Environmental Engineering and Management Journal March 2019, Vol.18, No. 3, 597-616
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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A HYBRID MULTI-CRITERIA DECISION ANALYSIS APPROACH FOR ENVIRONMENTAL PERFORMANCE EVALUATION: AN EXAMPLE OF THE TFT-LCD MANUFACTURERS IN TAIWAN

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Abstract

The study developed a quantitative evaluation model of environmental performance, using a hybrid multi-criteria decision making (MCDM) approach by key environmental indicators based on the ISO14031 environmental performance evaluation (EPE) dimensions. The causal relationships and influence intensity among the EPE dimensions were explored to construct the network evaluation structure. Three well-known thin film transistor-liquid crystal display (TFT-LCD) panel manufacturers in Taiwan were used as an illustrative example. The top three key environmental indicators were found to be factory sewage discharge, Greenhouse gas (GHG) emissions, and the ratio of green product designs in reducing CO_2. The model could be further adapted to other industries.

Keywords: environmental performance, environmental performance evaluation (EPE), environmental indicator, multi-criteria decision making (MCDM), ISO14031

Received: November, 2015; Revised final: February, 2016; Accepted: April, 2016; Published in final edited form: March, 2019

1. Introduction

With the rapid development of technology in recent years, the resources and natural ecology of the earth are being changed; this process has indirectly affected the living space of human beings, and issues related to ecological and environmental protection and green management. Such a trend is viewed as environment-oriented business management focusing on enterprises responding to environmental problems with a positive attitude management and has become global concerns (Greeno and Robinson, 1992; Pane Haden et al., 2009; Taylor, 1992). For years, managements have considered investment in the environment to be a net loss from an economical perspective, such that enterprises have lost the strength to obtain more developmental opportunities by investing in environmental protection (Aragón-Correa et al., 2008).

However, active environmental management actually could bring more space for development and competitive advantages for companies. In particular, by creating active and systematic statements of their environmental strategies, enterprises are likely to generate various benefits, including cost reductions, quality improvements, corporate image enhancement, and new marketing opportunities (Maxwell et al., 1997).

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In a broad sense, environmental performance measures the outcomes of environmental protection against specified objectives of environmental quality defined by the degree of environmental conditions and requirements to avoid negative and damaging effects, influences, consequences, and resource use efficiency (Bran et al., 2011; Srebotnjak, 2013). Indeed, enterprises that promote the active conservation of the natural environment and continuously improve their environmental performance could engender the satisfaction of interested parties to create further competitive advantages (Aragón-Correa et al., 2008; Elsayed and Paton, 2005). In other words, the application of environmental management is not merely the key to influencing environmental quality which refers to the circumstance of natural resources (e.g., air, soil, water, biodiversity); it also has a profound effect on the management performance of enterprises (Claver et al., 2007; Wagner and Schaltegger, 2004).

Past research has proven that environmental performance has a positive effect on corporate performance (Lundgren and Zhou, 2017; Memguc and Ozanne, 2005; Montabon et al., 2007). Moreover, the proper implementation of environmental management systems (EMSs), integrating environmental responsibilities into organizations' day to day operations, can improve environmental performance efficiently and effectively (EPA, 2002). In addition, the advantages of implementing EMSs can help organizations become more competitive, save money, boost public image, retain valuable employees, and better manage environmental legal obligations (EPA, 2002). Accordingly, EMSs have been widely recognized as a means to promote environment performance (Morrow and Rondinelli, 2002).

The World Economic Forum (WEF) and related research centers first proposed the Environmental Sustainability Index (ESI) in 2000 to research and to calculate environmental sustainability in the world. The overall results are regarded as the relative scores for the comparison of environmental sustainability among various countries. Yale University and Columbia University have jointly formulated Environmental Performance Indicators (EPIs) that have been compiled every two years since 2002 (EPI, 2012). Both the ESI (WEF, 2005) and EPIs (EPI, 2012) compare countries (or regions), using an extensive and complicated evaluation process. However, for a specific industry, the evaluation (comparison) of ESIs and EPIs is not entirely appropriate. Moreover, the effect of environmental management on enterprises is higher than the effects of other competitive organizations. The operational activities of an enterprise are related closely with environmental protection (Morrow and Rondinelli, 2002). Consequently, the improvement of environmental management and, specifically, the development a simple environmental performance evaluation (EPE) model to diagnose the environmental performance of an enterprise is worthwhile issue to discuss (Bran et al., 2011).

In recent years, relevant research on environmental management has been developed to meet the market requirement of environmental consciousness, to conform environmental laws and regulations, to promote competitiveness in the market, and to respond to changes in the global environment. Most of the research has covered environmental quality analysis, environmental strategy application, and EPE for enterprises (Awasthi et al., 2010; Brent and Visser, 2005; Claver et al., 2007; Elsayed and Paton, 2005; Wagner and Schaltegger, 2004). However, previous research on environmental performance management mostly has emphasized the lifecycle assessment (LCA) of specific product input/output data (Benetto et al., 2004; Bovea et al., 2010; Hermann et al., 2007; Hur et al., 2005; Lim and Park, 2009), has been restricted to the establishment of EMSs and technical analyses (Warburg et al., 2005; Tsai and Chou, 2009), or merely has analyzed parts of environmental quality and performance indicators (Bangviwat and Sittikruear, 2018; Färe et al., 2004; Gerven et al., 2007; Henri and Journeault, 2008; Jasch, 2000; Maslesa et al., 2018; Munksgaard et al., 2007). Furthermore, most of these former studies adopted mainly empirical research or case studies, with questionnaire surveys for the collection of subjective information by traditional statistical analyses. As a result, the amount of objective and quantitative evaluation research performed on the integration of EPE indicator weights and environmental performance has been relatively modest.

With the trend of increase in the global demand for large panels and production lines, the Executive Yuan, the executive branch of the Republic of China (Taiwan, R.O.C.) government, proposed the "Two Trillion and Twin Star Development Program" industrial policy of selecting as the priority industry for development in January 2002 (CEPD, 2009). Therefore, the TFT-LCD panel industry in Taiwan has become internationally competitive, and its success is second only to the semi-conductor and petrochemical industries. The technology of TFT-LCD panel industry is relatively mature in comparison with the other high-tech industries. Nonetheless, the environmental impact of the TFT-LCD panel industry is considered not to be less than those of traditional industries. Therefore, the motive of this study was to establish an effective, convenient, objective, and quantified EPE model from the perspective of organizational evaluation, by using TFT-LCD panel manufacturers in Taiwan as the research subjects.

Environmental management is regarded as a complicated problem that should consider various facets such as the environmental economy and social factors (Morrissey and Browne, 2004). Environmental management should apply an innovative and multi-criteria analysis and set qualitative and quantitative goals to solve environmental management problems including depletion of resources, environmental impacts, and human health preservation (Herva and Roca, 2013). More specifically, environmental performance, including products, activities, and services, refers to the overall management performance of an organization where the major focus is its environmental impact. Numerous researchers have applied different viewpoints to study environmental performance.

The standards of the ISO14000 EMSs were established by 207 technical committees (ISO/TC 207, 2010) in 1993 (ISO, 2009). Within the ISO14000 EMSs, the structure of the ISO14031 EPE standard is considered to be a systematic procedure that continuously measures and evaluates the environmental performance of the organization (O'Reilly et al., 2000). The evaluation objects contain the management system, operational system, and surrounding environmental conditions. In consideration of the cost effectiveness, primary environmental parameters, and relevant criteria, selecting an appropriate performance indicator to precede a performance evaluation could help in the establishment of a constant monitoring system (Alwaer and Clements-Croome, 2010; ISO, 2009; Melnyk et al., 2003). With an appropriate indicator, an EPE is a procedure and tool aimed at transforming the environmental performance of an organization into understandable information; data from the internal collection, measurement, analysis, evaluation, and reporting are converted into a statement of environmental performance (IDB, 2000; ISO, 2009). Most enterprises, considering the specific applicability and feasibility of various environmental evaluation indicators for their management system, would select distinct evaluation indicators that are appropriate to their needs.

