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Evaluating offshore technologies for produced water management using *GreenPro-I* - a risk based life cycle analysis for green and clean process selection and design

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Abstract

Sustainable development and environmental protection require green products, processes, and waste management strategies. The selection and design of green and clean processes and products involve handling a huge set of data related to the environment, economics and technologies. Therefore, it is essential to employ a comprehensive technique to guide decision-making under uncertainty that can incorporate these factors.

The paper presents decision-making under uncertainty based on life cycle analysis and considering environmental, technological, and economical drivers in the analysis. The methodology, *GreenPro-I*, is applicable at any stage of a process design and can be used to evaluate the environmental burdens of a product or a process throughout its life cycle, and to identify and assess opportunities to make improvements. A weighting scheme is used to integrate various criteria and policies so that a most appropriate alternative can be selected.

The *GreenPro-I* methodology is applied to a case study for offshore produced water management. In the first stage, fourteen best available technologies (BAT) for treatment of produced water are evaluated individually using *cradle-to-gate* life cycle analysis. In the second stage, seven treatment strategies are developed from BAT and are further investigated. A treatment strategy that combines a hydrocyclone and produced water re-injection proved to be the best system among selected strategies. The combination of hydrocyclone and adsorption was found to be the next best treatment strategy. Two other noteworthy strategies were membrane and centrifuge combination, and down hole separation and injection.

Keywords: Green process design, process selection, decision-making, produced water, offshore, and life cycle analysis

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1 Introduction

The prescriptive regulatory-based approach for process design is being replaced by goal-based environmental management activities. This has been initiated due to recognition that strict compliance with standards, which are periodically adjusted to accommodate new research findings and changing expectations of the community, is expensive and resource-intensive and does not necessarily result in a reduction of environmental risk. Consequently, there has been a growing interest in ways that can help shift an organization's environmental management program from a reactive to a proactive strategy that encourages the organization to move beyond compliance and is beneficial from business view point.

The shift from process or product-specific impacts to long-term system-wide subsidiary impacts has created interest in the use of life cycle analysis (LCA) – an evaluation technique that assesses the environmental impacts of a product or service from *cradle to grave* or *cradle to gate*. The LCA's philosophy is to consider the true extent of the environmental burden, which can only be understood if the steps of a product's production, use and disposal are accounted for in the analysis. The LCA framework can be used to identify and assess potential improvements at any stage of a product's life. Growing acceptance of LCA by regulatory bodies and industries internationally has lead to the development of the ISO 14040 series of standards on environmental management (ISO 1998). The Society of Environmental Toxicology and Chemistry (SETAC) has proposed a framework for LCA based on an integrative approach to avoid substituting one set of environmental problems for another set of problems (UNEP 1996). Although both work independently, a general consensus on methodological frameworks has started to emerge.

In this paper, decision-making under uncertainty is performed using LCA, which considers environmental, technological and economical drivers in the analysis. *GreenPro-I*, a decision-making methodology previously developed (Khan *et al.* 2001; 2002), is applicable at any stage of a process design. In this paper, the *GreenPro-I* is applied to a case study for offshore produced water management. In the first stage, best available technologies (BAT) are evaluated for the treatment of produced water using *GreenPro-I*. In the second stage, seven treatment strategies are defined from the BAT options and are further investigated using *GreenPro-I*.

1.1 Approaches for process selection and design

Unlike traditional process selection and design in which engineers and designers focus on cheaper options, clean and green process selection and design highlight environmental considerations (Figure 1). In general, process simulators provide local scale models to predict mass and energy flows around a chemical process. Costs linked with these performance models can predict the profitability of a process. The goals in terms of profitability are defined. Researchers in academia and industry have been using simulators and modeling tools with defined environmental constraints to explore and improve profitability. Recently, Cabezas *et al.* (1997) proposed a Potential Environmental Impact (PEI) balance for the generalization of the Waste Reduction (WAR) algorithm introduced by Hilaly and Sikdar (1994). The PEI balance quantifies the environmental impact of the pollutants emitted in a process and determines the environmental friendliness of a given process. Cano-Ruiz and McRae (1998) have provided a comprehensive review of techniques used to incorporate environmental considerations into the process design. However, to handle conflicting objectives, a multi-objective approach is essential.

There are number of methods available for generating process alternatives. Hierarchical methods emphasize the use of heuristic techniques and approximate calculations (Douglas 1988). These methods initially emphasize the broad view and later focus at unit levels. Biegler *et al.* (1997) reviewed optimization methods for selecting process alternatives. Daichendt and Grossmann (1998) have described an integrated approach that combines hierarchical and optimization methods.

Chemical stressors emitted are classified based on specific environmental impacts, e.g., acid rain and smog formation. They are characterized for potential effects based on scoring methods e.g., WAR (Hilaly and Sikdar 1994) and SETAC (1993), which classify impact categories, and characterize their effects using weighting factors. Young and Cabezas (1999) have later modified the original WAR algorithm to include the potential environmental impact computation for the energy use in the process. Kniel *et al.* (1996) used LCA for a case study of a nitric acid process and incorporated environmental and economical constraints. Hernandez *et al.* (1998) tried to achieve the optimal degree of pollution abatement through a modeling approach. Azapagic and

co-workers (1999a-d) recommended LCA based design for process (and product) selection to guide decision-making. Azapagic (1999) and Azapagic and Clift (1999b, c) used LCA for the evaluation of process performance. Fu *et al.* (2000) initially applied evaluation techniques in a design procedure using a simple spreadsheet analysis to highlight the impact categories, streams, and components of the greatest concern. Later on they analyzed economical and environmental impacts at an advanced stage of the process design or operation.

Attempts have been made to integrate LCA with public decision-making, but this is not yet accepted as a part of the regulatory process. The European Union's eco-labeling schemes (Boustead 1992), the EC directive on Packaging and Packaging Waste (HMSO 1997), and the IPPC Directive (1996) are some examples in this direction.

Khan *et al.* (2001) proposed a methodology called *GreenPro* for the design problem formulation using LCA, and design problem solution using multi-objective optimization and multi-criteria decision-making (MCDM). Application of the methodology was demonstrated through a case study of a vinyl chloride monomer process (Khan *et al.* 2001). The *GreenPro* proved effective in design, but its application was restricted only to early stage design due to its extensive computational load and large data requirements. Khan *et al.* (2002) overcame earlier limitations with a more flexible, and robust methodology, *GreenPro-I*, which is applicable for any design stage, even when the data are scarce and qualitative. The *GreenPro-I* is applied here for the evaluation of BAT treatment options for offshore produced water management. In the present pursuit, the *GreenPro-I* is modified using various ranking methods, which increase the robustness and confidence in decision-making.

2 *GreenPro-I*

The *GreenPro-I* is comprised of two risk-based modules: 1) life cycle analysis and 2) multi-criteria decision-making. These two steps are further split into numerous sub-steps (see Figure 2). A step-by-step description of the methodology is presented here.

