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A rough set-based quality function deployment (QFD) approach for environmental performance evaluation: a case of offshore oil and gas operations

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A B S T R A C T

Activities in offshore oil and gas (OOG) that cause environmental impacts can be systematically managed through an environmental management system (EMS). Environmental performance evaluation (EPE) is an essential part of an EMS. However, previous studies on EPE indicate that existing lists of indicators little insight into how indicators are modified to more accurately assess environmental performance.

In this paper, a way is proposed to identify and define specific environmental performance indicators on a case-by-case basis, which consists of five steps: (1) describing environmental requirements; (2) determining favourable outcomes corresponding to the requirements; (3) identifying required activities or issues to achieve the outcomes; (4) searching for proper measures of the activities or issues; and (5) generating a list of key indicators. Based on these steps, a quality function deployment (QFD) approach is developed to determine key indicators and evaluate environmental performance. To handle uncertainties in QFD, the decision makers' evaluations are quantified through rough numbers using the concept of rough sets. The outputs of the proposed approach are different environmental performance indices. Using these indices, decision makers can easily determine whether an improved performance has been achieved through an EMS. The proposed approach is transparent and promising for use as a unified tool for EPE. An application of the proposed approach is demonstrated through a numerical example.

1. Introduction

Offshore Oil and Gas (OOG) production is rising steadily. This industry sector offers several benefits including alternative energy sources, local employment through construction and servicing of the production sector, use of the product by local industry, and increased revenue to the region (Curran et al., 2006). However, these benefits usually come at a cost of environmental degradation that is caused by discharges of produced water and drilling wastes, a large amount of atmospheric emissions, seismic disturbance during the geological and geophysical survey, and other waste streams. With intensified environmental pressures, OOG operators have been searching for an effective tool to manage environmental issues. An environmental management system (EMS) can be utilized to systematically manage all activities in OOG operations that cause environmental impacts. Current EMSs, such as ISO 14001 (ISO, 2004) or the EU-EMAS (ECC, 1993), require an explicit commitment for continuous improvement of environmental performance. The connection between EMSs and environmental performance is discussed in recent studies (Nawrocka and Parker, 2009; Perotto et al., 2008).

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

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In addition, various quantitative models have been established to assist with environmental performance evaluation. Jung et al. (2001) proposed a framework called "GScore" to evaluate corporate environmental performance based on voluntary environment, health and safety (EHS) reporting by aggregating the points of five categories of measurements. Shen et al. (2005) suggested calculations of the environmental performance score through an information technology supported program. Hermann et al. (2007) proposed an evaluation approach that combines life cycle assessment, multi-criteria analysis and environmental performance indicators. Data envelopment analysis (DEA), a well established nonparametric methodology for evaluating the relative efficiency of a set of comparable entities with multiple inputs and outputs, was applied to develop performance evaluation models (Zhou et al., 2008). Based on fuzzy multiple attribute analysis, Nasiri and Huang (2008) developed a decision aid model for environmental performance assessment in waste recycling.

Several frameworks that provide lists of environmental indicators have been developed (Veleva et al., 2001; Azapagic and Perdan, 2000; Krajnc and Glavič, 2003), but these lists give limited insight into how these indicators can be used for different cases to more precisely assess environmental performance. Moreover, no framework is applicable as a whole to evaluate environmental performance (Veleva and Ellenbecker, 2001). The current paper proposes an approach which employs quality function deployment (QFD) as a tool to identify key indicators and evaluate environmental performance. Rough set theory is suggested to handle uncertain information in QFD analysis. The proposed approach identifies and establishes specific indicators on a case-by-case basis to evaluate environmental performance more accurately. To the authors' knowledge this is the first application of rough set theory in QFD analysis that has been used for the evaluation of environmental performance.

The rest of this paper is organized as follows. Section 2 discusses basics of QFD. Section 3 illustrates the methods to handle uncertainties in QFD. This is followed by a presentation of the proposed methodology in Section 4. Section 5 demonstrates the application of the approach to a hypothetical case of OOG operations. Finally, Section 6 includes the conclusions and future work.

2. Quality function deployment (QFD)

QFD was originally developed in 1972 at Mitsubishi. QFD aims to translate customer requirements into engineering characteristics, process specifications, and production requirements in sequence. This translation requires a series of matrices or houses in four phases of a conventional QFD as given in Fig. 1 (Bossert, 1991). Its basic concept is to use a series of houses to transform qualitative requirements into quantitative specifications.

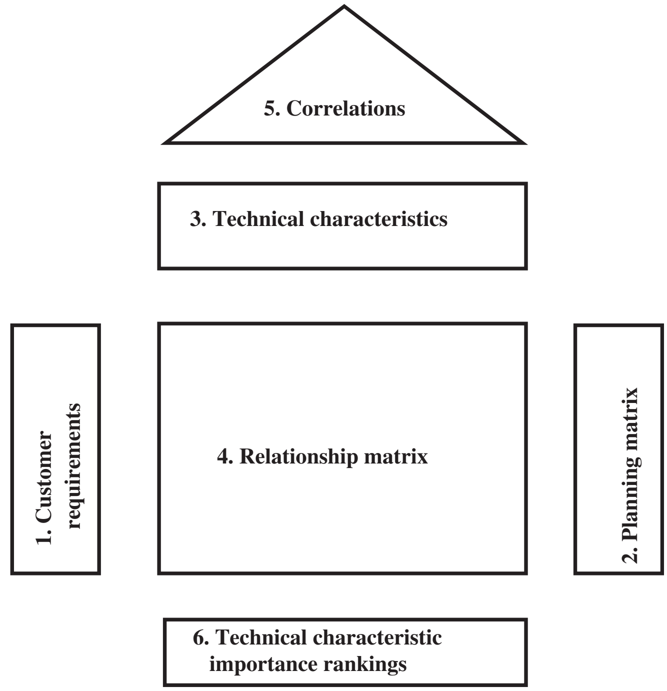

Fig. 2. House of Quality (HoQ) (Bergquist and Abeysekera, 1996).