In addition, multi-criteria decision making (MCDM) has been applied successfully to the areas of manufacturing, service, transportation, energy, and education (Afgan and Carvalho, 2008; Kaya and Kahraman, 2010; Nigim et al., 2004; Tzeng et al., 2005; Wu et al., 2011; Zeleny, 1982). MCDM is also applicable to issues related to environmental performance-related fields (Bonoli et al., 2015; Chen et al. 2017; Comăniță et al., 2018; Convertino et al., 2013; De Luca et al., 2015; Ferrarini et al., 2001; Garfì et al., 2011; Henry and Kato, 2011; Herva and Roca, 2013; Nas et al., 2010; Wang, 2002). Therefore, the MCDM approach can be used to analyze EPEs, which must consider various dimensions and criteria that might have distinct relevance for different industries. Utilizing the ISO14031 EPE standard as its basis, this study implemented MCDM to analyze key evaluation indicators that affect environmental quality performance and attempted to establish a synthesized evaluation model of environmental performance. The research objectives were as follows: (1) to organize the relevant literature on environmental management, determine the causal relationships and influence intensity among the EPE dimensions, and identify key evaluation criteria (i.e., environmental indicators) and their relative weights, so as to establish a synthesized quantitative evaluation model of environmental performance; and (2) to collect related quantitative secondary data of environmental performance for current TFT-LCD panel manufacturers and assess environmental performance by the established EPE model. The proposed model would provide a crucial reference for enterprises to promote overall environmental quality. It would provide direction to enterprises for future policy making for continued environmental improvement as well.

The paper is organized as described below. Concepts and research issues related to environmental management are briefly introduced in Section 1. The proposed model, including the research analytical framework and major data analysis methods, are presented in Section 2. Section 3 illustrates a practical case of TFT-LCD panel manufacturers, through an empirical analysis that covers secondary data description, and analysis results. Discussions that explore the importance of the results of the study are provided in Section 4. Finally, significant research results, managerial implications, and future suggestions are concluded in Section 5.

2. Material and methods

As the literature review summarized in the introduction section, the MCDM approach has been widely applied in environmental management performance-related fields. However, very little research has been focused on industry-specific companies. The rapid development of TFT-LCD panel manufacturing, which has brought great global economic benefits but also environmental impacts, has ushered in an emergence of environmental awareness, such as implementing the Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) Directives. With the overall goal of helping enterprises to achieve sustainable management, unlike some of the former relevant studies that use subjective qualitative information (e.g., 7-point Likert-type scale by self-reported evaluation) (Henri and Journeault, 2008) and some requiring detailed numerical data of complicated calculations by LCA (Benetto et al., 2004; Bovea et al., 2010; Hermann et al., 2007; Hur et al., 2005; Lim and Park, 2009), the present study is motived to perform empirical analyses of the environmental management performance evaluations of TFT-LCD panel manufacturers, using a hybrid MCDM approach with objective quantitative data collected from secondary sources.

As introduced previously, MCDM has been applied to various industries and it can be adopted to analyze environmental performance. Because MCDM can consider several evaluation factors and help prioritize the relative weights among factors to create the optimal alternative, it conforms to the analytical features of decision-making in practical management. However, there are several analytical techniques or tools for MCDM (Zeleny, 1982), including the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Decision Making Trial and Evaluation Laboratory (DEMATEL), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and Grey Relational Analysis (GRA) etc. Some environment-related research concerning MCDM has been conducted in recent years. For examples, Kaya and Kahraman (2010) incorporated fuzzy set theory and VIKOR-AHP to analyze renewable energy selection and to decide energy production sites for Istanbul with the fuzzy linguistic preference of the subjective opinions of quantified experts. ALwaer and Clements-Croome (2010) utilized AHP to analyze the priority level of various key performance indicators and to evaluate the overall performance level to obtain the sustainability score. Tsai and Chou (2009) integrated with DEMETEL, ANP, and ZOGP to establish a management system selection model for the sustainable development of small and medium-sized enterprises (SMEs). Awasthi et al. (2010) applied fuzzy TOPSIS to evaluate environmental management performance. Khan and Faisal (2007) utilized ANP to analyze wastewater treatment, and Ip et al. (2009) applied GRA to evaluate the environmental quality of rivers. Garfi et al. (2011) applied AHP to strategic environmental assessment procedures for selecting and monitoring the optimal alternative for safe water availability. Hsu et al. (2011) adopted the FDM and ANP to construct a sustainability balanced scorecard for the semiconductor industry. Lastly, Yan et al. (2015) constructed a hybrid environmental assessment model with a combination of DANP and VIKOR for green building system. Tsai et al. (2015) used the DANP with VIKOR to evaluate the environmental performances of suppliers.

Therefore, the purpose of this study was to establish an efficient and effective integrated EPE model for environmental management by a hybrid MCDM approach. To make the evaluation model more objective and complete, interactions among various dimensions in environmental performance were considered. The relative importance of each indicator (criterion) is discussed, and secondary data were used for empirical analyses. The research analytical framework and data analysis methods are described below, followed by a detailed description of the data collection and questionnaire design developed by this study.

2.1. Research analytical framework

The research analytical framework is depicted in Fig. 1. This study was divided into four stages: (1) An extensive literature review was conducted, and the relevant evaluation dimensions and criteria that would affect the environmental performance were summarized. The criteria were further deduced from the three evaluation dimensions, Management Performance Indicators (MPIs), Operational Performance Indicators (OPIs), and Environmental Condition Indicators (ECIs) of the ISO14031 EPE standard.

On the basis of the characteristics of the TFT-LCD panel display industry, a panel of experts was consulted to select key environmental indicators (criteria), so as to collect relevant secondary environmental data. (2) The decision-making trial and evaluation laboratory (DEMATEL) tool was applied to evaluate the causal relationships and influence intensity among the evaluation dimensions; the network evaluation structure of environmental performance was then established. (3) The relative weights of various evaluation criteria (i.e., environmental indicators) from experts were obtained by analytic network process (ANP). (4) Secondary data concerning the environmental performance of the top three largest Taiwanese TFT-LCD panel display manufacturers were collected from relevant databases, and the synthesized environmental performance was further ranked by grey relational analysis (GRA) against the previously established evaluation criteria and relative weights. As described previously, it is critical to select proper evaluation indicators for environmental performance, because the selection of evaluation indicators affects the implementation of the performance.

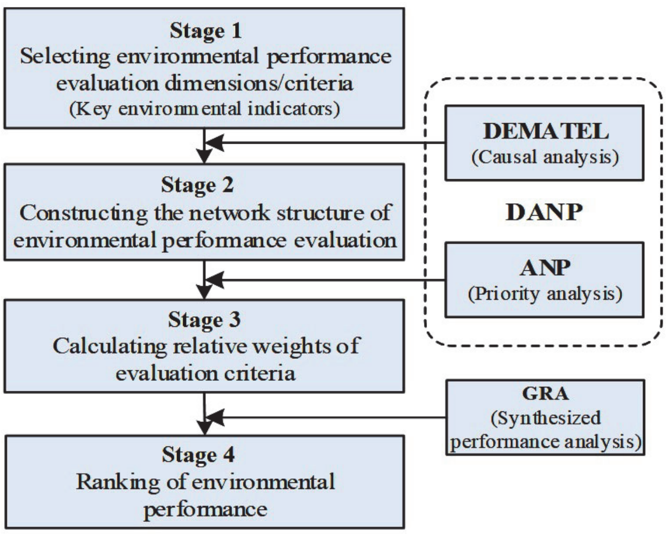

Fig. 1. The proposed research analytical framework

The formal definition of EPE originated in the early 1990s with the formulation of the ISO14031 EPE indicators; however, the concept of EPE was developed years ago (Perotto et al., 2008; O'Reilly et al., 2000). The previous related studies have demonstrated that EPE indicators could be utilized as performance evaluation tools for organizations that have established or tend to establish EMSs (Niemeijer and de Groot, 2008). Therefore, the present study, according to the structure of the ISO14000 EMSs, focuses on the standard of EPE with respect to organizational evaluation. Referring to the three EPE dimensions (i.e., MPIs, OPIs, and ECIs) in ISO14031, key environmental indicators were selected mainly on the basis of the ISO14031 classification table by the Industrial Development Bureau (IDB) of Ministry of Economic Affairs (MOEA), R.O.C. (IDB, 2000), which summarizes some of most commonly used environmental performance indicators as presented in Appendix A.