2.1 Risk-based life cycle analysis (RBLCA)

Risk-based life cycle analysis (RBLCA) is a process of weighting policy alternatives and selecting the most appropriate one. For a given alternative, it evaluates human health, ecological,

safety and economical risks quantitatively or qualitatively. RBLCA considers the complete material and energy supply chains within the system boundary. It includes material and energy flows into the system, outflows from the system, and consumption within the system. It classifies the environmental burden of all activities within the system boundary from material extraction (and/or excavation) to refining, transportation, construction and commissioning, production, and to decommissioning of the plant, and finally to the ultimate disposal. This module is comprised of four main steps, which are discussed below.

2.1.1 Scope and boundary

RBLCA defines the scope of the study and sets system boundaries. This requires backtracking from the conventional process system to the natural state of raw materials, which are available at no environmental penalty. Different technological routes for the production of the same set of raw materials should be included in the system boundary. The advantage of defining a *global* system boundary is that inputs (to the conventional process), together with their routes, can be accounted for with the output emissions forming an aggregated waste vector. Note that, although this definition is consistent with the conventional LCA, here it does not include the routes and stages of the product after leaving the process (*cradle-to-gate*).

2.1.2 Life cycle inventory (LCI)

The life cycle inventory (LCI) analysis is performed to collect data and quantify environmental loads (ELs) by making material and energy balances for each operation within the system. If the information is incomplete, the adopted data used in the analysis should be conservative and clearly reported. Data quality varies depending upon the source, therefore the selection of best available sources must be ensured.

The guiding principle for the LCI analysis is that all input and waste streams in a system (or subsystem) must be allocated to the respective non-waste output streams. When an output stream becomes an input stream to the next process step, it carries ELs into the next output streams. Therefore, the final products are assigned the sum of ELs of raw materials, energy, and wastes in this process chain. Figure 3 illustrates a general framework for life cycle inventory methodology.

2.1.3 Environmental impact and risk analysis

The environmental impact and risk analysis examines the potential or actual environmental and human health effects from the use of resources and waste releases. It is performed in three stages: classification, characterization, and valuation.

Classification is the process of assigning and aggregating results from the inventory into homogeneous impact categories. This involves identifying stressors and organizing them with respect to impact on the ecosystem. For example, stressors CO, NO_x, and CH₄ have the potential for global warming. It may also include complex stressors and impact chains, because a single stressor has multiple impacts, and a primary impact can result in secondary (or greater) impacts. General categories are resource depletion, ozone depletion, acid rain potential, and health and safety risks related to human and ecological communities. These categories may change with the scope of the problem, however, the basic steps remain the same. In our case study, in addition to the above categories, the treatment efficiency parameters (dispersed oil, heavy metals, and others) are also considered.

Characterization assesses the impacts for each category in order to translate LCI data into impact descriptors. Impact equivalency units are available for subsets of stressors. Where these are unavailable, new impact equivalency units must be established.

Valuation assigns relative importance values to different impacts to determine the total score for each criterion. The valuation involves a structured description of the hierarchical relationships among the problem elements, beginning with an overall goal statement to developing a decision tree. Weights are estimated based on an expert panel who reach to consensus before using it for RBLCA. The expert panel may include economists, chemical and environmental engineers, and management representatives (see Khan *et al.* 2002 for details).

2.1.4 Design problem formulation

A traditional chemical process design requires knowledge of mass and energy balances, thermodynamics, reaction engineering, and economics. Cabezas *et al.* (1997, 1999) incorporated environmental impacts (EI) into the process design through a mass balance. It is expressed mathematically by:

$$\partial I_{\text{system}} / \partial t = I_{\text{in}}^{\text{cp}} + I_{\text{in}}^{\text{ep}} - I_{\text{out}}^{\text{cp}} - I_{\text{out}}^{\text{ep}} - I_{\text{we}}^{\text{cp}} - I_{\text{we}}^{\text{ep}} + I_{\text{gene}}^{\text{system}} \quad (1)$$

where I_{system} is an amount of EI inside the system (chemical process is denoted by the superscript “cp” and energy generation process is denoted by “ep”); $I_{\text{in}}^{\text{cp}}$ and $I_{\text{out}}^{\text{cp}}$ are the input and output rates of EI to the chemical process; $I_{\text{in}}^{\text{ep}}$, and $I_{\text{out}}^{\text{ep}}$ are the input and output rates of EI to the energy generation process; $I_{\text{we}}^{\text{cp}}$ and $I_{\text{we}}^{\text{ep}}$ are the outputs of EI associated with waste energy from the chemical and energy generation processes, respectively; and $I_{\text{gene}}^{\text{system}}$ is the rate of generation of EI in the system. For steady state, this expression reduces to

$$0 = I_{\text{in}}^{\text{cp}} + I_{\text{in}}^{\text{ep}} - I_{\text{out}}^{\text{cp}} - I_{\text{out}}^{\text{ep}} - I_{\text{we}}^{\text{cp}} - I_{\text{we}}^{\text{ep}} + I_{\text{gene}}^{\text{system}} \quad (2)$$

It is necessary to relate the conceptual EI to measurable quantities. A generalized linear theory proposed by Mallick *et al.* (1996) and Cabezas *et al.* (1999) has been adopted in this study. It relates EI to measurable quantities such as stream flow rates, compositions and chemical specific environmental impacts (ϕ_k). The chemical specific environmental impact (ϕ_k) may be calculated using the WAR algorithm. The expression for chemical process is described as follows:

$$I_{\text{in}}^{\text{cp}} = \sum I_j^{\text{in}} = \sum M_j^{\text{in}} \sum X_{jk} \phi_k + \dots \quad (3)$$

$$I_{\text{out}}^{\text{cp}} = \sum I_j^{\text{out}} = \sum M_j^{\text{out}} \sum X_{jk} \phi_k + \dots \quad (4)$$

$$I_{\text{in}}^{\text{ep}} = \sum I_j^{\text{in}} = \sum M_j^{\text{in}} \sum X_{jk} \phi_k + \dots \quad (5)$$

$$I_{\text{out}}^{\text{ep}} = \sum I_j^{\text{out}} = \sum M_j^{\text{out}} \sum X_{jk} \phi_k + \dots \quad (6)$$

where I_j^{cp} is the rate of EI into or out of the chemical process; I_j is the EI flow rate with stream j , which may be an input or an output stream; M_j is the mass flow rate of stream j , which may be an input or an output; X_{kj} is the mass fraction of component k in stream j ; and ϕ_k is the EI for chemical k . The same notation with superscript “ep” is used for energy production. In order to analyze the relationship between environmental impact and process cost, a mathematical framework has been used. The process is represented by a set of mathematical equations that describe the properties of the inlet stream, waste stream, and equipment specifications, cost functions and the degree of pollutant removal. This methodology uses the WAR algorithm to calculate basic chemical environmental impact and a modified WAR algorithm to calculate

energy related potential environmental impact. The details of WAR may be seen in Hilaly and Sikdar (1994) and the modified WAR in Young and Cabezas (1999).