The House of Quality (HoQ) is the most important tenet of QFD. Fig. 2 (Bergquist and Abeysekera, 1996) gives a standard structure of HoQ, which consists of the following six elements (Bossert, 1991):

(1) *Customer requirements (WHATs)* organized into proper classifications are one of the most significant contributions that QFD can make to the successful development of a product or production process;
(2) *Planning matrix* usually contains the information regarding the relative importance of customer requirements and the customer's satisfaction levels with the organization's current operation;
(3) *Technical or engineering characteristics* (*HOWs*) corresponding to the customer requirements are identified by translating qualitative requirements into measurable quantitative characteristics;
(4) *Relationship matrix* indicates the extent to which each *HOW* affects the satisfaction of each *WHAT*;
(5) *Correlation matrix* presents the interdependencies among *HOWs* to capture the trade-offs between various engineering parameters;

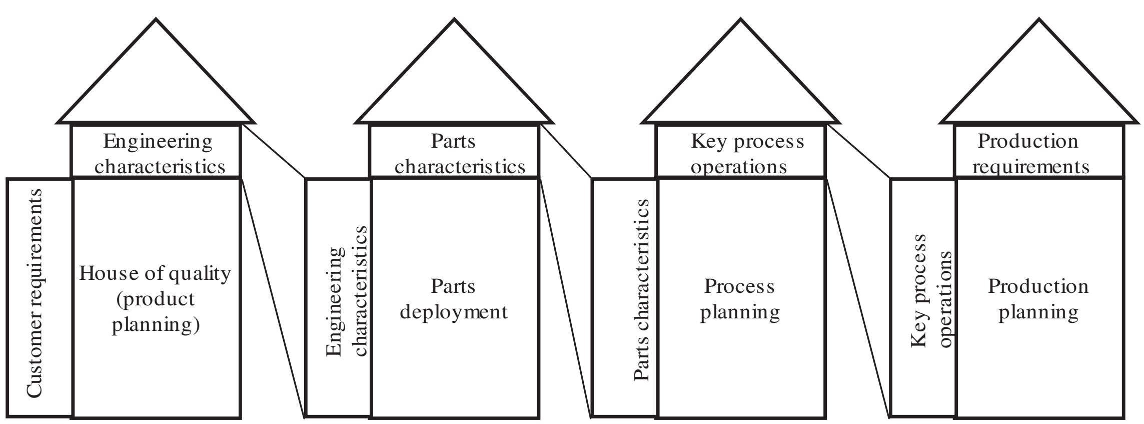

Fig. 1. Four phases of a conventional QFD (Bossert, 1991).

Table 1
Proposed methods in the literature to handle uncertainties in QFD analysis.

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

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

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

3. Handling uncertainties in QFD

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

(1) Vague descriptions, e.g., *strong* relationship, *low* importance;
(2) Inconsistent information, e.g., differences in the opinions of different experts or customers on the same issue;
(3) Incomplete or missing information, e.g., information is missing when an expert cannot decide the relative importance of technical requirements or cannot provide any information about such assessment.

Conventional mathematical logic is incapable of handling these uncertainties. In this respect, a significant number of studies on quantitative approaches to deal with uncertain information in QFD have been conducted. Fuzzy set theory (Zadeh, 1965) has been widely used in QFD in various areas to translate vague descriptions into fuzzy numbers that can be manipulated through fuzzy operators (Chan et al., 1999; Bevilacqua et al., 2006; Chen et al., 2006; Zhang and Chu, 2009). Rough set theory, first introduced by Pawlak (1982), is another generalization of classical set theory for handling vagueness and uncertainty. Recent studies (Zhai et al., 2009; Li et al., 2009) show that rough set theory provides an effective tool for dealing with inconsistency in QFD analysis. The Dempster–Shafer theory of evidence (Shafer, 1976) has been recently applied in QFD to model incomplete information using a belief structure such as (0–9, 100%) (Chin *et al.*, 2009). Table 1 summarizes the advantages and disadvantages of the above-mentioned methods that are used to handle uncertainties in QFD.

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

(1) Rough sets are also capable of approximating vague descriptions by means of the boundary region of a set;
(2) The subjective selection of membership functions is avoided;
(3) Data availability is very limited for the learning or training process to generate and adjust membership functions objectively, for example, through neural networks;
(4) Fuzzy sets alone cannot handle inconsistent information;
(5) Compared to evidence theory, the computational process is less complicated.

Rough set theory considers the indiscernibility between objects and characterizes it by an equivalence relation. Basically, a rough set is a formal approximation of a crisp set in terms of a pair of sets which

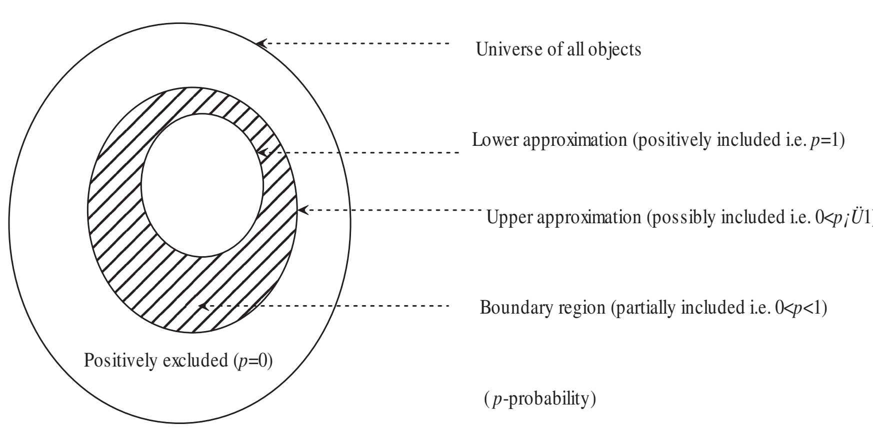

Fig. 3. Boundary region of a rough set (adapted from Zhai et al., 2009).

