.043

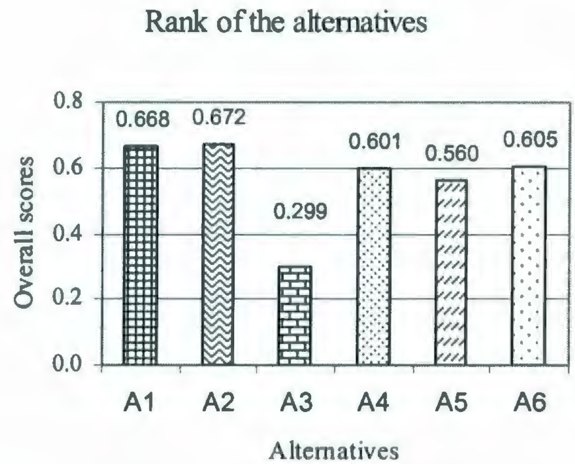

Figure 6.6: Rank of the alternatives from fuzzy methods

From the overall scores for each PW management option presented in Figure 6-6, the two best alternatives A_2, and A_1 were found to be similar in rank with the traditional method described in the previous sections. The technologies A_2, and A_1 attained overall values of 0.672 and 0.668 respectively, the third rank was found changed from the previous analysis. The Figure 6.6 shows the alternative A_4 and A_6 gained almost the same scores. Therefore, based on the overall values alone, these options A_2, and A_1 can be considered the optimum alternatives for PW management under the established set of criteria. The alternative A_5 is at the developmental stage, but was ranked fifth with overall scores of 0.560. Alternative A_5 can be considered the most promising option for future offshore applications.

6.4 Final ranking

The additive ranking rule was used to determine the average ranking order of an alternative (A_i), which is the arithmetic mean of the rankings made by all the ranking methods.

6.5 Summary

A hypothetical case study related to PW management for an offshore platform was considered to illustrate the proposed framework. The traditional and fuzzy based techniques were applied on the same case study. The results form both techniques are summarised in Table 6.18. The results shown almost similar ranking in the two methods.

Table 6.18: Ranking order of various PW management options

Alternatives	Traditional method		Fuzzy based method		Final ranking order, R_{Ai}
	Overall Scores (V_i)	Order	Overall scores (V_i)	Order	
A_1	0.343	2	0.668	2	2
A_2	0.355	1	0.672	1	1
A_3	0.247	6	0.299	6	6
A_4	0.325	3	0.601	3	3
A_5	0.291	4	0.560	5	4
A_6	0.285	5	0.605	4	4

From the traditional analysis the three best alternatives A_2, A_1 and A_4 were ranked first, second and third respectively. The first, second and third ranked alternatives from the fuzzy based analysis were also A_2, A_1 and A_4 expecting. The forth and fifth ranked alternatives from traditional analysis were found A_5 and A_6, but for fuzzy based analysis these were two ranked differently. The sixth rank for both analyses was similar.

The fuzzy based methodology is a combination of FAHP and TOPSIS. The fuzzy technique is sophisticated and widely used but it has a limitation with respect to the problem size. According to Chen et al. (1992), the fuzzy method is not convenient when the criteria are more than 10. It requires enormous computational efforts. The proposed fuzzy based methodology can handle both qualitative and quantitative data. The TOPSIS was used to determine the crisp rank or a dimensionless number by which the DM can easily be compared the alternatives.

On the other hand the traditional methodology is a combination of the AHP and the additive value model. It can handle both qualitative and quantitative data. This technique can readily handle more alternatives and criteria than fuzzy based approach. The sensitivity and uncertainty analysis were also covered by this methodology. It required less computational efforts than the fuzzy based approach. In the present case study; six alternatives were evaluated by 24 criteria. Since the results from both analysis techniques were found to be similar any methodology can be used in this case but considering the number of criteria for this case, the traditional methodology is more suitable than the fuzzy based approach. However, for less criteria and a more sophisticated problem, the fuzzy based approach is more realistic than traditional methods.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This thesis presents an evaluation of a PW management system for an offshore platform. A multi-criteria decision making technique was used to evaluate the PW management options. After screening by threshold criteria six PW management systems, including a macro porous polymer extraction (A_1), steam stripping (A_2), produced water reinjection (A_3), compact flotation unit (A_4), C- tour process (A_5), and downhole oil water separation (A_6) were evaluated. Technical feasibility, environmental, cost effects, and health and safety aspects were considered as the decision making criteria in the evaluation. The main decision making criteria were subdivided into 24 sub-criteria. The options were compared using a deterministic MCDM model where the individual criteria were weighted according to their importance. To calculate weighting factors, pair-wise comparisons were made between the elements at each level of the hierarchy with respect to the connected elements in the above level. Two separate MCDM frameworks namely, the traditional concept, that integrated the AHP technique with the additive value model and the fuzzy concept, which combined the FAHP and TOPSIS. Keeping the objectives in perspectives, the following are the conclusions from this study:

Based on the evaluation results, three PW management options namely, steam stripping (A_2), macro porous polymer extraction (A_1), and produced water reinjection (A_3) were found to be the best fitted for the offshore platform.