The total EI of the system can be expressed by an environmental function like $I = I(X)$. Any type of EI (e.g., global warming, and ozone depletion) can be incorporated into this function, usually as an environmental index. It allows all emissions from different compounds to be lumped together into a single number, which represents the impact. Thus, the environmental function is expressed as the sum of environmental impacts generated by both outputs and inputs from each species.

2.2 Risk-based multi-criteria decision-making (RBMCDM)

There are many approaches available for multi-criteria decision-making (Sadiq 2001).

GreenPro-I used fuzzy composite programming (FCP) which is briefly presented below (see Sadiq *et al.* 2003 for details). A traditional MCDM problem can be expressed in a matrix form

$$\begin{array}{c}
 X_1 \quad X_2 \quad \dots \quad X_n \\
 \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} X_{11} & X_{12} & \dots & X_{1n} \\ X_{21} & X_{22} & \dots & X_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ X_{m1} & X_{m2} & \dots & X_{mn} \end{bmatrix}
 \end{array} \quad (7)$$

where

$A_i = 1, 2, \dots, m$ are possible courses of action or alternatives;

$X_i = 1, 2, \dots, n$ are attributes, by which alternatives are measured; and

X_{mn} = Performance (rating) of alternative A_i with respect to attribute or criteria X_i .

Often X_{mn} cannot be determined precisely due to unquantifiable, incomplete, or unobtainable information. Subjectivity may also arise due to ignorance of factual conditions. Unquantifiable information refers to subjectivity such as *good*, *poor*, *high*, and *low*. Examples of incomplete information are statements like *about* one million, and *less than* 10 km/h. Sometimes crisp data can be obtainable, but require a lot of resources, whereas *approximation* can be achieved with

less effort and time. Often linguistic descriptors are useful because of unavailability of information or resources. Fuzzy set theory is an important tool to deal with these limitations and leads to fuzzy-based MCDM.

Fuzzy-based MCDM involves two main steps: *aggregation* and *ranking*. The *aggregation* determines the final utility value (performance score expressed by a fuzzy number) for each alternative by grouping the performance measures of the various individual attributes (criteria). In crisp MCDM, the final performance scores are real numbers, so the *ranking* is self-explanatory. In fuzzy-based MCDM, the *ranking* involves ordering of the alternatives based on *defuzzification* of a final utility value.

MCDM requires information about the relative importance of criteria involved in the analysis. In case of "n" criteria, a set of weights can be written as

$$\underline{W}^T = (w_1, w_2, \dots, w_j, \dots, w_n), \quad \sum_{j=1}^m w_j = 1 \quad (8)$$

By multiplying equation 7 with 8, the decision matrix becomes

$$\mathbf{D} = X_{ij} \otimes W = \begin{bmatrix} X_{11} & X_{12} & \cdot & \cdot & X_{1n} \\ X_{21} & X_{22} & \cdot & \cdot & X_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ X_{m1} & X_{m2} & \cdot & \cdot & X_{mn} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ w_n \end{bmatrix} \quad (9)$$

Saaty (1988) proposed analytic hierarchy process (AHP) to estimate the relative weights of each attribute in a group based on pair-wise comparisons. Cheng and Lin (2002) defined linguistic variables for fuzzy importance factors (Table 1). The scale starts at *very low*, and goes on to *low*, *medium low*, *medium*, *medium high*, *high* and *very high*. The higher the importance of an attribute, the higher is the expected weight. The w_j for each attribute in a group is given by:

$$w_j = \frac{Im_j}{\sum_{j=1}^m Im_j} \quad (10)$$

where Im_j is the importance factor, which can be selected from Table 1 for each attribute in a group. Chen and Hwang (1992) have provided eight scales to convert linguistic terms into fuzzy numbers. The same linguistic terms have different meanings in different scales. The principle of this system is to pick a scale that contains all verbal terms given by a decision-maker and use the fuzzy numbers in that scale to represent the meaning of verbal terms. We used Cheng and Lin's (2002) linguistic variables (Table 1) to convert linguistic terms into fuzzy numbers.

2.3 Fuzzy composite programming (FCP)

It is important to select an appropriate RBMCDM strategy when the values of input variables, such as environmental risks, costs, and technical feasibility attributes are uncertain, or, vague. FCP is used to assist decision-makers in solving problems of multiple attributes and conflicting objectives with uncertainties. FCP is an extension of compromise programming (Bogardi and Bardossy 1983). Lee (1992) and Lee *et al.* (1991) used FCP for the management of dredged material disposal and for developing management strategies for nitrate control in drinking water, respectively. Stansbury *et al.* (1989) also conducted a risk-cost tradeoff study for dredged materials disposal using FCP. Sadiq (2001) and Sadiq *et al.* (2003) used FCP for the management of drilling waste disposal in the offshore to determine the best discharge scenario from risk, cost and technical feasibility viewpoints. Khan *et al.* (2002) used FCP for selecting the best source of energy for urea production.

2.3.1 Aggregation

FCP is a step-by-step procedure of grouping basic indicators to form generalized indicators. The cost, technical feasibility, environmental damages, and treatment efficiency parameters are defined as basic indicators. The first step in FCP is the normalization of the basic indicators to convert non-commensurate indicators into unitless entities. This is necessary because all basic indicators have different units and are difficult to compare in their respective units. The efficiency of removal of dispersed oil, Benzene, Toluene, Ethyl benzene, and Xylene (BTEX), Poly-cyclic aromatic hydrocarbons (PAH), Naphthalene, Phenanthrene, and Dibenzothiophene (NPD), heavy metal, and naturally occurring radioactive material (NORM) present in produced water can be grouped into a index for treatment efficiency. The environmental parameters - global warming, air pollution, critical water mass, and solid waste mass - can be combined into a

generalized group environmental index. The index for technical feasibility is obtained by grouping basic indicators like ease of operation, efficiency, status of technology and control measures. The grouping of different attributes is performed in steps to get the final system index. This trade-off analysis for different alternatives can be made at different hierarchy levels. The value of the (Level 3) system index represents the contributions of the grouped indexes at Level 2 (see Figure 4).

By defining $Z_i(x)$ as a fuzzy number of the i^{th} basic indicator with a triangular membership function of $\mu[Z_i(x)]$, various management alternatives under uncertainty can be evaluated. The confidence level for an uncertain value can be determined using observed or measured variability. Since units of basic indicators are different, the actual value of each basic indicator should be transformed into an index, $S_{i,h}(x)$, using the best (BES) or the worst (WOR) value of the indicator as shown in Figure 5 (Lee *et al.* 1991). Using the normalized index values of basic indicators, the Level 2 index values, $L_{j,h}(x)$, of composite indicators can be defined by

$$L_{j,h}(x) = \left\{ \sum_{i=1}^{n_j} w_j [S_{i,h,j}(x)] \right\} \quad (11)$$

The variables are defined in the nomenclature. The index value $L_{k,h}(x)$, of a third level composite indicator can be calculated by the index values of the second level composite indicators - environment, cost, treatment efficiency and technical feasibility. The w_j values are estimated using equation 10.

2.3.2 Ranking

The final performance rating determines how well an alternative satisfies the decision-maker's utility. The alternative with the highest rating will be most desirable. If the final ratings are real numbers, then it is straightforward to decide the best alternative.