2.2. DEMATEL

Decision-making trial and evaluation laboratory (DEMATEL), which originated in 1971 from the Battelle Association of the Geneva Research Center, effectively incorporates the structure of complicated causality. Based on the effects between two elements, the causal relationship and the effect degree of all of the elements are calculated with a matrix and relevant mathematical theories. This method has been widely applied in corporate planning and decision-making, urban planning and design, environmental evaluation, and global problem analysis (Fontela and Gabus, 1976; Gabus and Fontela, 1972, 1973).

The DEMATEL tool was applied to analyze the causality among various evaluation dimensions/criteria of environmental performance to establish the environmental performance evaluation system. An example of a DEMATEL procedure is illustrated below:

Step 1: Define elements and determine relationships. Through literature review or brainstorming to identify and define the system elements, the relationship between elements is judged subjectively by professionals via questionnaires. The professional questionnaire is based on a criteria comparison for each element pair, and the responses are represented by numbers that range from 0 ("no influence") to 4 ("very high influence").

Step 2: Establish a direct-relation matrix. After comparing the influential degree between each element, an "$n \times n$" matrix is obtained. The direct-relation matrix, represented as $\boldsymbol{Z}$ (Eq. (1)), is shown in Fig. 2. The numbers inside the matrix represent the influential extent between the elements.

Step 3: Normalize the direct-relation matrix. The elements of the direct-relation matrix ($\boldsymbol{Z}$) (Eq. (1)) are multiplied by S (Eq. (2)) to obtain a standardized direct-relation matrix (X) (Eq. (3)).

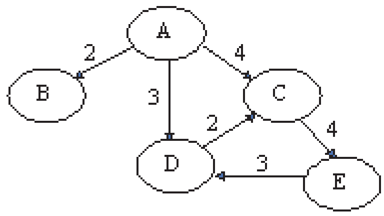

Fig. 2. A sample of the DEMATEL method

$$\boldsymbol{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1j} & \cdots & z_{1n} \\ \vdots & & \vdots & & \vdots \\ z_{i1} & \cdots & z_{ij} & \cdots & z_{in} \\ \vdots & & \vdots & & \vdots \\ z_{n1} & \cdots & z_{nj} & \cdots & z_{nn} \end{bmatrix} \tag{1}$$

$$S = \min \left[\frac{1}{\max \sum_{j=1}^{n} z_{ij}}, \frac{1}{\max \sum_{i=1}^{n} z_{ij}} \right] \tag{2}$$

$$\boldsymbol{X} = S \times \boldsymbol{Z} \tag{3}$$

Step 4: Compute the total-relation matrix.

Using $T = \lfloor t_{ij} \rfloor \quad i, j \in \{1,2,3...n\}$ to represent the total-relation (direct/indirect) matrix, I as a unit matrix (or called identity matrix), a square matrix in which all the main diagonal elements are 1's and all the remaining elements are 0's, $X = \lfloor x_{ij} \rfloor_{n \times n}$ as a direct matrix, and $\lim_{k \to \infty} (X^2 + ... + X^k)$ as an indirect matrix, $\lim_{k \to \infty} X^k = 0$ when $0 \le x_{ij} \le 1$. The total-relation matrix (T) is calculated by Eq. (4):

$$T = \lim_{k \to \infty} (X + X^2 + ... + X^k) = \lim_{k \to \infty} X \; (I + X^1 + ... + X^{k-1}) = X(I - X)^{-1} \tag{4}$$

Step 5: Draw a causal diagram and analyze the results. The total amount of each row in the total-relation matrix (T) is represented by D_i (Eq. (5)), and the total amount of each column in the total-relation matrix (T) is represented by R_j (Eq. (6)).

$$D_i = \sum_{j=1}^{n} t_{ij} \quad i = 1, 2, ..., \mathrm{m} \tag{5}$$

$$R_j = \sum_{i=1}^{n} t_{ij} \quad j = 1, 2, ..., \mathrm{n} \tag{6}$$

The causal diagram uses (D_i+R_i, D_i-R_i) as ordered pairs. The horizontal axis (D_i+R_i) is referred to as the *centrality*, because it measures the degree of the central role that element i plays in the problem. The horizontal axis indicates the strength of influences given and received. The vertical axis (D_i-R_i) is referred to as the *causality*, because it measures the influential degrees of the relationships between one element and other elements. The vertical axis indicates that element i is a *cause-factor* if (D_i-R_i) is positive and an *effect-factor* if (D_i-R_i) is negative. Therefore, the sophisticated causality of elements themselves can be observed as a simple and explicit structure by the causal diagram. The structure could be used as a guide for determining strategies against problems invented by decision makers or managers.

2.3. Incorporating DEMATEL with ANP (DANP)

Analytic network process (ANP) is an extension of AHP, and ANP contains feedback that replaces the previous hierarchical levels in AHP. Both methods can achieve decision making through systematic methods (Ong et al., 2005; Saaty, 1996; Saaty, 2001); however, the evaluation factors are assumed to be independent in AHP, whereas ANP considers the inner and outer dependences among evaluation factors (Saaty, 1996). Similar to AHP, the ANP method obtains and predicts the inner relations of all criteria, objectives, or projects with 1-9-ratio scales. That is, with the eigenvector of a pairwise comparison matrix, a supermatrix is substituted to obtain the convergent value.

A supermatrix can be prepared to compare the criteria in the entire system. This process is achieved through pairwise comparisons by asking "How much importance does a criterion have compared to another criterion, with respect to our interests or preferences?" Values of the relative importance of pairwise comparisons can be categorized from 1 (equal importance) to 9 (extremely unequal importance) (Saaty, 1980, 1996).

Eq. (7) shows the general form of the supermatrix, in which C_n represents the nth cluster, e_{nm} represents the mth element in the nth cluster, and W_{ij} is the principal eigenvector of the effect of the elements compared in the jth cluster to the ith cluster. If the jth cluster has no impact on the ith cluster, then $W_{ij} = [0]$. The geometric mean is used to integrate all of the subjective preferences of the experts, whereas the decision is made by a group of experts.