The technical feasibility, environmental, and cost effectives were found to be the dominant criteria, in the offshore platform to assess the PW management options.

Uncertainty and sensitivity analyses were conducted to verify the robustness of the results. Uncertainty reflects the reliability of the overall scores due to the limited availability of data. The reliability was most affected by the data available for the various options.

The selected best three options were found to have the highest scores when uncertainty values were considered along with the overall scores. They also had relatively low uncertainties, as the data for these options were readily available for offshore application. In addition to the best three options, the forth-ranked option the C-tour process (A_5) was considered to be the most promising technology future for offshore applications. Since this management system is under development, the information is rarely available and that leads to be higher uncertainties during the evaluation. The size, weight, pollutants removal efficiency, energy consumption etc of the C- tour process were the most important uncertainties that should be considered if it is to be selected as a possible offshore management system.

The effects of changes to the criteria weights on the ranks of the options were observed through a sensitivity analysis. It was shown that the three highest ranked technologies were unchanged in most cases. It can therefore be concluded that the best three options do not change significantly with the assignment of different weights. This is largely due to the fact that the top three options were obviously superior in important criteria, which resulted in the options scoring higher regardless of the weight alterations. Another possible reason was that there were many criteria used in the evaluation and the total weight was distributed among a larger number of criteria. This makes the weights for individual criteria small and therefore rankings are less sensitive to changes in the criterion weights.

As mentioned, the number of criteria has a considerable effect on the quality of the evaluation. Therefore, criteria should be selected so that only criteria that are significant in comparing the options are included. The dominating criteria for this evaluation included costs, ecological risk, waste generation, treatment capacity, treatment efficiency, size, and weight. This was because these criteria contributed relatively more to the difference among the overall scores of the options compared with other criteria.

The reliability and validity of the evaluation results were influenced by many factors. The validity of the results depended considerably on the discharge regulations that were used as the threshold criterion in this evaluation. As regulations for PW discharge vary from place to place and are moving toward zero discharge in some jurisdictions, the results of this evaluation are only valid for the specified regulations mentioned in this study.

The reliability of the results is limited by the availability and the quality of the data. As some options have never been used in offshore (under development), some data used in the evaluation were generated through criteria mean values, rather than practical data, and therefore the application might be different when they are used offshore. As a consequence, the ranks of the technologies might change when data from offshore applications are available and would be used instead of generated data.

Another factor affecting the reliability of the evaluation results was the subjective consideration, for example to assign weights and to subjectively score the options. These processes might contain biased values, which may have changed the final results. To minimize the biased-ness, the fuzzy approach was used, but subjectivity still exits in the defuzzification. The biases from the weight assignments were minimized by making pair-wise comparisons; the weight distributions were also made consistent with the help of a specific consistency ratio. Furthermore, the errors due to the subjectively assigned weights were tested through the sensitivity analyses, which showed that the best three options were unchanged with the altered weight distributions. On the other hand, the subjective scoring that was performed in the evaluation might have had a larger effect on the results. This is because the ranges of the qualitative characteristics were large, and so there is a possibility that the score assigned to an option based on a linguistic terms did not provide an appropriate value for comparison. However, the subjective scoring for all the alternatives did not differ significantly. Hence, the bias initiated from the subjective scoring was considered less significant compared to the quantitative scores of the options, and did not affect the rankings to a large extent.

Innovative technologies, like TORR, were not included as evaluation options in this study as they are in the development stage and data are rarely available and did not meet the screening criterion. However, the technologies were reviewed on their status, general process, and potential for offshore applications. From the technology reviews, it was found that, the important factors in development of new technologies include compact size and very high treatment efficiency (to meet progressively more stringent discharge regulations). All of the reviewed innovative technologies involve use of chemicals to provide advanced fluid separation from the PW. As they involve chemical treatment processes, the issues in applying these innovative technologies are mostly related to the types of chemicals used and the environmental safety. Chemicals that are environmentally friendly (for example non-toxic and biodegradable) are preferable. From the reviews, the major limitation on most of the reviewed innovative technologies is cost, which is relatively high compared with conventional system. However, costs of treatment are expected to be reduced when technologies become more widely used.

This evaluation was designed to provide a simple but comprehensive methodology to initially assess PW management systems. As selecting the most suitable management system, many parameters influence the validity of the evaluation results, including the availability of data and the distribution of weights. Two parallel MCDM frameworks namely, the traditional method and the fuzzy based technique were used to make final results more reliable. In a real situation, selecting a management system is not simple or straightforward and depends on many site-specific issues. Good upfront planning is crucial to properly assess the problem and select the correct process. Decision making should be performed with care and a good understanding among decision makers and stakeholder. Modifications of some details of the methodology, such as the evaluation criteria, may also be required on a case by case basis. Use of more accurate or specific data will also provide better evaluation results.