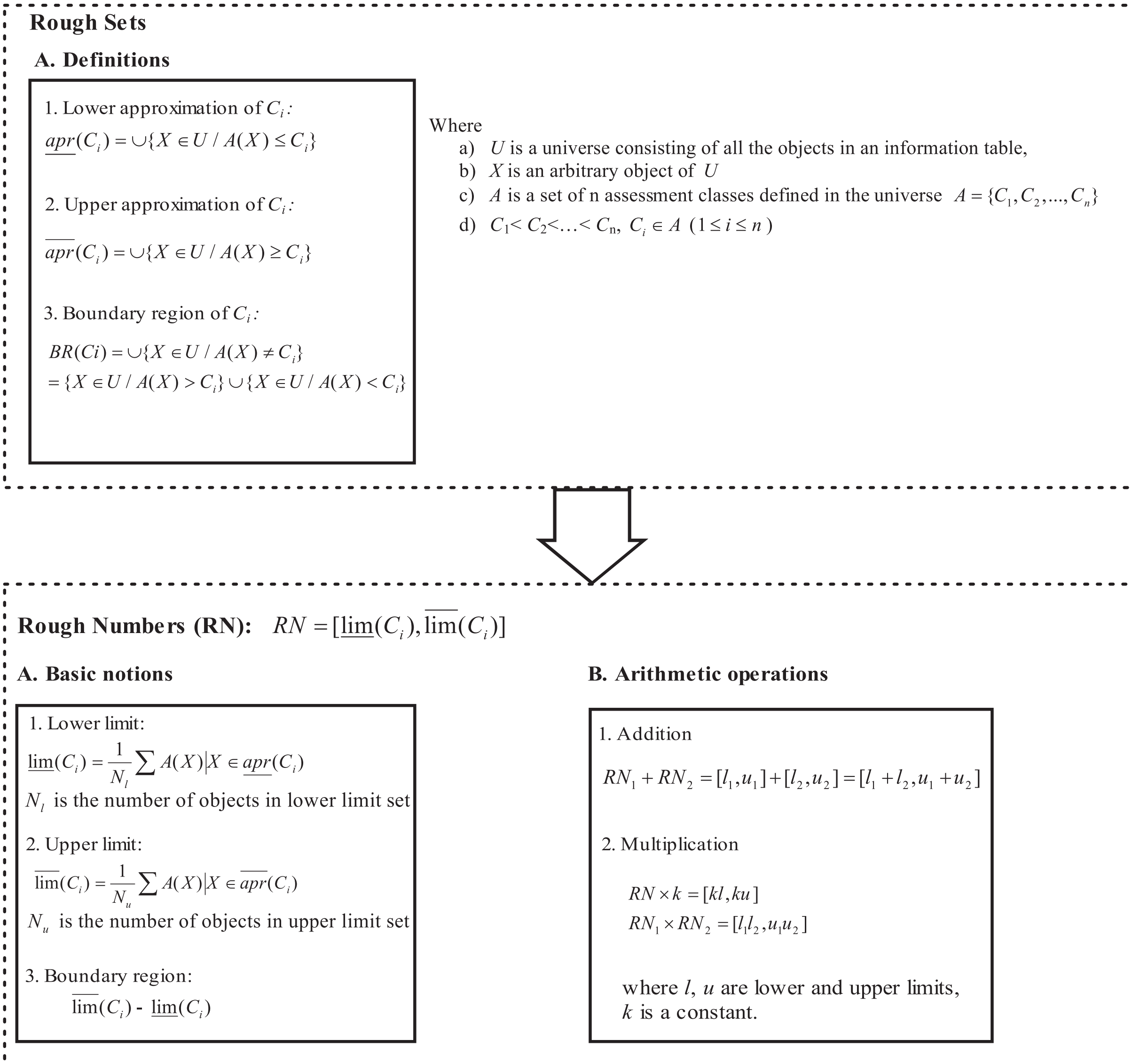

Fig. 4. The concept of rough numbers.

provide the lower and upper approximations of the target set. The lower approximation is the union of all objects that can be positively (i.e., unambiguously) classified as belonging to the target set while the upper approximation is the union of all objects that can possibly be identified as members of the target set (i.e., equivalence classes that have non-empty intersection with the target set). The boundary region given by the difference between the lower and upper approximations contains the objects that can neither be ruled in nor ruled out as belongings of the target set. Fig. 3 (adapted from Zhai et al., 2009) is a representation of the boundary region. Differing from fuzzy set theory that uses membership functions to model the vagueness, rough set theory adopts the non-empty boundary region to express uncertainties associated with imprecise and inconsistent information. Recent years have seen typical applications of rough set theory in areas such as attribute reduction (Wu, 2008; Wang et al., 2008) and rule extraction (Tsumoto, 2004; Wang & Wang., 2009). Recently rough set theory has also been applied to environmental decision support (Hu and Lu, 2009; Bai and Sarikis, 2010).

Based on the basic notions of rough sets, Zhai et al. (2009) proposed a novel concept of rough numbers along with their arithmetic operations to handle uncertain information in QFD. The outline of this concept is elaborated in Fig. 4. In the study by Zhai et al. (2009), the illustrated concept proved to be robust enough to handle vague and inconsistent information; however, the authors did not address another type of uncertainty, i.e., incomplete or missing information. In order to make this concept also capable of addressing missing information in QFD, steps to implement it are proposed in Fig. 5. The reason why the information is missing is that a decision maker is unable to select a suitable value from a set of assessment scales (e.g., 9-point assessment scale: 1, very low; 3, low; 5, moderate; 7, high; 9, very high), which indicates that any value in this set can be used to express an opinion. Therefore, missing information (null value) can be modelled using an interval covering the whole region of the set of the assessment scale, for example 1–9. Another simple method of addressing missing data is mean substitution which is accomplished by estimating missing values by using the mean of the available values. However, this is not suitable in QFD because the data size available for analysis is usually very small.

4. Methodology

In this study, an approach is proposed which describes a QFD-based process for evaluating environmental performance based on the identified key indicators (i.e., indicators that can best represent the environmental performance of a system from the decision makers'