The DEMATEL analysis was used to construct the network structure of our evaluation model, because there were dependences and feedbacks among dimensions and criteria (Ou Yang et al., 2008). Next, the influence intensities among the dimensions determined by DEMATEL were incorporated into the ANP process. When managing the normalization, the traditional supermatrix in ANP assumes that each cluster (i.e., dimension) has the same weight (importance). However, this assumption ignores the different influence intensities among the various clusters. For this reason, Ou Yang et al. (2008) proposed that DEMATEL be combined with ANP to solve such problems. In other words, the total-relation matrix (T) of DEMATEL is applied to the supermatrix in ANP. The implied "dynamic importance of influential relations" among the criteria in clusters is acquired by DEMATEL. After ANP is substituted for the normalized, weighted supermatrix, the relative weights of the various criteria are calculated (Ou Yang et al., 2008).

$$\boldsymbol{W} = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \cdots\cdots & C_n \\ e_{11}\ldots e_{1m_1} & e_{21}\ldots e_{2m_2} & & e_{n1}\ldots e_{nm_n} \end{array} \\ \begin{array}{c} C_1 \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ e_{1m_1} \end{array} \\ C_2 \begin{array}{c} e_{21} \\ e_{22} \\ \vdots \\ e_{2m_2} \end{array} \\ \vdots \\ C_n \begin{array}{c} e_{n1} \\ e_{n2} \\ \vdots \\ e_{nm_n} \end{array} \end{array} & \begin{bmatrix} \boldsymbol{W}_{11} & \boldsymbol{W}_{12} & \cdots & \boldsymbol{W}_{1n} \\ \boldsymbol{W}_{12} & \boldsymbol{W}_{22} & \cdots & \boldsymbol{W}_{2n} \\ \vdots & \vdots & \vdots\vdots\vdots & \vdots \\ \boldsymbol{W}_{n1} & \boldsymbol{W}_{n2} & \cdots & \boldsymbol{W}_{nn} \end{bmatrix} \end{array} \tag{7}$$

We applied the combination of DEMATEL and ANP (called DEMATEL-ANP, DANP) to solve the different influential relationships among the dimensions and to obtain the weight of each criterion. The DANP calculation procedure is explained by following steps:

Step 1: Use DEMATEL to calculate the total-relation matrix (T) (Eq. (8)).

$$T = \begin{bmatrix} t_{11} & \cdots & t_{1j} & \cdots & t_{1n} \\ \vdots & & \vdots & & \vdots \\ t_{i1} & \cdots & t_{ij} & \cdots & t_{in} \\ \vdots & & \vdots & & \vdots \\ t_{n1} & \cdots & t_{nj} & \cdots & t_{nn} \end{bmatrix} \tag{8}$$

Step 2: Apply Eq. (9) *to the total-relation matrix* (T) (Eq. (8)) *to obtain a normalized total-relation matrix* (T_S) (Eq. (10)).

$$d_i = \sum_{j=1}^{n} t_{ij} \tag{9}$$

$$\boldsymbol{T_S} = \begin{bmatrix} t_{11}/d_1 & \cdots & t_{1j}/d_1 & \cdots & t_{1n}/d_1 \\ \vdots & & \vdots & & \vdots \\ t_{i1}/d_i & \cdots & t_{ij}/d_i & \cdots & t_{in}/d_i \\ \vdots & & \vdots & & \vdots \\ t_{n1}/d_n & \cdots & t_{nj}/d_n & \cdots & t_{nn}/d_n \end{bmatrix} = \begin{bmatrix} t^s_{11} & \cdots & t^s_{1j} & \cdots & t^s_{1n} \\ \vdots & & \vdots & & \vdots \\ t^s_{i1} & \cdots & t^s_{ij} & \cdots & t^s_{in} \\ \vdots & & \vdots & & \vdots \\ t^s_{n1} & \cdots & t^s_{nj} & \cdots & t^s_{nn} \end{bmatrix} \tag{10}$$

Step 3: Derive the weighted supermatrix ($\boldsymbol{W_T}$) (Eq. (11)) *from the normalized total-relation matrix* (Eq. (10)) *and the unweighted supermatrix* (**W**) (Eq. (7)).

$$\boldsymbol{W}_T = \begin{bmatrix} t_{11}^S \times W_{11} & t_{21}^S \times W_{12} & \cdots & \cdots & t_{n1}^S \times W_{1n} \\ \vdots & \vdots & \vdots & & \vdots \\ t_{1i}^S \times W_{i1} & \cdots & t_{ji}^S \times W_{ij} & \cdots & t_{ni}^S \times W_{in} \\ \vdots & \vdots & \vdots & & \vdots \\ t_{1n}^S \times W_{n1} & t_{2n}^S \times W_{n2} & \cdots & \cdots & t_{nn}^S \times W_{nn} \end{bmatrix} \quad (11)$$

Step 4: Multiply the weighted supermatrix by itself several times to obtain a limit supermatrix (Eq. 12)*, which is used to obtain the weights of criteria, where* $\boldsymbol{W}_T$ *is the weighted supermatrix and k is a random number.*

$$\lim_{k \to \infty} \boldsymbol{W}_T^K \quad (12)$$

2.4. Grey relational analysis (GRA)

Grey theory was developed by Deng (Deng, 1982). Grey theory proposes new concepts and solutions that emphasize the exploration of the nature of a system when the information is deficient and supplements information to make the grey system become white. Based on the trend development between systems, GRA projects the system data into geometric space to measure the closeness of geometric shapes. The closer the geometric shapes appear between two systems, the stronger the relationship between the systems (Deng, 1982, 1985). This method also can be applied in prioritizing alternatives.

The GRA calculation procedure is described below.

Step 1: Confirm the reference sequence (X_o) *and the compared sequence* (X_i).

It is supposed that $X_o = (x_{oj} \mid j=1,2,.....n)$ is the reference sequence and $X_i = (x_{ij} \mid j=1,2,.....n)$ is the comparison sequence, where $i=1,2,....,m$. The reference sequence is the base vector of reference values with which all sequences are compared. The value of the reference sequence depends on the type of the attribute (i.e., the characteristic of evaluation criterion). Generally, the highest value is taken for a benefit-type attribute, the lowest value for a cost-type attribute and the optimal or predetermined preferred value for the optimization or "targeted value"-type attribute (Lu and Wevers, 2007). In the current study, the value of the reference sequence depends on the characteristic of EPE criteria (indicators). For instance, if the EPE criterion is "number of pollution prevention implementation", which belongs to benefit-type attribute, the highest value would be selected as the value of the reference sequence (base vector).

Step 2: Perform normalization (i.e., render the data dimensionless).

The upper-bound effectiveness of measurement (i.e., larger-the-better) is:

$$x^*_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \quad (13)$$

The lower-bound effectiveness of measurement (i.e., smaller-the-better) is:

$$x^*_{ij} = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \quad (14)$$

The moderate effectiveness of measurement (i.e., nominal-the-best) is:

$$x^*_{ij} = 1 - \frac{\left| x_{ij} - x_{obj} \right|}{\max \left\{ \max_i x_{ij} - x_{obj}, x_{obj} - \min_i x_{ij} \right\}} \quad (15)$$

Step 3: Calculate the difference sequence (Δ_{oij}).

$$\Delta_{oij} = \left| x^*_{oj} - x^*_{ij} \right|, \text{ where } i = 1,2,\ldots,m, \; j = 1,2,\ldots,n \quad (16)$$

Step 4: Calculate the grey relational coefficient (γ_{oij}).

$$\gamma_{oij} = \frac{\min_{\forall i} \min_{\forall j} \Delta_{oij} + \zeta \max_{\forall i} \max_{\forall j} \Delta_{oij}}{\Delta_{oij} + \zeta \max_{\forall i} \max_{\forall j} \Delta_{oij}} \quad (17)$$

where ζ is the identification coefficient, normally set to $\zeta = 0.5$.

Step 5: Calculate the grey relational grade (Γ_{oi}).

$$\Gamma_{oi} = \sum_{j=1}^{n} w_j \times \gamma_{oij} \quad (18)$$

where w_j is the weight and $\sum_{j=1}^{n} w_j = 1$.

Step 6: Arrange the grey relation ordinal.

The grey relational grades (Γ_{oi}) of the different compared sequences provide a ranking of the alternatives, in which a higher value indicates a better alternative.

2.5. Data collection and questionnaire design

As shown in Fig. 1, in addition to the literature review and secondary data collection at the first stage and the synthesized performance analyses at the fourth stage, DEMATEL analyses at the second stage and ANP analyses at the third stage were combined with a professional questionnaire survey for opinions on various evaluation criteria. The expert panel comprised three industry specialists with environmental quality management experience (i.e., environmental quality auditors and senior supervisors of the environmental protection department in an enterprise), two government officers in the Environmental Protection Administration (EPA) (i.e., environmental protection officials), and three academic professionals with environmental management background (including professors and researchers).