7.2 Recommendations for future work

1. This study should be used as a basis in the evaluation of PW management systems using multicriteria decision making. Therefore, this method can be applied as an initial screening process to be followed by more detailed evaluation for specific conditions. The results of the study and the reviews of technologies can also be used to facilitate different PW management decision making problems.
2. In the detailed evaluation, uncertainty should be considered if the data distribution is used.
3. The evaluation should be modified by changing the evaluation criteria as well as weighting factors.
4. As the data for the evaluating options significantly affect the reliability of the evaluation results, improving data quality is critical to enhance performance of the evaluation. More reliable data, especially those specifically for offshore PW management, should be used. Updates of the existing data and collection of newly available data should be done in the future. These data additions can easily be incorporated into this method.
5. The weights and scores assigned in the evaluation should be verified or re-assigned by the people with expertise in PW management in order to obtain better results.
6. The PW discharge standards are becoming more stringent and there are no current offshore PW treatment technologies that can provide zero discharge conditions.

The studies and the results of the evaluation should be used to determine the direction in the development of PW management systems.

7. Detailed studies on potential technologies or management mechanisms should be conducted in order to further develop or reduce limitations.
8. After modification the innovative technologies can be used as new technologies that may be useful in offshore applications in the future. These technologies should be studied further to determine effective alternative.
9. A detailed risk assessment study is needed to know the environmental impact of PW.
10. Criteria should be selected so that only criteria that are significant in comparing the options are included.

7.3. Originality of this study

The originality of this research can be viewed from the following perspectives:

This research develops a new decision making framework for PW management that will guide the decision makers during selection of the best alternative. The most widely used AHP and fuzzy AHP models were used to develop this decision making framework. The decision making tool attempts to minimize the conflicts that occur due to various opinions and subjective assessments by decision makers. The application of the proposed methodology was conducted by collecting data from different sources. The detailed database for the management options is given in Appendix-A. To calculate the ecological risk from PW this research has been used the toxicological data of different contaminants like group of PAHs which were rarely considered before in PW. The detailed data base for the PW contaminants is provided in Appendix-B.

The application of this methodology can be extended to the variety of decision management and environmental studies including project evaluation, waste management, and other practical fields related to multicriteria problems.

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Appendix

Appendix-A

Technology data base

Continue appendix-A :			
	Criteria	Data	References
Technology : Macro porous polymer extraction (End stream) (A1)			
C_1	**Technical Feasibility**		
C_{12}	Size m3	67.5	OGP, 2002
C_{13}	Weight (tons)	22	OGP, 2002
C_{14}	Design capacity m3/hr	10	OGP, 2002
Pollutants removal efficiency %-			
C_{16}	BTEX removal efficiency	99	OSPAR, 2002
C_{17}	PAHs removal efficiency	99	OSPAR, 2002
C_{18}	NPD removal efficiency	99	OSPAR, 2002
C_{19}	Dispersed Oil removal efficiency	99	OSPAR, 2002
C_{110}	Dissolved Oil removal efficiency	99	OSPAR, 2002
C_{111}	Metals removal efficiency	0	OSPAR, 2002
C_2	**Environment**	-	-
C_{21}	Ecological risk	-	Calculated in Chapter 4
C_{22}	Energy consumption	-	Assigned in Table 6.4
C_3	**Costs**	-	-
C_{31}	Capital (new) million €	51.80	OSPAR, 2002
C_{32}	Operation cost million € /yr	17.55	OSPAR, 2002
C_{33}	Benzene removal cost [€/kg]	145	OSPAR, 2002
C_{34}	Dispersed oil removal cost [€/kg]	1193	OSPAR, 2002
Technology : steam stripping (end flow) (A_2)			
C_1	**Technical Feasibility**		
C_{12}	Size m3	90	OSPAR, 2002
C_{13}	Weight (tons)	20	OSPAR, 2002
C_{14}	Design capacity m3/hr	6	OSPAR, 2002
Pollutants removal efficiency %-			
C_{16}	BTEX removal efficiency	90	OSPAR, 2002
C_{17}	PAHs removal efficiency	90	OSPAR, 2002
C_{18}	NPD removal efficiency	90	OSPAR, 2002
C_{19}	Dispersed Oil removal	85	OSPAR, 2002

Continue appendix-A :			
	Criteria	Data	References
	efficiency		
C_{110}	Dissolved Oil removal efficiency	90	OSPAR, 2002
C_{111}	Metals removal efficiency	0	OSPAR, 2002
C_2	**Environment**	-	-
C_{21}	Ecological risk	-	Calculated in Chapter 4
C_{22}	Energy consumption	-	Assigned in Table 6.4
C_3	**Costs**	-	-
C_{31}	Capital (new) million €	84.0	OSPAR, 2002
C_{32}	Operation cost million € /yr	27.69	OSPAR, 2002
C_{33}	Benzene removal cost [€/kg]	226	OSPAR, 2002
C_{34}	Dispersed oil removal cost [€/kg]	191	OSPAR, 2002
Technology : produced water reinjection (A_3)			
C_1	**Technical Feasibility**		
C_{12}	Size m3	72	OSPAR, 2002
C_{13}	Weight (tons)	15-25	OSPAR, 2002
C_{14}	Design capacity m3/hr	6	OSPAR, 2002
Pollutants removal efficiency %-			
C_{16}	BTEX removal efficiency	100	OSPAR, 2002
C_{17}	PAHs removal efficiency	100	OSPAR, 2002
C_{18}	NPD removal efficiency	100	OSPAR, 2002
C_{19}	Dispersed Oil removal efficiency	100	OSPAR, 2002
C_{110}	Dissolved Oil removal efficiency	100	OSPAR, 2002
C_{111}	Metals removal efficiency	100	OSPAR, 2002
C_2	**Environment**		-
C_{21}	Ecological risk	-	Calculated in Chapter 4
C_{22}	Energy consumption	-	Assigned in Table 6.4
C_3	**Costs**		-
C_{31}	Capital (new) million €	610	OSPAR, 2002
C_{32}	Operation cost million € /yr	147.8	OSPAR, 2002
C_{33}	Benzene removal cost [€/kg]	1578	OSPAR, 2002
C_{34}	Dispersed oil removal cost [€/kg]	5784	OSPAR, 2002