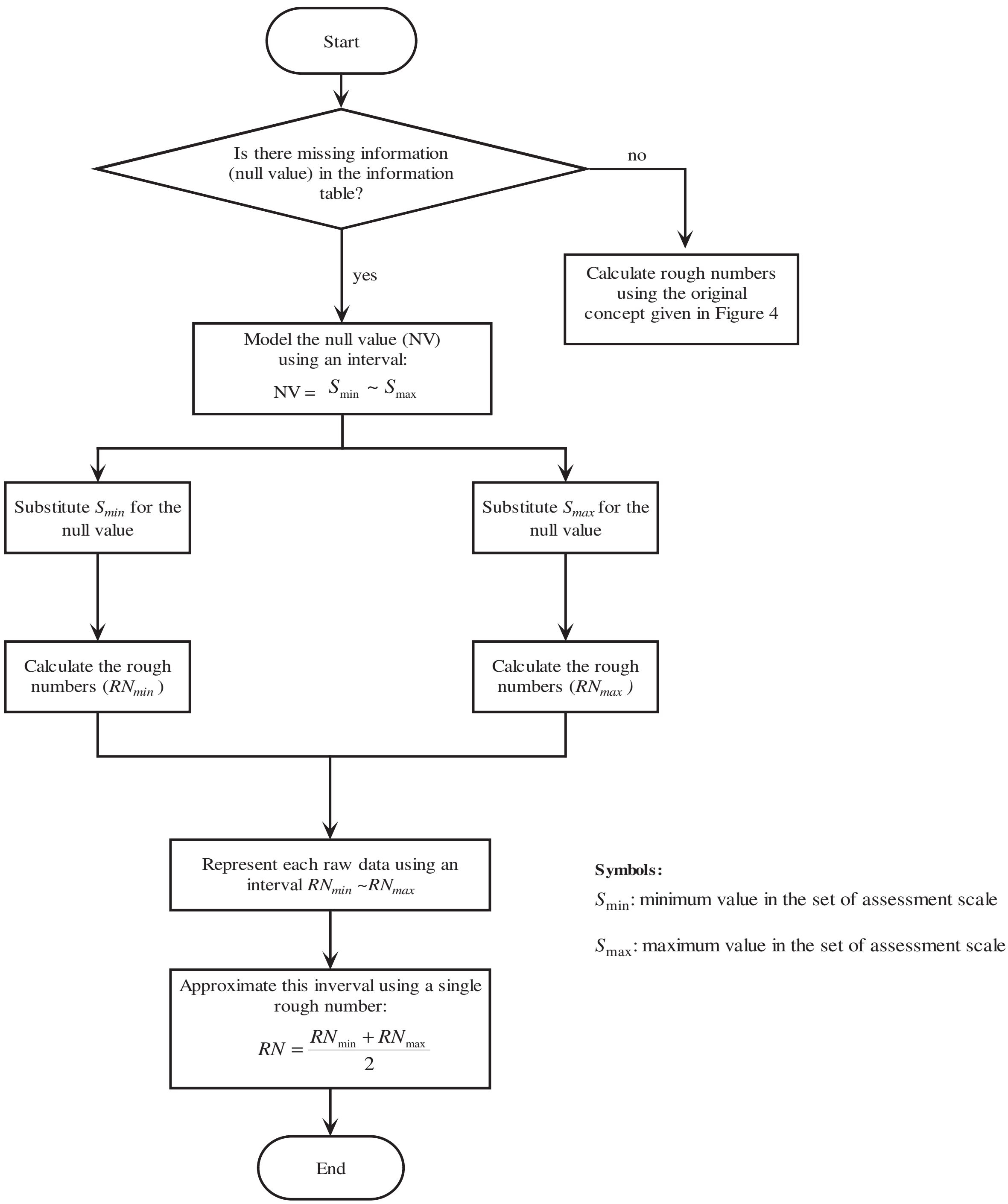

Fig. 5. Proposed procedure to implement the concept of rough numbers.

perspectives). The basic concept of QFD is to use a series of houses to translate qualitative requirements into quantitative specifications. In the current study, QFD is used to transform environmental requirements into quantitative indicators. Since this is a new application, the structure of conventional QFD that has four houses is not applicable.

The proposed approach (Fig. 6) consists of two major stages. Stage I consists of six houses that are used to identify:

(1) *Performance indicators* that provide information about the environmental performance of the operations within an organization and the management efforts to influence the organization's environmental performance; and
(2) *Condition indicators* that describe the direct impacts on the environment and the status of regulatory compliance.

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

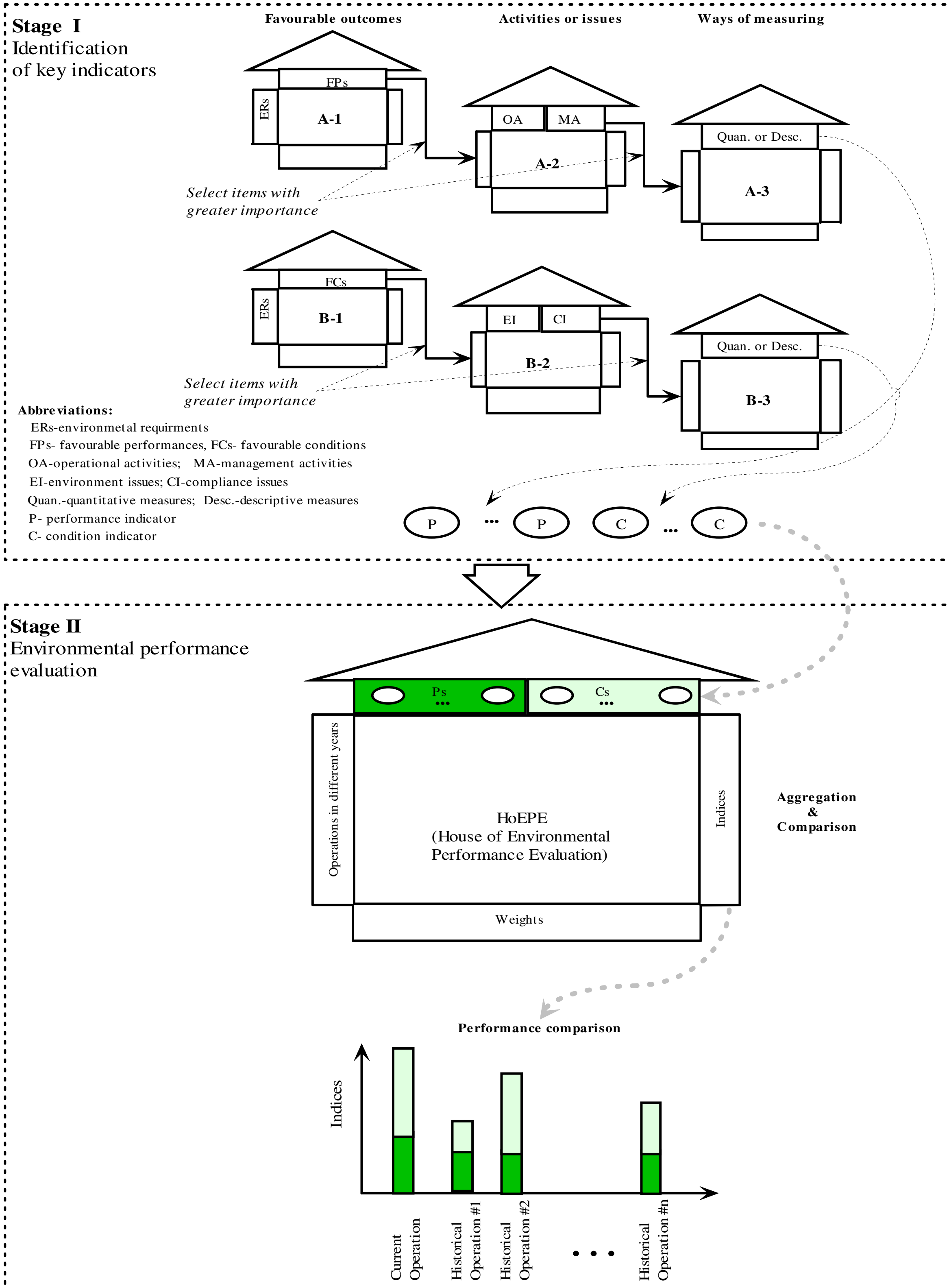

Fig. 6. Rough set-based QFD approach for environmental performance evaluations.