All of the consulted experts had over 10 years of environmental management-related experience. Due to the complexity of questionnaires, the experts' opinions were solicited and confirmed in person. In the second stage, as introduced in Section 2.2, a "3 x3" matrix including the three evaluation dimensions (i.e., MPIs, OPIs, and ECIs) of the ISO14031 EPE standard and a "10 x10" matrix consisting of the 10 evaluation criteria were constructed as the DEMATEL professional questionnaires to derive total-relation matrices for unraveling causal relationships among dimensions/criteria. Experts were then consulted and conducted mutual direct influence evaluation using five degrees (numbers from 0 to 4) to represent different influential extents aiming at each evaluation dimension/criterion. In the third stage, as illustrated in Section 2.3, the ANP professional questionnaire was then developed based on the mutual influential causality (i.e., interrelationships) of the evaluation dimensions and setting up networked level evaluation structure by DEMATEL in the previous stage (i.e., Stage 2).

According to the formulated relationships, each criterion is considered as a controlling factor for a pairwise comparison matrix. Pairwise comparisons are performed with respect to all those factors (i.e., criteria) that have impact on other factors within their own cluster (i.e., dimension) or other clusters of the network. The question is asked such as: *"With respect to a specific factor (i.e., criterion), which of a pair of factors more influenced?"* For instance, assuming that the MPIs dimension has influence on the ECIs dimension after formulating interrelationships by the DEMATEL analyses, the result demonstrates the criteria within the MPIs dimension may have impact on those within the ECIs dimension. Subsequently, the experts are requested to make pairwise comparisons among the criteria (e.g., Greenhouse gas (GHG) emissions, CO_2-absorption efficacy of factory afforested areas, Factory sewage discharge) of ECIs by taking consideration of the influence of each criterion of MPIs.

In more detail, experts were asked, *"With respect to 'Pollution prevention implementation' (one criterion of MPIs), how much importance does 'Greenhouse gas (GHG) emissions'(one criterion of ECIs) have compared to 'CO_2-absorption efficacy of factory afforested areas'(another criterion of ECIs) using Saaty's 9-point priority scale representing equal importance to extreme importance?"*

3. Empirical analysis and results

In accordance with the proposed research analytical framework (Fig. 1), the data were collected and analyzed to establish an evaluation model for environmental performance. Three well-known TFT-LCD panel display manufacturers in Taiwan were used for the empirical analyses. The key environmental indicators selection and related data analyses at each stage are described below.

3.1. Establishing the key environmental indicators

Because the TFT-LCD panel display industry was selected as the research subject, the current situation of its environmental management was examined and communicated. Relevant data (e.g., environmental evaluation criteria and environmental data) from the EPA websites, corporate annual reports (CARs), corporate social responsibility (CSR) reports, and the ISO14031 classification table by the IDB of MOEA, R.O.C. (IDB, 2000), were analyzed for key environmental indicators.

Unlike traditional environmental evaluation tools (e.g., LCA, environmental risk assessment, etc.) that require more complete information from a life cycle perspective of products to perform rigorous and exhaustive evaluation (Herva and Roca, 2013), the proposed approach focuses on a quick and efficient assessment.

According to the guidelines of an ideal indicator selection elaborated by Perotto et al. (2008) and the related primary literature (Henri and Journeault, 2008; IDB, 2000; ISO, 2009; Jasch, 2000; Melnyk et al., 2003; Rao et al., 2006), 10 key environmental indicators were finally selected for the TFT-LCD panel display industry in consultation with the domain experts holding a focus group discussion (FGD) based on the most commonly used environmental performance indicators as detailed in Table A.1 (Appendix A).

More precisely, the chosen environmental indicators were confirmed by a consensus among experts' judgments. Table 1 lists the 10 selected indicators, which were grouped into three regulated EPE dimensions (i.e., MPIs, OPIs, and ECIs) of the ISO 14031 standard.

3.2. Constructing the network structure of the EPE by DEMATEL

From the questionnaire survey of DEMATEL at the second stage, the opinions of experts were first summarized by arithmetic means. The total-relation matrix of the various EPE dimensions was then obtained by using Eqs. (1) to (4). Eqs. (5) and (6) were utilized to calculate the centrality (i.e., $D_i + R_i$) and causality (i.e., $D_i - R_i$) (Table 2). The causal diagram of the EPE dimensions (Fig. 3) was drawn on the basis of the information in Table 2. In terms of the centrality analysis, the ($D_i + R_i$) value of the OPIs dimension presented the highest value (4.1288), revealing a stronger causal relationship between the OPIs dimension and the other two dimensions. It indicated that the OPIs dimension was the core factor and presented high interdependence with the MPIs and ECIs dimensions.

In terms of the causality analysis, the ($D_i - R_i$) value of the MPIs dimension presented the highest positive value (1.3820), indicating that the MPIs dimension was the *cause-factor* and was the major evaluation dimension affecting the other evaluation dimensions. However, the $(D_i - R_i)$ values in the OPIs and ECIs dimensions were negative and belonged to the *effect-factor*. The network evaluation structure of EPE was established as depicted in Fig. 4, on the basis of the analyses provided in Table 2.

3.3. Utilizing DANP to analyze the weight of the EPE indicators

As elaborated in Section 2.3, at the third stage, the weights of the criteria were calculated by the DANP method, a combination of DEMATEL and ANP proposed by Ou Yang et al. (2008) that considers the different influential degrees among clusters (dimensions). These weights were used to calculate the total-relation matrix ($\boldsymbol{T_S}$) of the EPE dimensions (Table 2).

The normalized total-relation matrix (Table 3) was further obtained through Eqs. (8) - (10). From Eq. (11), the normalized total-relation matrix ($\boldsymbol{T_S}$) (Table 3) was imported into the unweighted supermatrix ($W=[W_{ij}]$) (Table 4) obtained from the ANP questionnaire analysis using Eq. (7), and the weighted supermatrix $W_T = \left[t_{ji}^{s} \times W_{ij}\right]$ (Table 5) was derived. From Eq. (12), the weighted supermatrix (Table 5) converged into a limiting supermatrix $\lim_{k\to\infty} x^k = 0$ (Table 6), which represents the relative weights of the EPE criteria by the ANP analysis.

3.4. Ranking the synthesized performance of the EPE by GRA

At the fourth stage, the three major TFT-LCD display panel manufacturers (A, B, and C) in Taiwan were selected as the research subjects for our empirical study. The established EPE model for environmental performance was verified by GRA. The raw data (original values $[X_{ij}]$) of various environmental indicators and the data sources are summarized in Table 7. According to the characteristics of the evaluation criteria, the normalization formulas (i.e., larger-the-better, smaller-the-better, and nominal-the-best) for the data were determined.

Table 8 displays the normalized values (X_{ij}^*) of environmental indicators (criteria) of the three TFT-LCD panel manufacturers. Together the data presented in Table 8, Eqs. (16) and (17) were used to calculate the grey relation distance value (Δ_{oij}) (Table 9) and grey relation coefficient (γ_{oij}) (Table 10). Finally, substituting the relative weights (Table 6) of the environmental criteria analyzed by DANP and the grey relation coefficient (γ_{oij}) (Table 10) into Eq. (18), the grey relational grades (Γ_{oi}) of the environmental criteria were obtained (Table 11). The environmental performances of the three major TFT-LCD display panel manufacturers in Taiwan were ranked by GRA as B (0.9540), C (0.5349), and A (0.4034).

4. Discussions

The proposed evaluation model of environmental performance integrates three MCDM techniques: DEMATEL, ANP, and GRA. Each of the MCDM methods applied has individual features fit for the purpose of the analysis at the corresponding stage in the study. Generally, DEMATEL, Structural Equation Modeling (SEM), and Interpretive Structural Modeling (ISM) are optional causal analysis tools. In this research, since it possesses advantages over other methods, DEMATEL uses the experts' knowledge to analyze the structural model of EPE system in order to investigate the interactive relationships among EPE indicators (Wu, 2011).