Continue appendix-A :			
	Criteria	Data	References
Technology : compact flotation two stages unit (A_4)			
C_1	**Technical Feasibility**		
C_{12}	Size m3	30.63	OSPAR 2006
C_{13}	Weight (tons)	16.0	http://www.epconoffshore.com/
C_{14}	Design capacity m3/hr	540	http://www.epconoffshore.com/
Pollutants removal efficiency %-			
C_{16}	BTEX removal efficiency	40-80	OSPAR 2006
C_{17}	PAHs removal efficiency	32-47	Kundsen et al. 2004
C_{18}	NPD removal efficiency	17	Kundsen et al. 2004
C_{19}	Dispersed Oil removal efficiency	50-75	Kundsen et al. 2004
C_{110}	Dissolved Oil removal efficiency	0	OSPAR 2006
C_{111}	Metals removal efficiency	0	OSPAR 2006
C_2	**Environment**		
C_{21}	Ecological risk	-	Calculated in Chapter 4
C_{22}	Energy consumption	-	Assigned in Table 6.4
C_3	**Costs**		
C_{31}	Capital (new) million €	218.7	Used mean values
C_{32}	Operation cost million € /yr	61.335	Used mean values
C_{33}	Benzene removal cost [€/kg]	686.25	Used mean values
C_{34}	Dispersed oil removal cost [€/kg]	1804	Used mean values
Technology : C- tour process (A_5)			
C_1	**Technical Feasibility**		
C_{12}	Size m3 (3.7*1.6*2 m)	11.84	OSPAR, 2006
C_{13}	Weight (tons)	4	OSPAR, 2006
C_{14}	Design capacity m3/hr	175	OSPAR, 2006
Pollutants removal efficiency %-			
C_{16}	BTEX removal efficiency	0	Kundsen et al. 2004
C_{17}	PAHs removal efficiency	32-47	Kundsen et al. 2004
C_{18}	NPD removal efficiency	70	Kundsen et al. 2004
C_{19}	Dispersed Oil removal efficiency	50-70	Kundsen et al. 2004
C_{110}	Dissolved Oil removal efficiency	0	Kundsen et al. 2004
C_{111}	Metals removal efficiency	0	Kundsen et al. 2004
C_2	**Environment**		

Continue appendix-A :			
	Criteria	Data	References
C_{21}	Ecological risk	-	Calculated in Chapter 4
C_{22}	Energy consumption	-	Assigned in Table 6.4
C_3	**Costs**		
C_{31}	Capital (new) million €	218.7	Used mean values
C_{32}	Operation cost million € /yr	61.335	Used mean values
C_{33}	Benzene removal cost [€/kg]	686.25	Used mean values
C_{34}	Dispersed oil removal cost [€/kg]	1804	Used mean values
Technology : Down hole oil-water separation (oil) (*A_6*)			
C_1	**Technical Feasibility**		
C_{12}	Size m3	0	OSPAR, 2002, neglected
C_{13}	Weight (tons)	0	OSPAR, 2002, not occupy in platform
C_{14}	Design capacity m3/hr	175	OSPAR, 2002
Pollutants removal efficiency %-			
C_{16}	BTEX removal efficiency	50	OSPAR, 2002
C_{17}	PAHs removal efficiency	50	OSPAR, 2002
C_{18}	NPD removal efficiency	50	OSPAR, 2002
C_{19}	Dispersed Oil removal efficiency	50	OSPAR, 2002
C_{110}	Dissolved Oil removal efficiency	50	OSPAR, 2002
C_{111}	Metals removal efficiency	50	OSPAR, 2002
C_2	**Environment**		
C_{21}	Ecological risk	-	Calculated in Chapter 4
C_{22}	Energy consumption	-	Assigned in Table 6.4
C_3	**Costs**		
C_{31}	Capital (new) million €	129.00	OSPAR, 2002
C_{32}	Operation cost million € /yr	52.30	OSPAR, 2002
C_{33}	Benzene removal cost [€/kg]	796.0	OSPAR, 2002
C_{34}	Dispersed oil removal cost [€/kg]	48.0	OSPAR, 2002