4.1. *Stage* I *– identification of key indicators*

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

(1) Describe the environmental requirements within a system boundary, e.g., the environmental policy and objectives of an EMS within an offshore platform;
(2) Determine favourable outcomes that are aligned with these requirements, i.e., Favourable performance and conditions;

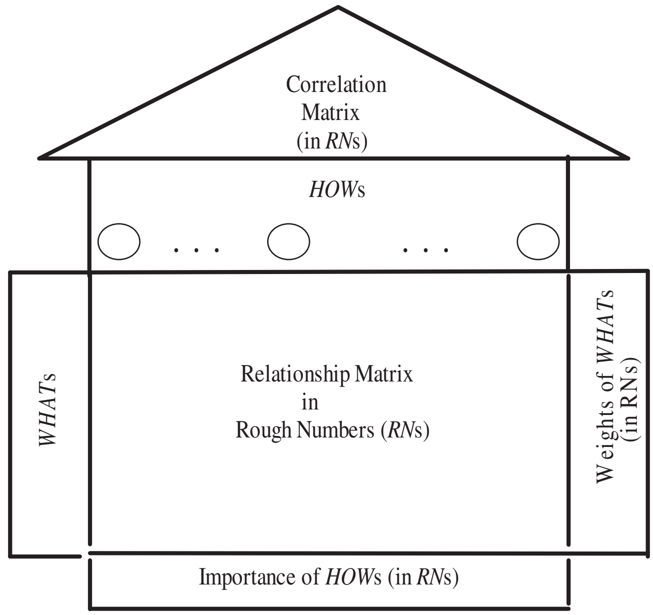

Fig. 7. General structure of the houses at Stage I.

(3) Identify activities or issues that must be implemented to reach favourable outcomes, i.e., activities or issues associated with operational and management performance, environmental condition, and compliance condition;
(4) Search for ways of measuring or monitoring the activities and issues; Warren and Craig (1996) proposed two general categories:
  a) *Quantitative measures* that refer to traditional means of measuring the amount of pollution discharged into the environment; and
  b) *Descriptive measures* that provide an indication of the quality of the system and whether progress has been achieved, but do not quantify the degree of progress in terms of environmental impacts.
(5) Generate a list of key indicators based on identified measures.

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

(1) Through a series of interactive matrices, QFD is robust enough to address the prioritization considering all relevant issues and ensure that the key indicators can be identified; and
(2) QFD gives proper consideration to the requirements of a system and deploys them throughout the identification process (Fig. 6).

Since ISO 14031 classifies environmental performance indicators into two general categories (i.e., performance and condition indicators), two parallel series of houses have been designed to identify the indicators (as shown in Fig. 6):

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

Fig. 7 gives a general structure of the six houses at Stage I (in Fig. 6). Major components of this house are described in detail as follows.

4.1.1. Weights of WHATs

Perceptions on the importance of the *WHATs* in Houses A-1 and B-1 (in Fig. 6) can be solicited from decision makers and represented in the form of an information table. Based on this, rough numbers are calculated using the method presented in Section 3. For illustration purpose, suppose some opinions expressed by three decision makers for a pollution prevention program within an office building are given in Table 2. This evaluation was conducted using the "9-point" assessment scale for importance. The rough numbers for the classes concerning the importance scale were calculated and are given in Table 3. For example, the rough numbers of "class 7" (shaded value in Table 2) can be calculated as follows:

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

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

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

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

$$W_i = \frac{1}{n}\sum_{j=1}^{n} IR_j \tag{1}$$

Table 2
Decision makers' evaluations on *WHATs*.

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

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

Table 3
Quantification of the evaluations on *WHATs* using rough numbers.

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

where W_i denotes the weight of *WHATs*, n is the number of decision makers, and IR_j denotes the importance ratings of each *WHAT* determined by the jth decision maker and quantified into rough numbers.

Using Eq. (1), the individual evaluations in the previous example can be aggregated:

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

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

Moreover, the weights of *WHATs* in Houses A-2, A-3, B-2, and B-3 are the importance of the key *HOWs* directly obtained from the previous houses (as given in Fig. 6). For example, the weights of *WHATs* in House A-2 are the importance of the key *HOWs* in House A-1.

4.1.2. Relationship matrix

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

Following the previous example, for instance, decision makers' evaluations on the relationship between *HOWs* and *WHATs* are given in Table 4. The so-called *null value* is used to indicate the situation of missing information in this table. The rough numbers were calculated through the proposed procedure (Fig. 5) and summarized in Table 5. For example, the shaded information in Table 4 was treated in the following way to achieve a single rough number:

Null value (NV) = 1–9

a) Substitute 1 for "*" and calculate the rough numbers
 $RN_{\min}(7) = [4,8]$; $RN_{\min}(1) = [1,6]$; $RN_{\min}(9) = [6,9]$
b) Substitute 9 for "*" and calculate the rough numbers
 $RN_{\max}(7) = [7,8]$; $RN_{\max}(9) = [8,9]$; $RN_{\max}(9) = [8,9]$
c) $RN(7) = [4,8] - [7,8] \approx [(4+7)/2, (8+8)/2] = [6,8]$
 $RN(*) \approx [5,8]$
 $RN(9) \approx [7,9]$
d) Aggregation (group consensus)
 $RN = [(6+5+7)/3, (8+8+9)/3] = [6,8]$

Table 5
WHAT–HOW relationships represented by rough numbers.

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

4.1.3. Correlation matrix

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

$$R'_{ij} = \sum_{k=1}^{n} R_{ik} r_{kj}, \quad i = 1, \ldots, m; \; j = 1, \ldots, n \tag{2}$$

where R'_{ij} denotes the adjusted relationship between the ith *WHAT* and jth *HOW*, m is the number of *WHATs*, and n is the number of *HOWs*; r_{kj} denotes the correlations between the kth and the jth *HOWs*. R'_{ij}, R_{ik}, and r_{kj} are in rough numbers.