Performance ratings X_{ij} can be crisp, fuzzy, and/or linguistic. When fuzzy data are incorporated into MCDM, the final ratings will be fuzzy numbers, not crisp, which are not straightforward to compare. In MCDM applications when the final ratings are fuzzy, different ranking methods can be used. Chen and Hwang (1992) have classified ranking methods into four major groups:

preference relation, fuzzy mean and spread, fuzzy scoring, and linguistic expression. Fuzzy scoring techniques are the most popular. In the present study, we used three methods for ranking: Chen's ranking method, simple averaging method, and weighted averaging method. For details refer to Chen (1985), Cheng and Lin (2002), and Khan *et al.* (2002).

In the case of group decision-making, there are different techniques available for the aggregation of preferences (Smolikova and Wachowiak 2002). In this study, an additive ranking rule is employed to arrive at a robust ranking order. The additive ranking rule determines the average ranking order of an alternative (A_i), which is the arithmetic mean of the rankings made by all ranking methods.

$$R_{Ai}^N = rank \left(\frac{\sum_{K=1}^N R_{Ai,K}}{N} \right)_{i \in m} \quad (12)$$

The parameters of the above equation are defined in the nomenclature.

2.3.3 Second stage assessment for comparing strategies

The second stage analysis is performed if r numbers of alternatives are combined and described as a strategy. The results of the first stage analysis are grouped at the highest hierarchy level using equal weights. The strategy (S_r) can be established as

$$S_r = W(1) \cdot A_1 + W(2) \cdot A_2 + \dots + W(r) \cdot A_r \quad (13)$$

where

$$W(1) \text{ and } W(2) = 0.50, \quad \text{if } r = 2$$

$$W(1), W(2) \text{ and } W(3) = 0.33, \quad \text{if } r = 3 \text{ and so on.}$$

3 Produced Water Management

Produced water is a byproduct of the production of oil and gas. Water is naturally present in the reservoirs and, despite all efforts to produce the hydrocarbons selectively, some water is

produced, admixed as a liquid with the oil or as vapor in the hydrocarbon. Produced water contains dispersed oil and dissolved organic compounds, including light aromatic hydrocarbons such as BTEX, PAH, heavy aromatic NPD, organic acids, phenols, inorganic compounds, as well as traces of NORM. The chemical composition varies over a wide range and depends mainly on the attributed to the reservoir's geology. The composition of produced water may also change slightly through the production life of a reservoir. After a couple of years, wells start producing increased quantities of water of almost stable composition. However, if water is injected for pressure maintenance, or for any other reason, the composition of produced water changes, due to dilution of the reservoir water. This would displace the water composition from equilibrium and create the potential for additional dissolution of aromatics from the oil phase (O&G 2002).

Produced water from oil production fields differs from gas production fields. Water from gas production fields generally has a higher content of low molecular weight aromatic hydrocarbons than water from oil production platforms. However, the total amount of water produced from gas fields is considerably smaller than oil production fields.

3.1 Fate of offshore produced water

Most aromatic compounds in produced water are volatile. They readily evaporate from the sea surface or from produced water plumes that reach the surface due to density gradients. The depressive mixing results in a $50\text{-}150 \times 10^3$ -fold reduction of the benzene concentration in seawater 20m away from the point of discharge (Rabalais *et al.* 1991; Tetrens and Tait 1996; Furuholt and Kinn 1996; Riksheim and Johnsen 1994; O&G 2002). The NPD compounds are less volatile, but still are reduced by evaporation. This is particularly important for high-temperature produced water discharges, or for produced water with a gas/air injection before discharge. The less water-soluble fraction of aromatic compounds, the PAH compounds, is expected to be associated with particulate and oil droplets and is likely to follow the plume, or be retained at certain depths of the water column depending upon the buoyancy of the supporting particulate matter.

Past studies in the North Sea revealed that PAH concentration levels exceeding the toxicity threshold levels can be found within a distance of 500m from the discharge point and may vary

spatially and temporally depending on the hydrodynamics (O&G 2002). The regulatory threshold limit is only dependent on the discharge concentration. In general, a dilution factor of 1000 or less is assumed sufficient to reach *predicted no-effect concentration* for PAH (OOC 1997).

There are many technologies available for the treatment of dispersed and dissolved oil, and other wastes in produced water. Applicability of these technologies to produced water treatment must consider time, space, load, and vulnerability limitations. This study aims to evaluate different treatment options and a brief description of the BAT options is presented in the following section (for details see O&G 2002).

3.2 Treatment technologies

Three methods are used to reduce and control potential environmental impacts of produced water:

1. *Avoid water production from the well.* The production of formation and connate waters may be controlled, but equilibrium water due to condensation can not be avoided;
2. *Re-injection.* After surface separation of the water from the hydrocarbons, the water may be reinjected back into the formation. This technique is only possible when a well is available for disposal; and
3. *Removal of hydrocarbons from the water.* This can be done at several steps between the well bottom and discharge point.

Methods 2 and 3 are discussed in the present paper. A range of technologies exists for the treatment of offshore produced water, and many of them are referred to as BAT. The key technologies evaluated in this paper are summarized in Table 2.

3.2.1 Physical separation

The majority of the technologies in this group remove dispersed oil and PAHs to a certain extent. However, the performance achieved by each system will depend on the process variables at each installation. These variables include reservoir type, temperature, pressure, oil type and viscosity,

emulsion stability, oil droplet size, water salinity, flow rate etc. The technologies in this group have limitations on efficiency, weight, size and processing time.

3.2.2 *Enhanced separation*

Further removal of dispersed oil can be obtained by enhanced separation after modifying the oil droplet characteristics in the upstream feed to the primary treatment system. This includes the use of mechanical coalescing systems (Pect-F, Mare's tail) and other commercially available technologies such as centrifuges and hydrocyclones.

Limitations to this technology for offshore operations are weight and space. The application of hydrocyclones (most widely used in the oil industry) enables large water volumes to be processed, often without needing additional power input or chemicals. The residence time for hydrocyclones is very short (often in seconds), but reduces size, weight and cost of the treatment facilities significantly.

3.2.3 *Polishing*

Polishing technologies are suitable for the removal of dissolved aromatic hydrocarbons. The advantages and disadvantages of several polishing technologies are briefly discussed here. The details of the technology presented below are adopted from O&G (2002).

Hydrocarbon contaminated water is passed through a column packed with Macro Porous Polymer Extraction (MPPE) particles. An extraction liquid immobilized within the polymer matrix removes the hydrocarbons from the water. The purified water passes out of the column directly for reuse or discharge. Adsorption is a process in which a soluble contaminant (the adsorbate) is removed from water by contact with a solid surface (the adsorbent). The binding to the surface is usually weak and reversible. C-Tour process system is an enhancement to hydrocyclone technology, which extracts hydrocarbons from water using gas condensate. The injected gas condensate acts as an extraction-solvent. The solvent extracts the dissolved hydrocarbons from the water phase and is later removed in the hydrocyclone. Membrane removes dissolved hydrocarbons at the molecular level. All hydrocarbons larger than the membrane material will be rejected (including dispersed oil). Steam stripping and distillation is

based on vapor-liquid equilibrium. In a typical stripper column, a vapor stream enters at the bottom while the liquid enters from the top. The vapor stream, which could be steam, air or any other gas, picks up the most volatile components in the liquid stream. Biodegradation employs microbes to break down and remove oil and aromatics from produced water. The processes require a medium to long residence time for the organisms to grow and stabilize for effective operation. After separation of the water and oil, produced water can be injected into a disposal well or preferably the same reservoir from where it originated. This process alone does not enable an operator to meet performance standards in the portion of produced water being discharged.