Appendix - B

Lethal Toxicity (LC50/ EC50) data for Marine species/ groups

Continue Appendix –B

Species	Toxicant	LC_{50}/EC_{50} mg/L	Time	Reference
Crangonyx pseudogracilis	Cadmium (Cd)	1.7	96 hr	Martin, and Holdich 1986
Palaemon elegans		1.46	96 hr	S. Lorenzon, 2000
Callianassa australiensis (Dana) shrimp		6.33	96 hr	K.W. Lee, 2007
Paratya tasmaniensis		0.06	96 hr	Thorp and Lake 1974
Crangon semtemspinosa		0.32	96 hr	Eisler, 1971
Palaemoneter vulgaris		0.42	96 hr	Eisler, 1971
Pagurus longicarpus		0.32	96 hr	Eisler, 1971
Carcinus maenas		4.1	96 hr	Eisler, 1971
Tigriopus japonicus		25.2	96 hr	Levent et al. 1999
Crangonyx pseudogracilis		34.6	48 hr	Martin, and Holdich 1986
Allorchestes compressa		0.2-4	120 hr	Ahsanullah, 1976
Austrochiltonia subtenuis		0.04	96 hr	Thorp and Lake 1974
Corophium insidiosum		0.68	96 hr	Reish 1993
Elasmopus bampo		0.57-0.9	96 hr	Reish 1993 , Hong and Reish 1987
Rhepoxynius abronius		0.24	96 hr	Hong and Reish 1987
Sterechinus neumayeri		0.69	6-8d	King and Riddle , 2001
Sterechinus neumayeri		0.2	20-23d	King and Riddle , 2001
Strongylocentrotus purpuratus		0.5	2-3d	Dinnel,1990
Strongylocentrotus droebachiensis		1.8	2-3d	Dinnel,1990
Strongylocentrotus intermedius		0.5-2.5	96hr	Gnezdilova et al., 1985
Arbacia punctulata j		13.9	2-4d	Bay et al., 1993
Paracentrotus lividus		1.1	2d	Pagano et al., 1986
Diadema setosum		0.2-0.5	2d	Kobayashi ,1994
Palaemon elegans	Copper (Cu)	3.27	96 hr	S. Lorenzon, 2000
Callianassa australiensis (Dana) shrimp		1.03	96 hr	K.W. Lee, 2007
Asellus aquaticus		9.2	96 hr	Martin and Holdich 1986
Crangonyx pseudogracilis		2.4	48 hr	Martin and Holdich 1986
Corophium insidiosum		0.6	96 hr	Reish 1993

Continue Appendix –B

Elasmopus bampo		0.25	96 hr	Reish 1993
Sterechinus neumayeri		0.0114	6-8d	King and Riddle , 2001
Sterechinus neumayeri		0.0014	20-23d	King and Riddle , 2001
Centrostephanus rodgersii		0.0118	3d	King ,1999
Heliocidaris tuberculata		0.0094	3d	King ,1999
Heliocidaris erythrogramma		0.0264	7d	King ,1999
Strongylocentrotuspurpuratus		0.0063	2-3d	Dinnel,1990
Strongylocentrotus droebachiensis		0.021	2-3d	Dinnel,1990
Arbacia punctulata		0.014	2-4d	Bay et al., 1993
Paracentrotus lividus		0.032	2d	Pagano et al., 1986
Anthocidaris crassispina		0.05-0.10	1d	Kobayashi ,1985
Hemicentrotus pulcherrimus		0.001-0.002	2d	Kobayashi ,1990
Echinometra mathaei		0.002-0.005	2d	Heslinga ,1976
Diadema setosum		0.069	5hr	Ramachandran et al., 1997
Diadema setosum		0.043	2d	Ramachandran et al., 1997
Echinogammarus olivii		0.25	96 hr	Levent et al.,1999
Sphaeroma serratum		1.98	96 hr	Levent et al.,1999
Palaemon elegans		2.52	96 hr	Levent et al.,1999
Palaemon elegans	Zinc (Zn)	26.3	96 hr	S. Lorenzon, 2000
Callianassa australiensis (Dana) shrimp		10.2	96 hr	K.W. Lee, 2007
Polychaete (sp.1)		3.5-10.7	96 hr	US EPA, 1976
Asellus aquaticus		18.2	96 hr	Martin and Holdich 1986
Crangonyx pseudogracilis		19.8	96 hr	Martin and Holdich 1986
Allorchestes compressa		0.58	96 hr	Ahsanullah ,1976
Corophium insidiosum		1.9	96 hr	Reish,1993
Elasmopus bampo		12.5	96 hr	Reish,1993
Echinogammarus olivii		1.3	96 hr	Levent et al.,1999
Sphaeroma serratum		6.12	96 hr	Levent et al.,1999
Palaemon elegans		12.3	96 hr	Levent et al.,1999
Sterechinus neumayeri		2.23	6-8 d	King and Riddle , 2001
Sterechinus neumayeri		0.3267	20-23 d	King and Riddle , 2001
Centrostephanus rodgersii		0.2894	3d	King ,1999
Heliocidaris tuberculata		0.280	3d	King ,1999
Heliocidaris erythrogrammam		0.0268	7d	King ,1999
Strongylocentrotus purpuratus		0.023	2-3d	Dinnel,1990