Table 1. Selected key environmental indicators

Dimensions	*Criteria*
Management performance indicators (MPIs)	Number of pollution prevention implementations (MPI1)
	Penalty for violations of environmental laws (MPI2)
	Number of environmental labeling (MPI3)
	Number of received environmental protection prizes (MPI4)
Operational performance indicators (OPIs)	Recycling ratio of factory waste (OPI1)
	Ratio of green product designs in reducing CO_2 (OPI2)
	Energy efficiency ratio of factory electricity consumption (OPI3)
Environmental condition indicators (ECIs)	Greenhouse gas (GHG) emissions (ECI1)
	CO_2-absorption efficacy of factory afforested areas (ECI2)
	Factory sewage discharge (ECI3)

Table 2. The total-relation matrix ($T=[t_{ij}]$), $D_i + R_i$, and $D_i - R_i$ of the EPE dimensions

Dimensions	*MPI*	*OPI*	*ECI*	$D_i + R_i$ [a]	$D_i - R_i$ [b]
MPI	0.4421	1.0300	1.2361	4.0343 (3)	1.3820 (1)
OPI	0.5150	0.5107	1.0129	4.1288 (1)	-0.0515 (2)
ECI	0.3691	0.5494	0.4592	4.0858 (2)	-1.3305 (3)

[a]The ranking of $D_i + R_i$ is indicated in ( ); [b]The ranking of $D_i - R_i$ is indicated in ( ).

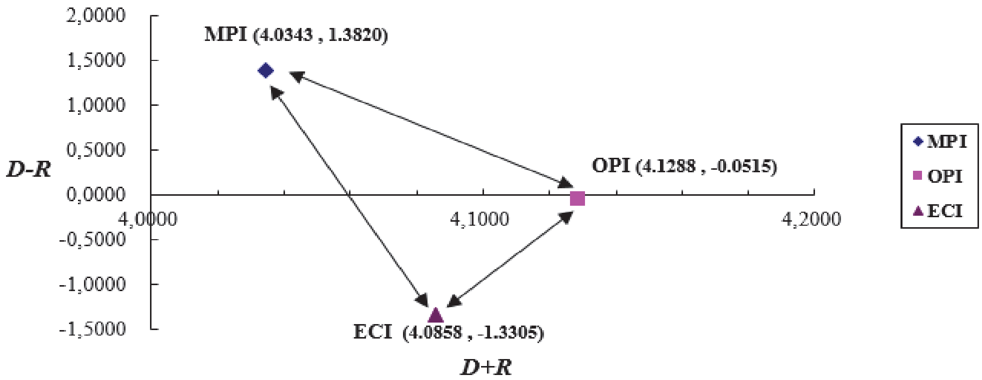

Fig. 3. The causal diagram of the EPE dimensions

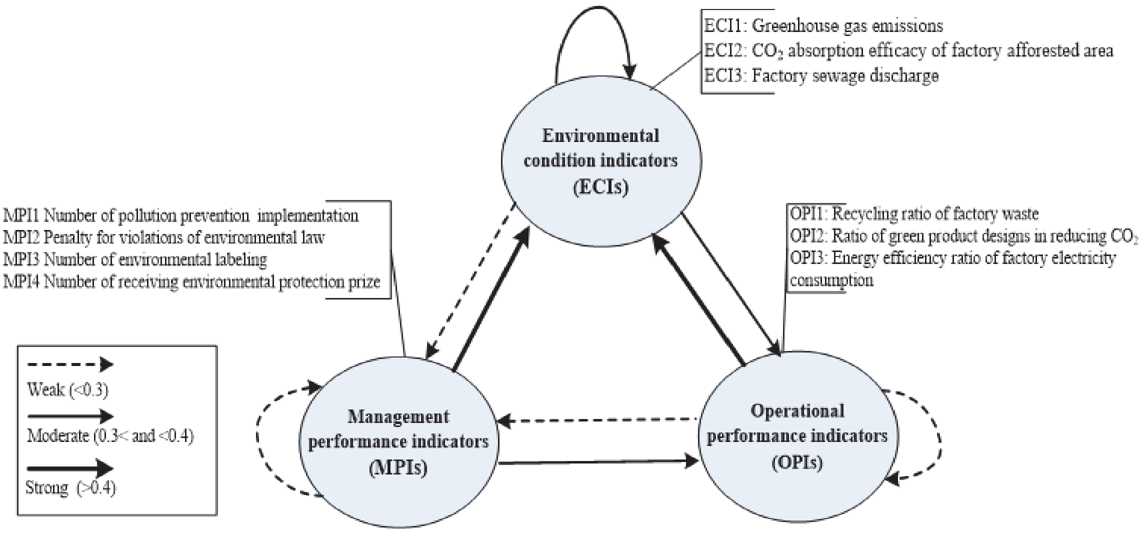

Fig. 4. The network evaluation structure of environmental performance

Table 3. The normalized total-relation matrix ($T_S = \left[t_{ij}^{s}\right]$) of the EPE dimensions

Dimensions	*MPI*	*OPI*	*ECI*
MPI	0.1632	0.3803	0.4564
OPI	0.2526	0.2505	0.4968
ECI	0.2679	0.3988	0.3333

Table 4. Unweighted supermatrix ($W = [W_{ij}]$)

Criteria	*MPI1*	*MPI2*	*MPI3*	*MPI4*	*OPI1*	*OPI2*	*OPI3*	*ECI1*	*ECI2*	*ECI3*
MPI1: Number of pollution prevention implementations	1.0000	0.0000	0.0000	0.0000	0.2458	0.4630	0.0963	0.0968	0.3853	0.2395
MPI2: Penalty for violations of environmental laws	0.0000	1.0000	0.0000	0.0000	0.5183	0.1264	0.0963	0.1628	0.0853	0.5215
MPI3: Number of environmental labelings	0.0000	0.0000	1.0000	0.0000	0.0962	0.2603	0.2495	0.3120	0.1445	0.0860
MPI4: Number of received environmental protection prizes	0.0000	0.0000	0.0000	1.0000	0.1397	0.1503	0.5579	0.4284	0.3849	0.1530
OPI1: Recycling ratio of factory waste	0.1140	0.5714	0.1365	0.1005	1.0000	0.0000	0.0000	0.1047	0.1168	0.2297
OPI2: Ratio of green product designs in reducing CO_2	0.4806	0.1429	0.6250	0.4665	0.0000	1.0000	0.0000	0.2583	0.1998	0.6483
OPI3: Energy efficiency ratio of factory electricity consumption	0.4054	0.2857	0.2385	0.4330	0.0000	0.0000	1.0000	0.6370	0.6833	0.1220
ECI1: Greenhouse gas (GHG) emissions	0.4579	0.2857	0.4000	0.2970	0.2255	0.1339	0.6908	1.0000	0.0000	0.0000
ECI2: CO_2-absorption efficacy of factory afforested areas	0.1260	0.1429	0.2000	0.1634	0.1007	0.3420	0.1488	0.0000	1.0000	0.0000
ECI3: Factory sewage discharge	0.4161	0.5714	0.4000	0.5396	0.6738	0.5241	0.1603	0.0000	0.0000	1.0000

Table 5. Weighted supermatrix ($W_T = [t_{ji}^{s} \times W_{ij}]$)