3.5 Offshore treatment strategies

Different treatment technology alternatives are efficient in the removal of different pollutants and complement each other by enhancing the treatment efficiency if used in series or parallel. Various treatment alternatives can be grouped to develop a complete treatment strategy. Seven treatment strategies are identified in Table 3, which are evaluated in the second stage assessment of the proposed methodology.

4 Application of *GreenPro-I*

4.1 First stage assessment

Fourteen treatment technology options were evaluated individually in the first stage assessment (Table 2). The *GreenPro-I* was applied to each treatment option to estimate the utility function (U_i) as described before. The available data for various basic indicators are either quantitative or qualitative in nature (Figure 4).

As a first step of this assessment, environmental impact for chemicals and energy use was calculated for all the fourteen treatment options using the WAR algorithm. In the environment category, five main impacts (resource depletion, global warming, air pollution, critical water mass, and critical solid mass) were estimated (Table 4a). The same approach is used to compute the treatment category performance impacts for dissolved oil, BTEX, NPD, PAH, Heavy metal, and NORM. Four qualitative parameters related to technical feasibility and three parameters

related to cost factors were also determined.

As the original input data were non-commensurate the normalization was carried to bring all parameters in the same scale. The normalization was done using either cost (WOR > BES) or benefit (BES > WOR) criteria depending on its type. The WOR > BES represents those indicators for which worst values are more than their best values, e.g., risk and cost. The BES > WOR represents those indicators for which best values are more than their worst values, e.g., technical feasibility (see Sadiq 2001 for details). The normalization process used here is illustrated in Figure 5.

The maximum likely estimates reported in Table 4a (developed with the help of O&G, 2002 data and WAR and its derivative algorithm) were fuzzified. The uncertainty in the normalized scale ($b = c$; maximum likely estimate) was expressed by a factor of $\pm 50\%$ representing the largest likely interval between a and d (base of a triangular fuzzy number). The normalized triangular fuzzy data are reported in Table 4b.

To develop a weight or priority matrix, the importance scales (Im_j) were assigned to various basic indicators (at level-I) and sub-attributes (at level-II) as given in Table 1. These importance factors were converted into normalized weights (w_j) using equation 10. The weighting scheme for the first stage assessment is given in Table 5. The fuzzy composite structure described in Figure 4 was used to group indicators at two hierarchical levels.

Figure 6 describes the system index of various treatment technologies after the first stage assessment. The bigger base of the TFN represents higher uncertainty in the system index. Different ranking methods (described in the previous section) were used for *defuzzification* of the system index. The alternatives A10, A12 and A13 were found to be at the top of the list (Table 6). The comparison of treatment technologies from different categories (physical and enhanced separation, and polishing techniques) are compared. To make a comparison of commercially available technologies which are generally used in series, we performed a second stage assessment.

4.2 Second stage assessment

For the second stage assessment, seven treatment strategies (which are combinations of different

technologies) were established based on the result of the first stage assessment. These strategies are listed in Table 3. The proposed strategies were evaluated using the same procedure as followed in the first stage assessment. The indices obtained from the evaluation of these strategies are shown in Figure 7. Three ranking methods were employed to establish the final ranking order for these seven proposed strategies (Table 7).

The treatment strategy S3 (hydrocyclone and produced water re-injection) was found to be the best treatment system available and is rated best. The two technologies involved in this strategy are well tested and are currently in practice. Furthermore, the operating cost and environmental impacts of these technologies are the lowest. The treatment strategy S1 (hydrocyclone and adsorption) was also found to be among best treatment options available. This is also commercially available technology. The strategy, S5 (membrane and centrifuge) was rated 3rd among the seven strategies, but extensive data were not available. Strategy S4 (down hole separation and injection) - a clean option of produced water management - was also very close. However, due to some unresolved technical and regulatory issues this technology has not been well practiced.

The ranking order obtained using this methodology is not necessarily fixed. Where more detailed data and information becomes available, the methodology developed here can help in re-evaluating the alternatives (or strategies) in the light of emerging information. The intention here is to show the methodology, which has the flexibility to incorporate qualitative and quantitative data, and yet is comprehensive enough to guide in decision-making for product and process selection and design.

5 Summary and Conclusions

In green and clean process selection and design, different alternatives are evaluated. These alternatives may be basic conceptual designs of the process or techniques or technologies of waste management. Each alternative would result in a different set of (environmental, economical, and technological) data. These data must be evaluated to select or design a process, product or waste management strategy. Therefore, it is required to adopt or develop a simple but comprehensive technique for design decision-making that can incorporate all these factors (data). In this regard, a few methodologies have been proposed in the literature. *GreenPro* and

GreenPro-I are flexible enough to apply for any design stage. In this paper, *GreenPro-I* is revisited and applied to a case study of offshore produced water management for the evaluation of BAT options.

In the first stage assessment, fourteen BAT options were evaluated considering the *cradle to gate* life cycle analysis. In the second stage assessment, seven treatment strategies were developed by utilizing the results of the first stage assessment. The treatment strategy combining a hydrocyclone and produced water re-injection was found to be the best treatment system available. The two technologies involved in this strategy are well tested and are in current practice. The ranking order obtained using this methodology may change by incorporating more precise data. The intention of this paper is to demonstrate the new methodology, which is flexible enough to incorporate qualitative and quantitative data in guiding decision-making for product and process selection and design.

Readers are encouraged to contact for their comments or views to: Dr. Rehan Sadiq (rehan.sadiq@nrc-cnrc.gc.ca) and Dr. Faisal Khan (fkhan@engr.mun.ca).