Following the example, Table 6 provides the information on the correlations between *HOWs*. Based on Table 6, rough numbers were calculated and are given in Table 7. Then the adjusted relationship matrix can be calculated as given in Table 8. The shaded value in Table 5 was adjusted in the following way:

$$\begin{aligned} R'_{11} &= R_{11}r_{11} + R_{12}r_{21} + R_{13}r_{31} \\ &= [6,8]\times[9,9]\times[6,7]\times[0,0]+[8,9]\times[1,2] \\ &= [62,90] \end{aligned}$$

4.1.4. Importance of HOWs

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

(1) Aggregation:

$$I_j^{bn} = \sum_{i=1}^{m} \left(W_i \times R'_{ij} \right) \tag{3}$$

where I_j^{bn} denotes the importance of the jth *HOW* before normalization, W_i is the weight of the ith *WHAT*, R'_{ij} is the adjusted relationship between the ith *WHAT* and the jth *HOW*, and m is the number of *WHATs*.

(2) Normalization:

$$I_j = \left[\frac{\left(I_j^{bn}\right)^L}{\left(I_j^{bn}\right)^L + \sum_{i\neq j}\left(I_i^{bn}\right)^U} \times 100, \frac{\left(I_j^{bn}\right)^U}{\left(I_j^{bn}\right)^U + \sum_{i\neq j}\left(I_i^{bn}\right)^L} \times 100 \right],$$
$$i \text{ and } j = 1, \ldots, n \tag{4}$$

where I_j denotes the importance of the jth *HOW*, $(I_j^{bn})^L$ and $(I_j^{bn})^U$ are the lower and upper limits of the importance of the jth *HOW*

Table 4
Decision makers' evaluations on the relationship between *HOWs* and *WHATs*.

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

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

Table 6
Assessments on the correlations between *HOWs*.

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

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

before normalization, respectively, and n is the number of *HOWs*. This equation aims to normalize the numbers into a scale of 100 instead of 1 to avoid narrowing the variance of the importance values.

Still following the previous example, the importance of *HOWs* was achieved and is given in Table 9. For example, I_1 (the importance of energy conservation) was calculated:

$$I_1^{bn} = [8,9]\times[62,90]+[6,7]\times[44,63] = [760,1251]$$
$$I_1 = \left[\frac{760}{760+(1008+1510)}\times 100,\ \frac{1251}{1251+(648+1308)}\times 100\right] = [23,40]$$

Table 9 indicates that energy conservation and paper use reduction are the two critical performances that will be analyzed in the next house. The above illustrates the calculation procedure in House A-1. This procedure needs to be iterated in Houses A-2 and A-3 to obtain the performance indicators. Table 10 gives examples of *HOWs* that can be used in House A-2. Through the analysis, critical operational and management activities can be achieved and used as *WHATs* in House A-3. Following the example, if House A-2 indicates that double-sided printing and performing routine analysis on implemented energy saving opportunities are the critical activities, Table 11 gives the potential measures that can be used as *HOWs* in House A-3. If the results show that "percentage of paper use reduction on a monthly basis (%)" and "number of implemented energy saving opportunities (#/year)" are of greater importance than the others, then these two measures will be used as performance indicators at Stage II.

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

4.2. *Stage II – environmental performance evaluation*

The objective of this stage is to evaluate the environmental performance of current operation and historical operations based

Table 7
Correlations between *HOWs* represented by rough numbers.

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

Table 8
WHAT-HOW relationships considering the correlations of *HOWs*.

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

on the indicators that have been identified at Stage I. Fig. 8 presents the House of Environmental Performance Evaluation (HoEPE) designed for this purpose. The components of the house are described as follows.

4.2.1. *Weights of indicators*

The weights of indicators are crisp numbers that are calculated by averaging the upper and lower limits of the rough numbers representing the importance of key *HOWs* in Houses A-3 and B-3. For instance, using the importance value [37, 52] found in Table 9, the weight will be (37 + 52)/2 = 45.

Satisfaction Degree (SD_{ij})

$$SD_{ij} = \frac{M_{ij}}{\max(M_{1i}, M_{2i}, \dots, M_{ni})}, \quad (i = 1,2,\dots,k \text{ and } j = 1,2,\dots,n) \tag{5}$$

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

$$SD_{ij} = \frac{\min(M_{1i}, M_{2i}, \dots, M_{ni})}{M_{ij}}, \quad (i = 1,2,\dots,k \text{ and } j = 1,2,\dots,n) \tag{6}$$

when a smaller value indicates a better performance/condition (negative development);

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

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

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

Table 9
Importance (in terms of rough numbers) of *HOWs*.

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

Table 10
Examples of *HOWs* in House A-2.

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

Table 11
Examples of *HOWs* in House A-3.

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

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

4.2.2. Correlation matrix

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

(1) Weights of the indicators are calculated considering the correlations among the performance and condition indicators, respectively; and
(2) The performance and condition indices are calculated independently.

4.2.3. Indices

$$PIi = \sum_{j=1}^{k}\left(SD_{ij}^{p} \times W_{j}^{p}\right), \quad (i = 1,2,\ldots,k \text{ and } j = 1,2,\ldots,n) \tag{7}$$

$$CIi = \sum_{j=k+1}^{l+k}\left(SD_{ij}^{c} \times W_{j}^{c}\right), \quad (i = k+1,\ k+2,\ldots,\ l+k \text{ and } j = 1,2,\ldots,n); \tag{8}$$

$$EPIi = PIi + CIi \tag{9}$$

where PI_i is the performance index of the ith operation. CI_i is the condition index of the ith operation. EPI_i is the environmental

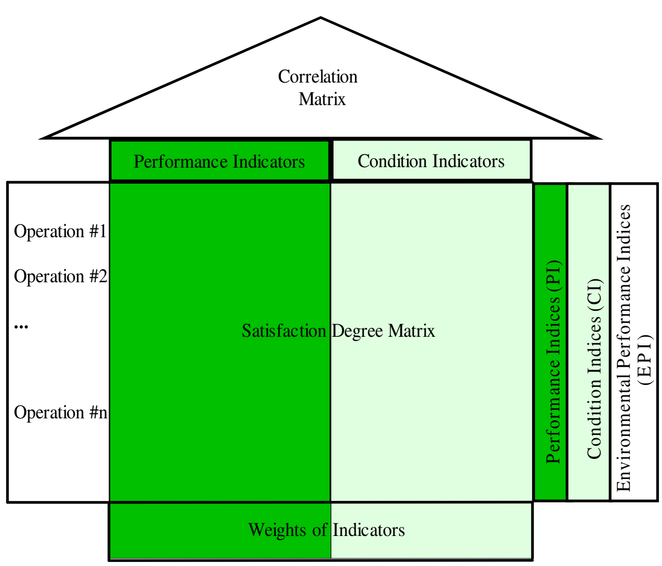

Fig. 8. House of Environmental Performance Evaluation (HoEPE).