Continue Appendix –B

Strongylocentrotus droebachiensis		0.027-0.051	2-3d	Dinnel,1990
Arbacia punctulataj		0.205	2-4d	Bay et al., 1993
Arbacia lixula		0.01-0.10	3d	Castagna et al.,1981
Paracentrotus lividusj		0.033	2d	Bay et al., 1993
Anthocidaris crassispina		0.05-0.10	1d	Kobayashi ,1985
Hemicentrotus pulcherrimus		0.01-0.02	2d	Kobayashi ,1990
Diadema setosum		0.01-0.02	2d	Kobayashi ,1994
	PAHs			
Copepod (E. affinis)	NA	3 800	24 hr	Ott et al., 1978:
Amphipod (Parhyale)	NA	>5 000	24 hr	Lee & Nichol, 1978a
Amphipod (E. pectenicrus)	NA	2 680	96 hr	Lee & Nichol, 1978b
Polychaete (N. arenaceodentata)	NA	3 800	96 hr	Rossi and Neff, 1978
Pacific Oyster (C. gigas)	NA	199 000	96 hr	LeGore, 1974
Brown Shrimp (P. aztecus)	NA	2 500	24 hr	Anderson et al., 1974
Brown Shrimp (P. aztecus)	NA	2 500	96 hr	Tatem et al., 1978
Grass Shrimp (P. pugio)	NA	2 350	96 hr	Tatem, 1976; Tatem et al., 1978
Dungeness Crab (C. magister)	NA	>2 000	96 hr	Caldwell et al., 1977
Crab (S. serrata)	NA	17 000	96 hr	Kulkarni and Masurekar, 1984
Sheepshead Minnow (C. variegatus)	NA	2 400	24 hr	Anderson et al., 1974
Pink Salmon (O. gorbuscha)	NA	920	24 hr	Thomas and Rice, 1978
O. gorbuscha	NA	1 200	96 hr	Moles and Rice, 1983
O. gorbuscha	NA	1 200	96 hr	Moles and Rice, 1983
Dungeness Crab (C. magister)	1-MNA	8 200	48 hr	Caldwell et al., 1977
Dungeness Crab (C. magister)	1-MNA	1 900	96 hr	Caldwell et al., 1977
Sheepshead minnow (C. variegatus)	1-MNA	3 400	24 hr	Anderson et al., 1974
Copepod (E. affinis)	2-MNA	1 300-1 500	24 hr	Lee & Nichol, 1978a, b; Ott et al., 1978
Grass Shrimp (P. pugio)	2-MNA	1 100	96 hr	Neff et al., 1976a; Tatem et al., 1978
Brown Shrimp (P. aztecus)	2-MNA	700	24 hr	Anderson et al., 1974
Brown Shrimp (P. aztecus)	2-MNA	600	96 hr	Tatem et al., 1978
Dungeness Crab (C. magister)	2-MNA	5 000	48 hr	Caldwell et al., 1977
Dungeness Crab (C. magister)	2-MNA	1 300	96 hr	Caldwell et al., 1977
Sheepshead minnow (C. variegatus)	2-MNA	2 000	24 hr	Anderson et al., 1974
Copepod (E. affinis)	d-MNA	850	24 hr	Ott et al., 1978

Continue Appendix –B

Polychaete (N. arenaceodentata)	d-MNA	2 600	96 hr	Neff et al., 1976a; Rossi and Neff, 1978
Grass Shrimp (P. pugio)	d-MNA	700	96 hr	Neff et al., 1976a; Tatem et al., 1978
Brown Shrimp (P. aztecus)	d-MNA	80	24 hr	Anderson et al., 1974
Brown Shrimp (P. aztecus)	d-MNA	80	96 hr	Tatem et al., 1978
Dungeness Crab (C. magister)	d-MNA	3 100	48 hr	Caldwell et al., 1977
C. magister	d-MNA	600	96 hr	Caldwell et al., 1977
Sheepshead Minnow (C. variegatus)	d-MNA	5 100	24 hr	Anderson et al., 1974
Polychaete (N. arenaceodentata)	t-MNA	2 000	96 hr	Rossi and Neff, 1978
Copepod (E. affinis)	t-MNA	320	24 hr	Ott et al., 1978
Alga (S. costatum)	ANA	500	96 hr	USEPA, 1978
Mysid shrimp (M. bahia)	ANA	970	96 hr	USEPA, 1978
Sheepshead minnow (C. variegatus)	ANA	2 230	96 hr	USEPA, 1978
C. variegatus	ANA	3 700	24 hr	Heitmuller et al., 1981
C. variegatus	ANA	2 300	48 hr	Heitmuller et al., 1981
C. variegatus	ANA	2 200	96 hr	Heitmuller et al., 1981
Amphipod (G. pseudoliminaeus)	FL	600	96 hr	Finger et al., 1985
Polychaete (N. arenaceodentata)	FL	1 000	96 hr	Rossi and Neff, 1978
Grass Shrimp (P. pugio)	FL	320	96 hr	Wofford and Neff, 1978
Sheepshead minnow (C. variegatus)	FL	1 680	96 hr	Wofford and Neff, 1978
Polychaete (N. arenaceodentata)	PH	600	96 hr	Rossi and Neff, 1978
Grass Shrimp (P. pugio)	PH	370	24 hr	Young, 1977
Polychaete (N. arenaceodentata)	1-MPH	300	96 hr	Rossi and Neff, 1978
Alga (S. costatum)	FLAN	45 000	96 hr	USEPA, 1978
Polychaete (N. arenaceodentata)	FLAN	500	96 hr	Neff et al., 1976a; Rossi and Neff, 1978
Mysid shrimp (M. bahia)	FLAN	40	96 hr	USEPA, 1978
Sheepshead minnow (C. variegatus)	FLAN	>560 000	96 hr	USEPA, 1978
C. variegatus	FLAN	>560 000	96 hr	Heitmuller et al., 1981