Nomenclature

A_i	An alternative
I_j	<i>Environmental impact</i> flow rate with stream j
Im_j	Importance factor of attribute j
I_{system}	Environmental Impact within the system
I_{in}	Input rates of <i>environmental impact</i> to the system (chemical process or energy generation)
I_{out}	Output rates of <i>environmental impact</i> from the system (chemical process or energy generation)
I_{we}	Output rate of <i>environmental impact</i> associated with waste energy from the system (chemical and energy generation processes)
I_{gene}	Rate of generation of <i>environmental impact</i> in the system
K	Ranking methods (1 – N)
$L_{k,h}(x)$	Third level composite indicator
M_j	Mass flow rate of stream j
N	Total number of ranking methods
n_j	Number of elements in second-level group j
$\text{rank}(\text{value})_{i \in m}$	Operator convert the alternative A_i into ranking order among m alternatives
$R_{Ai}^N =$	Average ranking order of an alternative A_i
$S_{i,h,j}(x)$	Basic value for i^{th} basic indicator in the second level group j of basic indicators with membership of h ;
w_j, W_j	Weight reflecting importance basic indicator (or attribute) in group j
X_i	Attributes by which alternatives are measured
X_{kj}	Mass fraction of component k in stream j
X_{mn}	Performance (rating) of alternative A_i with respect to attribute or criteria X_i
$Z_i(x)$	Fuzzy number of the i^{th} basic indicator with a triangular membership function
$\mu[Z_i(x)],$	Fuzzy triangular membership function
ϕ_k	<i>Environmental impact</i> for chemical k

Superscripts

system	system
cp	chemical process
ep	energy generation

Acronyms

AHP	Analytical hierarchy process
AP	Air pollution
BAT	Best available technology
BTEX	Benzene, Toluene, Ethyl benzene, and Xylene
CC	Capital cost
CM	Control measures
CT	Critical water mass
DO	Dissolved oil
EF	Efficiency
EI	Environmental impact
EL	Environmental Load
EnI	Environmental indicator
EO	Ease of operation
FCP	Fuzzy composite programming
GW	Global warming
HE & S	Human ecological and safety
HM	Heavy metals
ISO	International standardization organization
LCA	Life cycle analysis
LCI	Life cycle inventory
MCDM	Multi-criteria decision-making
MPPE	Macro porous polymer extraction
NORM	Naturally occurring radioactive material
NPD	Naphthalene, Phenanthrene, and Dibenzothiophene
OD	Ozone depletion
OM	Operation & maintenance
PAH	Poly-cyclic aromatic hydrocarbons
PEI	Potential environmental impact
RBLCA	Risk-based life cycle analysis
RBMCDM	Risk-based mMulti-criteria decision-making
RD	Resource depletion
SETAC	Society of environmental toxicology and chemistry
SI	System score or index
SM	Solid waste mass
ST	Status of technology
TFI	Technical feasibility index
TFN	Triangular fuzzy number
TI	Treatment efficiency index
WAR	Waste reduction
WC	Working cost

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Figure 1. Process simulation application

Figure 2. Basic framework for modified *GreenPro-I* (Khan *et al.* 2002)

Figure 3. Methodology for LCI and risk/impact analyses

Figure 4. The grouping framework for modified *GreenPro-I*

$$S_{i,h}(x) = \begin{cases} 1 & Z_{i,h}(x) \geq BESZi \\ \frac{Z_{i,h}(x) - WORZi}{BESZi - WORZi} & WORZi < Z_{i,h}(x) < BESZi \\ 0 & Z_{i,h}(x) \leq WORZi \end{cases}$$

$$\begin{aligned} Z_{i,h}(x) &\geq BESZi \\ WORZi &< Z_{i,h}(x) < BESZi \\ Z_{i,h}(x) &\geq WORZi \end{aligned}$$

$$S_{i,h}(x) = \begin{cases} 1 & Z_{i,h}(x) \leq BESZi \\ \frac{Z_{i,h}(x) - WORZi}{BESZi - WORZi} & BESZi < Z_{i,h}(x) < WORZi \\ 0 & Z_{i,h}(x) \geq WORZi \end{cases}$$

$$\begin{aligned} Z_{i,h}(x) &\leq BESZi \\ BESZi &< Z_{i,h}(x) < WORZi \\ Z_{i,h}(x) &\geq WORZi \end{aligned}$$

Figure 5. Transforming actual value $Z_{i,h}(x)$ into normalized index value $S_{i,h}(x)$ (Sadiq 2001)

Figure 6. Evaluation of system index - first stage assessment

Figure 7. Evaluation of treatment strategies - second stage assessment

Table 1. Linguistic measures of importance

Intensity of importance, Im_j	*Definition (TFN)
Very low (VL)	(0, 0.05, 0.1)
Low (L)	(0.1, 0.18, 0.25)
Medium low (ML)	(0.25, 0.33, 0.4)
Medium (M)	(0.4, 0.5, 0.6)
Medium high (MH)	(0.6, 0.68, 0.75)
High (H)	(0.75, 0.83, 0.9)
Very high (VH)	(0.9, 0.95, 1)

*TFN: Triangular fuzzy number; TFN (a, b, d) because b = c

Table 2. Details of the technology investigated in present study (modified after O&G 2002)

Technology name	Alternatives	**Efficient in dealing with				
		Dispersed oil	<i>BTEX</i>	<i>NPD</i>	<i>PAH</i>	<i>NORM</i>
Physical separation technologies						
Floatation	A1	Yes	No	No	Some	No
Sparging	A2	Yes	No	No	Some	No
Coalescence	A3	Yes	No	No	Some	No
Enhanced separation technologies						
Hydrocyclones	A4	Yes	No	No	Some	No
PECT-F and/or Mare’s Tail	A5	Yes	No	No	Some	No
Centrifuges	A6	Yes	No	No	Some	No
Polishing technologies						
MPPE	A7	Yes	Yes	Yes	Yes	Some
Adsorption	A8	Yes	Yes	*NC	NC	NC
C-Tour	A9	Yes	No	Yes	Yes	Some
Membranes	A10	Yes	Yes	Yes	Yes	Yes
Steam Stripping	A11	No	Yes	No	No	No
Biological	A12	Yes	Yes	NC	NC	Some
Produced water re- injection	A13	Yes	Yes	Yes	Yes	Some
Down hole separation	A14	Yes	Yes	Yes	Yes	Some

*NC: Not clear

** Abbreviations are defined in acronyms

Table 3. System of treatment strategies- second stage assessment

Strategy	System of technologies	Comments
S1	Hydrocyclone + Absorption	Commercially available and known as MPPE based technology (A7)
S2	Hydrocyclone + Solvent extraction	This is also commercially practiced and known as C-Tour (A9)
S3	Hydrocyclone + Produced water re-injection	Commercially used
S4	Down hole separation + injection	Commercially used
S5	Centrifuge + Membrane	Data not available
S6	Hydrocyclone + Coalescence + Biological treatment	With out biological treatment it is commercially known as Pect-F (A5)
S7	Flotation + Adsorption	Few places tested but not commercial in use

Table 4a. Discrete quantitative/qualitative input data for basic indicators used in present study*