Table 12
Assumed satisfaction degrees and weights of indicators.

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

performance index of the *i*th operation; An EPI has no value if it is not measured over time. SD_{ij}^p and SD_{ij}^c are the satisfaction degrees of the *j*th performance and condition indicator in the *i*th operation respectively. W_j^p and W_j^c are the weights of the *j*th performance and condition indicator respectively. k is the number of performance indicators, I is the number of condition indicators, and n is the number of operations to be evaluated.For instance, based on

Table 12, the indices were calculated using Equations (7), (8), and (9): $PI = 0.9 \times 17 + 1 \times 20 + 0.7 \times 22 = 51$; $CI = 1 \times 24 + 0.6 \times 17 + 0.5 \times 14 = 41$; $EPI = 51 + 41 = 92$.

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

5. A numerical application for the OOG industry

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

(1) Pollution prevention (P2) rather than pollution control and mitigation options are routinely identified, evaluated, and implemented throughout the operation; and
(2) All environmental protection options are evaluated based on a minimum environmental risk and the selected options are properly implemented.

To assist with the environmental performance evaluation in the above case, the proposed approach was implemented following the steps given in Fig. 9. This is relatively straightforward to carry out on a Microsoft Excel worksheet. W_1 and W_2 in both House A-1 and B-1 (in Fig. 6) are the above-mentioned two features of the EMS. The authors are the decision makers who made the required evaluations in this case study.

Table 13 summarizes the evaluations required for the analysis and the results at steps 1, 2, and 3 in Fig. 9. H_1–H_8 of House A-3 in

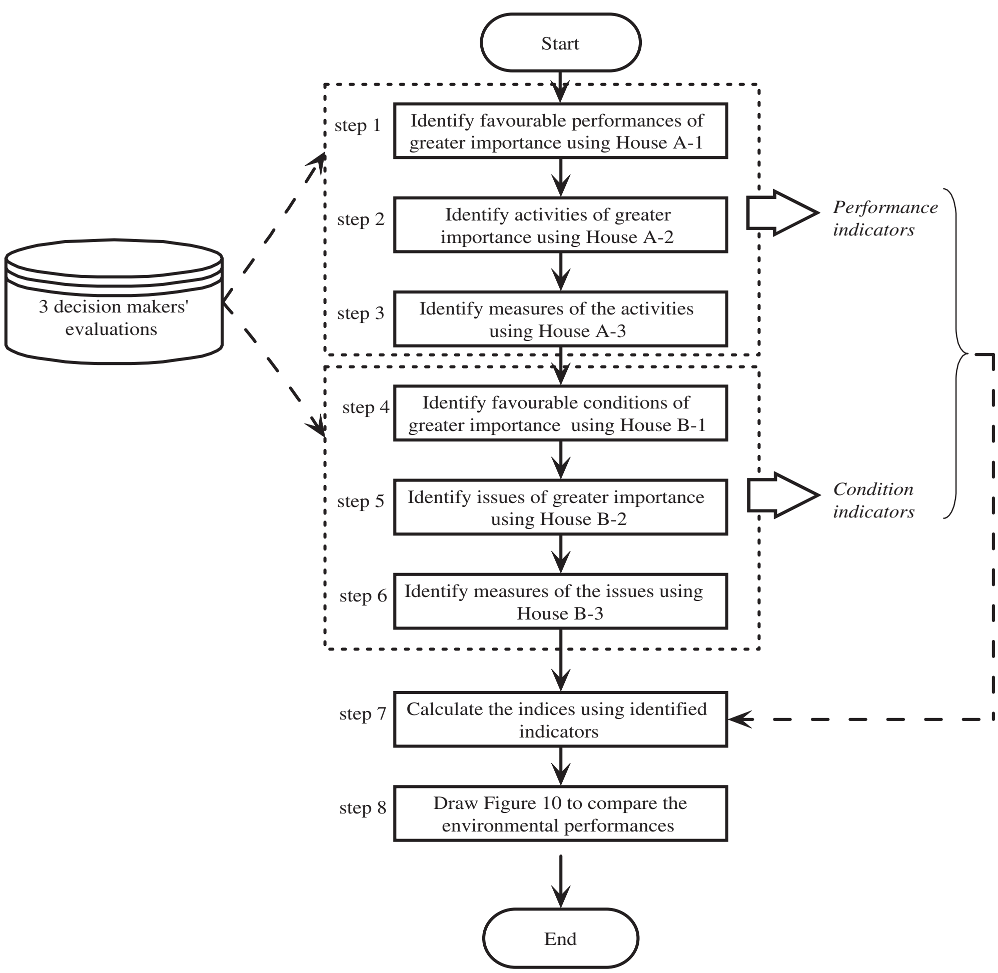

Fig. 9. Implementation procedure of the numerical application.

Table 13
Inputs and calculated results in the identification of performance indicators.

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

Note:(a) H_i in House A-1: H_1 - The use of materials (e.g., water, hazardous materials) and energy are minimized; H_2 - The quantity of drilling wastes and emissions are reduced at their sources; H_3 - The occurrence of oil spills in drilling operations and transportation is significantly reduced; H_4 - The environmental programs are effectively and efficiently managed. (b) H_i in House A-2: H_1 - Use synthetic oil-based fluids (SBF) in drilling; H_2 - Produced water is separated from oily-body down the well using sub-sea separation technology; H_3 - Apply advanced drilling tools (e.g., down-hole directional tool, three-dimensional seismic data interpretation) to enable operations to penetrate precise targets; H_4 - Reuse the waste natural gas condensate as fuel (e.g., power turbine generator for electricity); H_5 - Document, monitor, and update environmental objectives or targets; H_6 - Maintain proper investment or costs of the environmental improvement projects; H_7 - Organize environmental training programs for every employee; H_8 - Use service provider with a certified environmental management system.