Notes: NA = naphthalene; 1-MNA = 1-methylnaphthalene; d-MNA = dimethylnaphthalenes; t-MNA = trimethylnaphthalenes; ANA = acenaphthene; FL = fluorine; FLAN = fluoranthene; PH = phenanthrene; 1-MPH =1-methylphenanthrene; PAHs = Polycyclic Aromatic Hydrocarbons.

Appendix - C

MINITAB macro for RE from PNEC values

```
GMACRO
abdullah.mac
Note macro for RE from PNEC values
do k1= 1:1000
sample 5 c1 c2;
replace.
let c3 = log(c2)
let c4(k1)=mean(c3)
let c5(k1)=stdev(c3)
let c6(k1)=exp(c4(k1)-1.2815*c5(k1))
enddo
let c7=mean(c6)
let k2=c7
name k2 'Lowest 10 percentile of PNCE='
print k2
endmacro
```

Appendix - D

Typical composition of produced water from oil filed

	(1)			(2)	
Materials	Range	Median	Unit	Range	Unit
Dispersed oil	15-60	44	mg/l		
BTEX	1-67	6	mg/l		
NPD	0.06-2.3	1.2	mg/l		
PAHs	130-575	468	μg/l		
Organic Acids (<C6)	55-761	368	mg/l		
Phenols (C0-C4)	0.1-43	8	mg/l		
Arsenic (As)	-	-	-	<0.11-320	μg/l
Barium (Ba)	0.2-228	87	mg/l	1.0-650000	μg/l
Cadmium(Cd)	0.5-5	2	μg/l		
Chromium (Cr)	-	-	μg/l	<0.01-390	μg/l
Copper (Cu)	22-82	10	μg/l	-	-
Lead (Pb)	0.4-8.3	1.9	μg/l	-	-
Mercury (Hg)	<0.1-26	0.7	μg/l	-	-
Nickel (Ni)	0.02-0.3	0.14	mg/l	-	-
Zinc (Zn)	0.5-13	7	mg/l	-	-
Radium (226RA)	1.66	1.66	Bq/l	-	-
Radium (228RA)	3.9	3.9	Bq/l	-	-
Manganese (Mn)	0.1-0.5	0.45	mg/l	-	-
Berllium (Be)	0.02	0.02	mg/l	-	-
Cobalt (Co)	0.3-1	0.35	mg/l	-	-
Vanadium(V)	0.02-0.5	0.24	mg/l	-	-

(1) Compiled from Frost 1998, section 1.2 and E& P 1994, P.4
(2) Neff, J.M. (1997).

**PAHs	Unit	Ekofisk 2/4B-K	Ekofisk 2/4K	Statfjord	Gullfaks
NA	mg/l	0.157	0.038	0.261	0.398
1-MNA	mg/l	0.062	0.012	0.35	0.629
2-MNA	mg/l	0.018	0.002	0.199	0.584
d-MNA	mg/l	0.01	0.0005	0.132	0.55
ANA	μg/l	0.89	0.02	-	-
FL	μg/l	-	0.33	12	11.3
PH	μg/l	2.09	0.08	-	-
FLAN	μg/l	-	-	0.0854	0.195

Notes: NA = naphthalene; 1-MNA = 1-methylnaphthalene; d-MNA = dimethylnaphthalenes; t-MNA = trimethylnaphthalenes; ANA = acenaphthene; FL = fluorine; FLAN = fluoranthene; PH = phenanthrene; 1-MPH =1-methylphenanthrene; PAHs = Polycyclic Aromatic Hydrocarbons.

**Collected from Roe and Johnsen. 1996

Appendix - E

Questionnaire for data collection

E.1. Questionnaire for company person:

1. Have your company currently used a decision support system for produced water management?

Please mark

Yes	No

If yes, what is the name and type of your technology?

....

2. Which of the following criteria does your company take into account while making decision evaluating technologies of produced water management for offshore platform?

Criteria description	**Yes**	**No**
Technical feasibility		
Technical convenience		
Foot print		
Weight		
Capacity		
Chemical usage		
BTEX removal efficiency %		
PAHs removal efficiency %		
NPD removal efficiency %		
Dispersed Oil removal efficiency %		
Dissolved Oil removal efficiency %		
Metals removal efficiency %		
Pre- or post-treatment		
Environment		
Ecological risk		
Energy consumption		
Solid wastes		
Liquid wastes		
Green house gases emissions		
Non green house gases emissions		

Costs		
Capital costs		
Operational costs		
Per kilogram (kg) dispersed oil removal costs		
Per kilogram (kg) dissolved oil removal costs		
Health and Safety		
Human exposure		
Risks of accident		

Please add criteria that you think are missing in reflecting your decision making.