Alternatives	Environmental indicators (<i>EnI</i>)					Treatment efficiency indicators (<i>TI</i>)					
	<i>RD</i>	<i>GW</i>	<i>AP</i>	<i>CT</i>	<i>SM</i>	<i>DO</i>	<i>BTEX</i>	<i>NPD</i>	<i>PAH</i>	<i>HM</i>	<i>NORM</i>
A1	0.03	0.10	0.15	0.30	0.20	0.60	0.00	0.00	0.20	0.00	0.00
A2	0.35	0.15	0.20	0.20	0.20	0.60	0.00	0.00	0.30	0.00	0.00
A3	0.40	0.20	0.20	0.30	0.30	0.70	0.00	0.00	0.40	0.00	0.00
A4	0.55	0.15	0.30	0.35	0.25	0.90	0.00	0.00	0.50	0.00	0.00
A5	0.60	0.20	0.30	0.35	0.30	0.95	0.00	0.00	0.70	0.00	0.00
A6	0.45	0.20	0.20	0.15	0.20	0.95	0.00	0.00	0.50	0.00	0.00
A7	0.70	0.40	0.50	0.40	0.30	0.90	0.90	0.70	0.90	0.30	0.30
A8	0.60	0.35	0.40	0.35	0.50	0.95	0.95	0.70	0.80	0.10	0.10
A9	0.80	0.60	0.55	0.50	0.30	0.95	0.30	0.80	0.90	0.50	0.60
A10	0.70	0.50	0.30	0.40	0.80	0.95	0.90	0.80	0.90	0.60	0.70
A11	1.00	1.00	1.00	1.00	0.30	0.60	0.95	0.00	0.00	0.00	0.00
A12	0.30	0.35	0.30	0.20	1.00	0.90	0.95	0.60	0.70	0.40	0.10
A13	0.90	0.60	0.45	0.30	0.15	0.90	0.90	0.80	0.80	0.50	0.50
A14	0.85	0.60	0.30	0.35	0.15	0.90	0.95	0.80	0.90	0.60	0.50

Alternatives	Technical feasibility indicators (<i>TFI</i>)				Cost indicators (<i>CI</i>)		
	<i>EO</i>	<i>EF</i>	<i>ST</i>	<i>CM</i>	<i>WC</i>	<i>OM</i>	<i>CC</i>
A1	0.80	0.85	1.00	0.40	0.10	0.20	0.30
A2	0.80	0.90	1.00	0.50	0.10	0.25	0.35
A3	0.70	0.90	0.80	0.40	0.15	0.15	0.30
A4	0.90	0.95	1.00	0.80	0.20	0.20	0.25
A5	0.80	0.95	0.75	0.60	0.25	0.20	0.30
A6	0.80	0.95	1.00	0.70	0.20	0.20	0.35
A7	0.60	0.90	0.60	0.30	0.15	0.35	0.40
A8	0.60	0.90	0.60	0.30	0.15	0.40	0.50
A9	0.70	0.90	0.50	0.40	0.20	0.35	0.50
A10	0.60	0.90	0.50	0.30	0.15	0.35	0.50
A11	0.70	0.90	0.50	0.20	0.30	0.40	0.60
A12	0.90	0.90	0.60	0.10	0.10	0.20	0.50
A13	0.90	0.95	0.90	0.80	0.25	0.20	0.60
A14	0.90	0.90	0.70	0.90	0.20	0.60	0.70

*Abbreviations are defined in acronyms

Table 4b. Normalized input data (TFN) for basic indicators*

Ai	<i>RD</i>			<i>GW</i>			<i>AP</i>			<i>CT</i>			<i>SM</i>		
	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>
A1	0.03	0.02	0.05	0.10	0.05	0.15	0.15	0.08	0.23	0.30	0.15	0.45	0.20	0.10	0.30
A2	0.35	0.18	0.53	0.15	0.08	0.23	0.20	0.10	0.30	0.20	0.10	0.30	0.20	0.10	0.30
A3	0.40	0.20	0.60	0.20	0.10	0.30	0.20	0.10	0.30	0.30	0.15	0.45	0.30	0.15	0.45
A4	0.55	0.28	0.83	0.15	0.08	0.23	0.30	0.15	0.45	0.35	0.18	0.53	0.25	0.13	0.38
A5	0.60	0.30	0.90	0.20	0.10	0.30	0.30	0.15	0.45	0.35	0.18	0.53	0.30	0.15	0.45
A6	0.45	0.23	0.68	0.20	0.10	0.30	0.20	0.10	0.30	0.15	0.08	0.23	0.20	0.10	0.30
A7	0.70	0.35	1.05	0.40	0.20	0.60	0.50	0.25	0.75	0.40	0.20	0.60	0.30	0.15	0.45
A8	0.60	0.30	0.90	0.35	0.18	0.53	0.40	0.20	0.60	0.35	0.18	0.53	0.50	0.25	0.75
A9	0.80	0.40	1.20	0.60	0.30	0.90	0.55	0.28	0.83	0.50	0.25	0.75	0.30	0.15	0.45
A10	0.70	0.35	1.05	0.50	0.25	0.75	0.30	0.15	0.45	0.40	0.20	0.60	0.80	0.40	1.20
A11	1.00	0.50	1.50	1.00	0.50	1.50	1.00	0.50	1.50	1.00	0.50	1.50	0.30	0.15	0.45
A12	0.30	0.15	0.45	0.35	0.18	0.53	0.30	0.15	0.45	0.20	0.10	0.30	1.00	0.50	1.50
A13	0.90	0.45	1.35	0.60	0.30	0.90	0.45	0.23	0.68	0.30	0.15	0.45	0.15	0.08	0.23
A14	0.85	0.43	1.28	0.60	0.30	0.90	0.30	0.15	0.45	0.35	0.18	0.53	0.15	0.08	0.23

Ai	<i>DO</i>			<i>BTEX</i>			<i>NPD</i>			<i>PAH</i>			<i>HM</i>		
	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>
A1	0.60	0.30	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.10	0.30	0.00	0.00	0.00
A2	0.60	0.30	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.15	0.45	0.00	0.00	0.00
A3	0.70	0.35	1.05	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.20	0.60	0.00	0.00	0.00
A4	0.90	0.45	1.35	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.25	0.75	0.00	0.00	0.00
A5	0.95	0.48	1.43	0.00	0.00	0.00	0.00	0.00	0.00	0.70	0.35	1.05	0.00	0.00	0.00
A6	0.95	0.48	1.43	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.25	0.75	0.00	0.00	0.00
A7	0.90	0.45	1.35	0.90	0.45	1.35	0.70	0.35	1.05	0.90	0.45	1.35	0.30	0.15	0.45
A8	0.95	0.48	1.43	0.95	0.48	1.43	0.70	0.35	1.05	0.80	0.40	1.20	0.10	0.05	0.15
A9	0.95	0.48	1.43	0.30	0.15	0.45	0.80	0.40	1.20	0.90	0.45	1.35	0.50	0.25	0.75
A10	0.95	0.48	1.43	0.90	0.45	1.35	0.80	0.40	1.20	0.90	0.45	1.35	0.60	0.30	0.90
A11	0.60	0.30	0.90	0.95	0.48	1.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A12	0.90	0.45	1.35	0.95	0.48	1.43	0.60	0.30	0.90	0.70	0.35	1.05	0.40	0.20	0.60
A13	0.90	0.45	1.35	0.90	0.45	1.35	0.80	0.40	1.20	0.80	0.40	1.20	0.50	0.25	0.75
A14	0.90	0.45	1.35	0.95	0.48	1.43	0.80	0.40	1.20	0.90	0.45	1.35	0.60	0.30	0.90