Table 13 are listed as follows; and they were used as performance indicators (P_1–P_8):

(1) H_1 – percentage of achieved documented environmental objectives or targets (%);
(2) H_2 – number of employees who participated in environmental training program versus the number that need training (ratio);
(3) H_3 – number of environmental improvement suggestions from employees;
(4) H_4 – savings achieved through reductions in resource usage, control of pollution or wastes ($/yr);
(5) H_5 – research and development funds applied to environmental improvement projects with great significance;
(6) H_6 – number of advanced drilling tools implemented to enable operation to penetrate precise targets;
(7) H_7 – percentage of synthetic based fluids (SBFs) usage in the total consumption of drilling fluids (%/yr);
(8) H_8 – reduction of produced water discharge compared to a 3-year average (in 2005–2007) (%/yr).

Table 14 gives the evaluations and results at steps 4, 5, 6 in Fig. 9. H_1–H_4 of House B-3 in Table 14 are listed as follows and H_1, H_2, and H_3 were used as condition indicators (C_1–C_3):

(1) H_1 – monthly average of oil and grease content in ambient water at 1 km away from the platform (ppm);
(2) H_2 – monthly average of the concentration of benzopyrene in the ambient water at 1 km away from the platform (ppm);
(3) H_3 – number of non-compliance events;
(4) H_4 – number of audits on regulatory compliance.

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

In Tables 13 and 14, H_is of Houses A-1 and B-1 are favourable outcomes that are aligned with the environmental requirements (i.e., two features of the EMS in this case study); and H_is of House A-2 and B-2 are the activities or issues that must be implemented to reach these favourable outcomes.

Table 14
Inputs and calculated results in the identification of condition indicators.

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

Note: (a) H_i in House B-1: H_1 - Low contaminant concentrations in ambient air; H_2 - Low contaminant concentrations in ambient water; H_3 - High degree of regulatory compliance. (b) H_i in House B-2: H_1 - The concentrations of PAHs in ambient water are low; H_2 - The oil and grease content in ambient is low; H_3 - National and regional offshore environmental regulations are satisfied; H_4 - Water related industrial guidelines are followed.

Tables 15 and 16 summarize the inputs and results in HoEPE. Based on the results, Fig. 10 was developed. Fig. 10 presents an improving trend of the environmental performance, which indicates that better environmental performance has been achieved by implementing the EMS. The average of EPIs (the acceptable line in Fig. 10) can be used to determine whether the outcomes of the EMS are acceptable or not. Since this application is based on a hypothetical case, the results should not be interpreted as an accurate depiction of any specific OOG operation. However, the example demonstrates how the proposed methodology can be realized in practice.

Table 15
Inputs of HoEPE.

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

Table 16
Calculated indices in HoEPE.

Indices	Years		
	2010	2009	2008
Performance indices (PI)	136	140	95
Condition indices (CI)	93	71	69
Environmental performance indices (EPI)	229	221	164

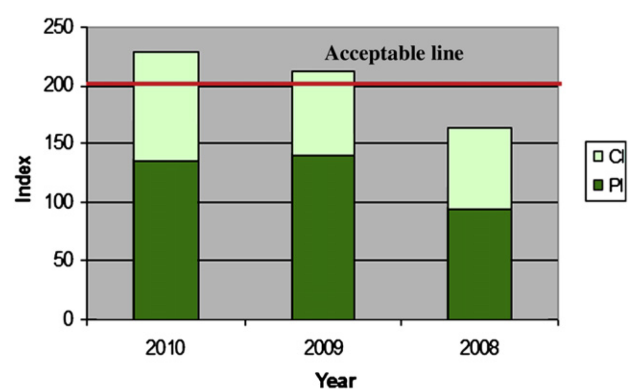

Fig. 10. Comparisons of the environmental performances.

6. Conclusions

Environmental performance evaluation (EPE) is essential for monitoring the improvements that an EMS has brought to OOG operations. Existing indicator frameworks provide little insight into how companies might update these indicators to more accurately measure environmental performance. Adopting QFD to implement a novel scheme to identify the specific indicators on a case-by-case basis, the proposed approach provides a transparent process for EPE. It is also the first time that QFD coupled with rough sets has been explored for EPE. Moreover, by implementing rough set theory, the approach enables decision makers to account for the impacts of incomplete and vague information in the evaluation process. Finally, this approach generates crisp indices, based on which environmental performances can easily be compared and potential improvements could be proposed.

Further validation on a real-world case is required and work in this direction is in progress. Although multiplicative preference relations (e.g., high-9) with rough set theory handle the uncertainty well in this approach, the prospect to use fuzzy preference relations with rough sets in QFD is an area worthy of further study. A problem exists in ensuring that the indicators measure what they are intended to measure. Future research is needed to eliminate this uncertainty in the proposed approach.

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References

Azapagic, A., Perdan, S., 2000. Indicators of sustainable development for industry: a general framework. Trans IChemE 78B, 243–261.

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

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

Bergquist, K., Abeysekera, J., 1996. Quality function deployment (QFD) – a means for developing usable products. International Journal of Industrial Ergonomics 18 (4), 269–275.

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

Bossert, J.L., 1991. Quality Function Deployment: A Practitioner's Approach. ASQC Quality Press, New York.

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

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

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

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

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

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

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

ECC, 1993. Council-regulation (EEC) No. 1836/93 Allowing Voluntary Participation by Companies in the Industrial Sector in a Community. EEC, Brussels, Belgium.

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

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

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

Ilinitch, A.Y., Soderstrom, N.S., Thomas, T.E., 1998. Measuring corporate environmental performance. Journal of Accounting and Public Policy 17 (4–5), 383–408.

ISO, 1999. Environmental Management – Environmental Performance Evaluation – Guidelines (ISO 14031: 1999). International Organization for Standardization, Geneva, Switzerland.

ISO, 2004. Environmental Management Systems – Requirements with Guidance for Use (ISO 14001: 2004). International Organization for Standardization, Geneva, Switzerland.

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

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

KPMG., 1992. A Measure of Commitment: Guidelines for Measuring Environmental Performance. KPMG, Inc, London, United Kingdom.

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

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

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

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

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

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

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

Shafer, G.A., 1976. Mathematical Theory of Evidence. Princeton University Press, Princeton, NJ.

Shen, L.Y., Lu, W.S., Yao, H., Wu, D.H., 2005. A computer-based scoring method for measuring the environmental performance of construction activities. Automation in Construction 14 (3), 297–309.

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

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

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

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

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

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

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

Warren, J., Craig, J., 1996. Measuring pollution prevention progress. In: Freeman, H.M. (Ed.), Industrial Pollution Prevention Handbook. McGraw-Hill, Inc., Montreal, Canada, p. 238.

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

Zadeh, L.A., 1965. Fuzzy sets. Information and Control 8, 338–353.

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

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

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

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