Criteria	*MPI1*	*MPI2*	*MPI3*	*MPI4*	*OPI1*	*OPI2*	*OPI3*	*ECI1*	*ECI2*	*ECI3*
MPI1: Number of pollution prevention implementations	0.1632	0.0000	0.0000	0.0000	0.0621	0.1170	0.0243	0.0259	0.1032	0.0642
MPI2: Penalty for violations of environmental laws	0.0000	0.1632	0.0000	0.0000	0.1309	0.0319	0.0243	0.0436	0.0229	0.1397
MPI3: Number of environmental labelings	0.0000	0.0000	0.1632	0.0000	0.0243	0.0658	0.0630	0.0836	0.0387	0.0231
MPI4: Number of received environmental protection prizes	0.0000	0.0000	0.0000	0.1632	0.0353	0.0380	0.1409	0.1148	0.1031	0.0410
OPI1: Recycling ratio of factory waste	0.0433	0.2173	0.0519	0.0382	0.2505	0.0000	0.0000	0.0418	0.0466	0.0916
OPI2: Ratio of green product designs in reducing CO_2	0.1828	0.0543	0.2377	0.1774	0.0000	0.2505	0.0000	0.1030	0.0797	0.2585
OPI3: Energy efficiency ratio of factory electricity consumption	0.1542	0.1087	0.0907	0.1647	0.0000	0.0000	0.2505	0.2540	0.2725	0.0487
ECI1: Greenhouse gas (GHG) emissions	0.2090	0.1304	0.1826	0.1355	0.1121	0.0665	0.3432	0.3333	0.0000	0.0000
ECI2: CO_2-absorption efficacy of factory afforested areas	0.0575	0.0652	0.0913	0.0746	0.0500	0.1699	0.0739	0.0000	0.3333	0.0000
ECI3: Factory sewage discharge	0.1899	0.2608	0.1826	0.2463	0.3348	0.2604	0.0797	0.0000	0.0000	0.3333

Table 6. Limiting supermatrix ($\lim_{k\to\infty} W_T^K$)

Criteria	*MPI1*	*MPI2*	*MPI3*	*MPI4*	*OPI1*	*OPI2*	*OPI3*	*ECI1*	*ECI2*	*ECI3*	*Ranking*
MPI1: Number of pollution prevention implementations	0.0578	0.0578	0.0578	0.0578	0.0578	0.0578	0.0578	0.0578	0.0578	0.0578	9
MPI2: Penalty for violations of environmental laws	0.0604	0.0604	0.0604	0.0604	0.0604	0.0604	0.0604	0.0604	0.0604	0.0604	8
MPI3: Number of environmental labelings	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	10
MPI4: Number of received environmental protection prizes	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	6
OPI1: Recycling ratio of factory waste	0.0639	0.0639	0.0639	0.0639	0.0639	0.0639	0.0639	0.0639	0.0639	0.0639	7
OPI2: Ratio of green product designs in reducing CO_2	0.1438	0.1438	0.1438	0.1438	0.1438	0.1438	0.1438	0.1438	0.1438	0.1438	3
OPI3: Energy efficiency ratio of factory electricity consumption	0.1357	0.1357	0.1357	0.1357	0.1357	0.1357	0.1357	0.1357	0.1357	0.1357	4
ECI1: Greenhouse gas (GHG) emissions	0.1526	0.1526	0.1526	0.1526	0.1526	0.1526	0.1526	0.1526	0.1526	0.1526	2
ECI2: CO_2-absorption efficacy of factory afforested areas	0.0820	0.0820	0.0820	0.0820	0.0820	0.0820	0.0820	0.0820	0.0820	0.0820	5
ECI3: Factory sewage discharge	0.1842	0.1842	0.1842	0.1842	0.1842	0.1842	0.1842	0.1842	0.1842	0.1842	1

Table 7. Original value (X_{ij}) of the EPE indicators (criteria) of the three TFT-LCD panel manufacturers

Dimensions/Criteria	*Company A*	*Company B*	*Company C*	*Data source*
Management performance indicators (MPI)				
MPI1 Number of pollution prevention implementations [a]	3	3	4	CSR Report 2008
MPI2 Penalty for violations of environmental laws [b]	NT$ 42,000	0	0	CAR 2008
MPI3 Number of environmental labelings [a]	0	14	0	EPA website [c]
MPI4 Number of received environmental protection prizes [a]	1	2	0	EPA website [c]
Operational performance indicators (OPI)				
OPI1 Recycling ratio of factory waste [a]	59%	93%	95.4%	CSR Report 2008
OPI2 Ratio of green product designs in reducing CO_2[a]	12%	39%	26%	CSR Report 2008
OPI3 Energy efficiency ratio of factory electricity consumption [a]	40%	54%	32%	CSR Report 2008
Environmental condition indicators (ECI)				
ECI1 Greenhouse gas (GHG) emissions [b]	2.07 (10^6 tons)	1.74 (10^6 tons)	1.87 (10^6 tons)	CSR Report 2008
ECI2 CO_2-absorption efficacy of factory afforested areas [a]	37.4 (tons)	61.3 (tons)	52.7 (tons)	CSR Report 2008
ECI3 Factory sewage discharge [b]	17.7 (10^6 tons)	16 (10^6 tons)	20.5 (10^6 tons)	CSR Report 2008

[a] "larger-the-better": The larger the data value, the higher the performance; [b] "smaller-the-better": The lower the data value, the higher the performance; [c] EPA website: http://greenliving.epa.gov.tw/greenlife/green-life/file_download.aspx.

Table 8. Normalized value (X_{ij}^*) of the EPE indicators (criteria) of the three TFT-LCD panel manufacturers

Dimensions/Criteria	*Company A*	*Company B*	*Company C*
Management performance indicators (MPI)			
MPI1 Number of pollution prevention implementations	0.0000	0.0000	1.0000
MPI2 Penalty for violations of environmental laws	0.0000	1.0000	1.0000
MPI3 Number of environmental labelings	0.0000	1.0000	0.0000
MPI4 Number of received environmental protection prizes	0.5000	1.0000	0.0000
Operational performance indicators (OPI)			
OPI1 Recycling ratio of factory waste	0.0000	0.9341	1.0000
OPI2 Ratio of green product designs in reducing CO_2	0.0000	1.0000	0.5185
OPI3 Energy efficiency ratio of factory electricity consumption	0.3636	1.0000	0.0000
Environmental condition indicators (ECI)			
ECI1 Greenhouse gas (GHG) emissions	0.0000	1.0000	0.6061
ECI2 CO_2-absorption efficacy of factory afforested areas	0.0000	1.0000	0.6402
ECI3 Factory sewage discharge	0.6222	1.0000	0.0000

Table 9. Grey relation distance value (Δ_{oij}) of the EPE indicators (criteria) of the three TFT-LCD panel manufacturers

Dimensions/Criteria	*Company A*	*Company B*	*Company C*
Management performance indicators (MPI)			
MPI1 Number of pollution prevention implementations	1.0000	1.0000	0.0000
MPI2 Penalty for violations of environmental laws	1.0000	0.0000	0.0000
MPI3 Number of environmental labelings	1.0000	0.0000	1.0000
MPI4 Number of received environmental protection prizes	0.5000	0.0000	1.0000
Operational performance indicators (OPI)			
OPI1 Recycling ratio of factory waste	1.0000	0.0659	0.0000
OPI2 Ratio of green product designs in reducing CO_2	1.0000	0.0000	0.4815
OPI3 Energy efficiency ratio of factory electricity consumption	0.6364	0.0000	1.0000
Environmental condition indicators (ECI)			
ECI1 Greenhouse gas (GHG) emissions	1.0000	0.0000	0.3939
ECI2 CO_2-absorption efficacy of factory afforested area	1.0000	0.0000	0.3598
ECI3 Factory sewage discharge	0.3778	0.0000	1.0000

Table 10. Grey relation coefficient (γ_{oij}) of the EPE indicators (criteria) of the three TFT-LCD panel manufacturers