Table 4b. Normalized input data (TFN) for basic indicators (contd.)*

Ai	<i>NORM</i>			<i>EO</i>			<i>EF</i>			<i>ST</i>			<i>CM</i>		
	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>
A1	0.00	0.00	0.00	0.80	0.40	1.20	0.85	0.43	1.28	1.00	0.50	1.50	0.40	0.20	0.60
A2	0.00	0.00	0.00	0.80	0.40	1.20	0.90	0.45	1.35	1.00	0.50	1.50	0.50	0.25	0.75
A3	0.00	0.00	0.00	0.70	0.35	1.05	0.90	0.45	1.35	0.80	0.40	1.20	0.40	0.20	0.60
A4	0.00	0.00	0.00	0.90	0.45	1.35	0.95	0.48	1.43	1.00	0.50	1.50	0.80	0.40	1.20
A5	0.00	0.00	0.00	0.80	0.40	1.20	0.95	0.48	1.43	0.75	0.38	1.13	0.60	0.30	0.90
A6	0.00	0.00	0.00	0.80	0.40	1.20	0.95	0.48	1.43	1.00	0.50	1.50	0.70	0.35	1.05
A7	0.30	0.15	0.45	0.60	0.30	0.90	0.90	0.45	1.35	0.60	0.30	0.90	0.30	0.15	0.45
A8	0.10	0.05	0.15	0.60	0.30	0.90	0.90	0.45	1.35	0.60	0.30	0.90	0.30	0.15	0.45
A9	0.60	0.30	0.90	0.70	0.35	1.05	0.90	0.45	1.35	0.50	0.25	0.75	0.40	0.20	0.60
A10	0.70	0.35	1.05	0.60	0.30	0.90	0.90	0.45	1.35	0.50	0.25	0.75	0.30	0.15	0.45
A11	0.00	0.00	0.00	0.70	0.35	1.05	0.90	0.45	1.35	0.50	0.25	0.75	0.20	0.10	0.30
A12	0.10	0.05	0.15	0.90	0.45	1.35	0.90	0.45	1.35	0.60	0.30	0.90	0.10	0.05	0.15
A13	0.50	0.25	0.75	0.90	0.45	1.35	0.95	0.48	1.43	0.90	0.45	1.35	0.80	0.40	1.20
A14	0.50	0.25	0.75	0.90	0.45	1.35	0.90	0.45	1.35	0.70	0.35	1.05	0.90	0.45	1.35

Ai	<i>WC</i>			<i>OM</i>			<i>CC</i>		
	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>	<i>b = c</i>	<i>a</i>	<i>d</i>
A1	0.10	0.05	0.15	0.20	0.10	0.30	0.30	0.15	0.45
A2	0.10	0.05	0.15	0.25	0.13	0.38	0.35	0.18	0.53
A3	0.15	0.08	0.23	0.15	0.08	0.23	0.30	0.15	0.45
A4	0.20	0.10	0.30	0.20	0.10	0.30	0.25	0.13	0.38
A5	0.25	0.13	0.38	0.20	0.10	0.30	0.30	0.15	0.45
A6	0.20	0.10	0.30	0.20	0.10	0.30	0.35	0.18	0.53
A7	0.15	0.08	0.23	0.35	0.18	0.53	0.40	0.20	0.60
A8	0.15	0.08	0.23	0.40	0.20	0.60	0.50	0.25	0.75
A9	0.20	0.10	0.30	0.35	0.18	0.53	0.50	0.25	0.75
A10	0.15	0.08	0.23	0.35	0.18	0.53	0.50	0.25	0.75
A11	0.30	0.15	0.45	0.40	0.20	0.60	0.60	0.30	0.90
A12	0.10	0.05	0.15	0.20	0.10	0.30	0.50	0.25	0.75
A13	0.25	0.13	0.38	0.20	0.10	0.30	0.60	0.30	0.90
A14	0.20	0.10	0.30	0.60	0.30	0.90	0.70	0.35	1.05

*Abbreviations are defined in nomenclature

Table 5. Weighting scheme (Im_j) for the first stage assessment

Level-I		Level-II		Level-III
*Basic indicators	Importance level	*Sub-attribute	Importance level	*Final attribute
<i>RD</i>	MH	<i>EI</i>	VH	<i>SI</i>
<i>GW</i>	VH			
<i>AP</i>	M			
<i>CT</i>	VH			
<i>SM</i>	VH			
<i>DO</i>	VH	<i>TI</i>	VH	
<i>BTEX</i>	H			
<i>NP</i>	MH			
<i>PAH</i>	MH			
<i>HM</i>	M			
<i>NORM</i>	ML			
<i>EO</i>	ML	<i>TFI</i>	M	
<i>EF</i>	H			
<i>ST</i>	M			
<i>CM</i>	VH			
<i>WC</i>	M	<i>CI</i>	VH	
<i>OM</i>	ML			
<i>CC</i>	M			

*Abbreviations are defined in acronyms

Table 6. Ranking order of various treatment alternatives

Alternatives	Average ranking method		Weighted average ranking method		Chen's ranking method (1985)		Final ranking order, R_{Ai}^N
	$^1U(t)_1$	Order	$^2U(t)_2$	Order	$^3U(t)_3$	Order	
A1	0.658	10	0.631	9	0.408	5	8
A2	0.651	11	0.621	11	0.398	8	10
A3	0.644	13	0.615	13	0.393	9	12
A4	0.678	7	0.645	7	0.408	4	6
A5	0.651	12	0.618	12	0.388	11	12
A6	0.688	6	0.656	5	0.416	3	4
A7	0.699	4	0.662	4	0.407	6	4
A8	0.674	8	0.638	8	0.390	10	9
A9	0.664	9	0.625	10	0.375	13	11
A10	0.705	3	0.665	3	0.401	7	3
A11	0.454	14	0.421	14	0.232	14	14
A12	0.711	2	0.675	2	0.422	1	2
A13	0.737	1	0.695	1	0.420	2	1
A14	0.695	5	0.651	6	0.382	12	7

$$U_i(x) = \frac{(a_i + b_i + c_i + d_i)}{4}; \quad {}^2U_i(x) = \frac{0.6(c_i - b_i) + 0.4(d_i - a_i)}{2}; \quad {}^3U_i(x) = \frac{1}{2} \left[\frac{(d_i - L_{min})}{(L_{max} - L_{min}) - (b_i - d_i)} + 1 - \frac{(L_{max} - c_i)}{(L_{max} - L_{min}) + (a_i - c_i)} \right]$$

Table 7. Ranking order of various treatment strategies

Alternatives	Average ranking method		Weighted average ranking method		Chen's ranking method (1985)		Final ranking order, R_{Si}^N
	$U(t)_1$	Order	$U(t)_2$	Order	$U(t)_3$	Order	
S1	0.699	2	0.662	2	0.336	3	2
S2	0.664	6	0.625	6	0.299	7	6
S3	0.708	1	0.670	1	0.346	1	1
S4	0.695	4	0.651	4	0.303	6	4
S5	0.697	3	0.660	3	0.340	2	3
S6	0.651	7	0.618	7	0.318	5	6
S7	0.666	5	0.634	5	0.332	4	4