E.2. Questionnaire for expert / planners:

By this questionnaire my intention is to develop a methodology for the management of produced water implementing multicriteria decision making (MCDM) approach. With this questionnaire I intent to get to know about your preferences and judgments considering the decision problem for the produced water management for offshore platform. For this purpose I selected the alternatives as below:

a) Macro porous polymer extraction (A_1)
b) Steam stripping (A_2)
c) Produced water reinjection (A_3)
d) Compact flotation unit (A_4)
e) C- tour process (A_5) and
f) Downhole oil water separation (A_6)

Following section I will ask few questions it will take 15-20 minutes please choose the best answer or answers as possible.

1. Please mark what would be the favourable alternative for your?

A_1	A_2	A_3	A_4	A_5	A_6

If others, what is the name and type of your technology?

....

2. The criteria matrix Table E-1 has been developed for evaluating produced water management alternatives for offshore platform, which of the following criteria do you think are the lease and most important factor? Please rank the parameter from the least (1) to the most important (10).

Table E-1: criteria matrix

Criteria description	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Technical feasibility										
Technical convenience										
Foot print										
Weight										
Capacity										
Chemical usage										
BTEX removal efficiency %										
PAHs removal efficiency %										
NPD removal efficiency %										
Dispersed Oil removal efficiency %										
Dissolved Oil removal efficiency %										
Metals removal efficiency %										
Pre- or post-treatment										
Environment										
Ecological risk										
Energy consumption										
Solid wastes										
Liquid wastes										
Green house gases emissions										
Non green house gases emissions										
Costs										
Capital costs										
Operational costs										
Per kilogram (kg) dispersed oil removal costs										
Per kilogram (kg) dissolved oil removal costs										
Health and Safety										
Human exposure										
Risks of accident										

Please add criteria that you think are missing in reflecting the decision making.

3. A criteria matrix shown in table E-2 has been developed to collect the information for the alternative. Please mark the appropriate box with the help of conversion scale shown in figure E-1

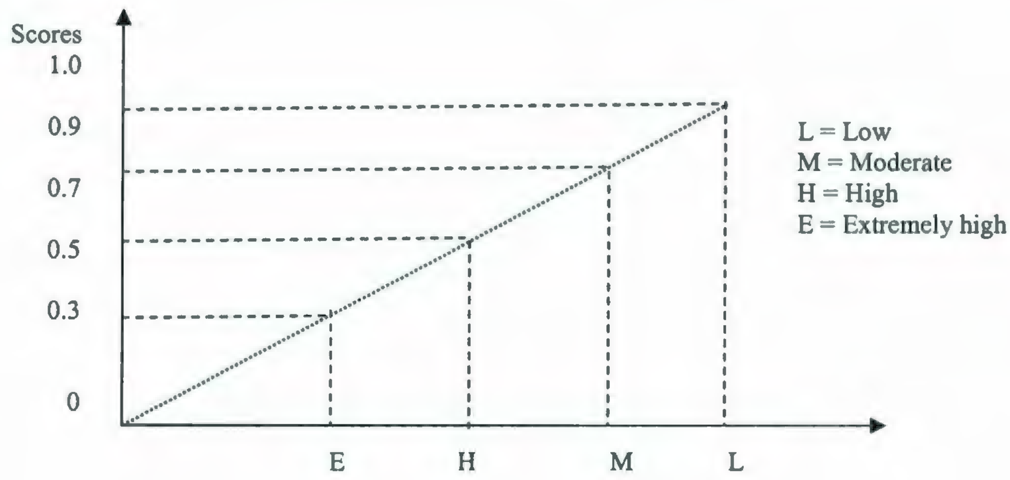

Figure E-1: conversion scale

Table E-2: Criteria matrix for the questionnaire

Criteria description	**E**	**H**	**M**	**L**
Energy consumption				
Solid wastes				
Liquid wastes				
Green house gases emissions				
Non green house gases emissions				
Human exposure				
Risks of accident				

4. What is your opinion about technical convenience criteria? Please mark the appropriate box below.

Extremely convenience (EC = 0.9)	Highly convenience (HC = 0.7)	Moderately convenience (MC = 0.5)	Low convenience (LC = 0.3)

5. Specify the type of pre/ post treatment required for the alternatives. Please mark the appropriate box below with the help of table E-3?

A	B	C	D	E

Table E-3: pre- or post-treatment requirement criteria

Pre/Post treatment requirement	Symbol	Scores
Basic: cooling, heating, settling, impoundment, etc.	A	0.9
Primary: pH adjustment, softening, few chemical addition, de-oiling, suspended solid removal, sand filtration, etc. + technologies	B	0.7
Primary: pH adjustment, softening, chemical treatment, de-oiling, suspended solid removal, high filtration, etc. + technologies	C	0.5
Moderate: regeneration, fouling prevention, trickling filter, constructed wetland, ionization and removal, UF or NF, low pressure RO, etc. + technologies	D	0.3
Significant: high pressure filtration, high pressure RO, NORM treatment, etc. + technologies	E	0.1

If others, please specify?

....

The questionnaire is finished. Thank you very much for your collaboration. The information you have provided is very important for the success of the study.