Dimensions/Criteria	*A*	*B*	*C*
Management performance indicators (MPI)			
MPI1 Number of pollution prevention implementations	0.3333	0.3333	1.0000
MPI2 Penalty for violations of environmental laws	0.3333	1.0000	1.0000
MPI3 Number of environmental labelings	0.3333	1.0000	0.3333
MPI4 Number of received environmental protection prizes	0.5000	1.0000	0.3333
Operational performance indicators (OPI)			
OPI1 Recycling ratio of factory waste	0.3333	0.8835	1.0000
OPI2 Ratio of green product designs in reducing CO_2	0.3333	1.0000	0.5094
OPI3 Energy efficiency ratio of factory electricity consumption	0.4400	1.0000	0.3333
Environmental condition indicators (ECI)			
ECI1 Greenhouse gas (GHG) emissions	0.3333	1.0000	0.5593
ECI2 CO_2-absorption efficacy of factory afforested areas	0.3333	1.0000	0.5815
ECI3 Factory sewage discharge	0.5696	1.0000	0.3333

Different from traditional SEM, DEMATEL does not require pre-hypotheses or large-data verifications to determine the causal relationships among various EPE dimensions. Moreover, in comparison with the ISM approach that merely takes into account causal directions among indicators, the DEMATEL method can not only help analyze causal directions but also identify the strengths of influence among EPE indicators. More specifically, with DEMATEL analysis, the influential directions and strengths (degrees) among the indicators can be used to prioritize the decision making of environmental performance improvement.

By using DANP to analyze the relative weights of the evaluation criteria, the sophisticated network relationships among the EPE dimensions are considered more deeply, so as to identify the key environmental criteria.

Table 11. Grey relational grade (Γ_{oi}) of the EPE indicators (criteria) of the three TFT-LCD panel manufacturers

Dimensions/Criteria	***Weight*** [a] ***(*** w_j ***)***	***Company A***	***Company B***	***Company C***
Management performance indicators (MPI)	0.2378 (3) [b]			
MPI1 Number of pollution prevention implementations	0.0578	0.0193	0.0193 [d]	0.0578 [c]
MPI2 Penalty for violations of environmental laws	0.0604	0.0201	0.0604 [c]	0.0604
MPI3 Number of environmental labeling	0.0475	0.0158	0.0475 [c]	0.0158
MPI4 Number of received environmental protection prizes	0.0721	0.0361	0.0721 [c]	0.0240
Operational performance indicators (OPI)	0.3435 (2)			
OPI1 Recycling ratio of factory waste	0.0639	0.0213	0.0565	0.0639 [c]
OPI2 Ratio of green product designs in reducing CO_2	0.1438	0.0479	0.1438 [c]	0.0733
OPI3 Energy efficiency ratio of factory electricity consumption	0.1357	0.0597	0.1357 [c]	0.0452
Environmental condition indicators (ECI)	0.4188 (1)			
ECI1 Greenhouse gas (GHG) emissions	0.1526	0.0509 [d]	0.1526 [c]	0.0853
ECI2 CO_2-absorption efficacy of factory afforested areas	0.0820	0.0273	0.0820 [c]	0.0477
ECI3 Factory sewage discharge	0.1842	0.1049	0.1842 [c]	0.0614 [d]
Grey relational grade (Γ_{oi})		0.4034 (3)	0.9540 (1)	0.5349 (2)

[a] The relative weights of environmental performance criteria (Table 6); [b] The ranking is indicated in ( ); [c] The highest performance among the three companies against environmental performance criterion; [d] The largest distance (gap) (from the highest performance as indicated by "c") among environmental performance criteria for each company.

In addition, GRA has the advantages of easy calculation and no typical normality as required by traditional statistics. It provides efficient decision making for the uncertainty with small samples, multi-input, and incomplete and discrete data (Deng, 1982, 1985, 1989). More explicitly, GRA is a normalization-based method as introduced previously, which only involves a simple and transparent evaluation procedure to compare various alternatives to establish a clear-cut ranking order of these alternatives (Lu and Wevers, 2007). Consequently, this study applied GRA that conquers the deficiencies of some other techniques (e.g., fuzzy theory, statistics) to perform an empirical analysis of a synthesized EPE for environmental management.

As stated earlier, relevant literature on environmental management indicates that EPE indicators are rather complicated. And most previous research on environmental performance has focused primarily on qualitative factors by subjective opinion surveys. Such studies seldom have regarded the influence of interdependences and feedback among the evaluation criteria. Taking a specific industry as the research subject, this study is to establish an objectively integrated evaluation model employing a hybrid MCDM methodology for systematic environmental management by key environmental indicators with relative weights, using quantitative secondary environmental data along with empirical analyses. Since the environmental impact of TFT-LCD panel industry is greater than that of traditional industries, the TFT-LCD panel industry is used as an illustrative example. The reason why the top three TFT-LCD display panel manufacturers in Taiwan are selected as case companies is that they not only have homogeneity of manufacturing facilities but also have almost the same scale in size. In terms of environmental indicators selection, the homogeneity nature is one of most considerations. Besides, comparison of case companies of similar scale would make more sense.

The quantitative secondary environmental data used in this study were more objective than those used in previous relevant research, which utilized qualitative indicators with subjective preferences (Awasthi et al., 2010; Balana et al., 2010). Moreover, the adopted environmental data were relatively simple and available because all sources of data can be referenced and easily obtained from public reports or websites as listed in Table 7. However, there are still some probable limitations of the current study. First, similar to all the other professional questionnaires, in the DEMATEL and ANP questionnaire surveys, responses might be subject to human prejudiced perception owing to the nature of subjective ability (or experience) of human beings' decision-making. Second, the design of professional questionnaires is considered more complex. Particularly, the ANP questionnaire is lengthy, which usually takes respondents longer time to fill out. Third, as mentioned earlier, there are numerous environmental indicators available for environmental performance evaluation. It is unavoidable that forming an expert panel will result in a bias in the selection of indicators even though the selected indicators were further confirmed by interviews with the committees of experts. Finally, the selected EPE criteria with respect to the ISO14031 EPE indicators for the case companies may not be suitable to other organizations because evaluation of different organizational characteristics may lead to very different outcome. Therefore, the applicability of the results to other situations should be viewed with discretion.

As the established network relations of the EPE dimensions presented in Fig. 3, the influential orientation and degrees among the three EPE dimensions were clearly quantified by the experts' judgment. Referring to Fig. 4, taking into account the relatively strong influence between any two dimensions, the MPIs dimension (belonging to the *cause-factor*) had moderate to strong effects on the OPIs and ECIs dimensions, whereas the OPIs dimension also showed a strong effect on the ECIs dimension (belonging to the *effect-factor)*. From a systems analysis view, the analytical result is primarily consistent with the causal relations of the "Driving Force Pressure State Impact Response (DPSIR)" framework for reporting on environmental issues proposed by Smeets and Weterings (1999), which is an extension of the "Pressure State Response (PSR)" model (OECD, 1993). According to the causal links (Fig. 4), the MPIs dimension, as "Response of society", feeds back to the "State of the environment changes" (i.e., the ECIs dimension) and "Pressure" (i.e., the OPIs dimension) through human activities, while "Pressure" (i.e., the OPIs dimension) exert on the environmental conditions ("State"). In other terms, this can imply that enterprises should first address the environmental aspects of management performance (e.g., environmental policies, objectives, target, financial performance, compliance, and public relations with interested parties) to affect their environmental operational performance, and should focus on issues such as the materials recycled and reused, energy resources, and pollutants involved in factories, equipment, materials, and energy supply. After dealing with the environmental aspects, they can further enhance their environmental performance, which may be reflected in the environmental condition indicators.

In the third stage, the relative weights of the EPE criteria were prioritized by the DANP analysis. As summarized in Table 6, the factory sewage discharge (ECI3) received the highest weight, whereas number of environmental labeling (MPI3) presented the least weight. This result indicates that factory sewage discharge is the most critical EPE criterion for the TFT-LCD panel display industry, and that the acquisition of environmental labels is less important. In general, based on the analysis results, the TFT-LCD panel manufacturers were advised to place more emphasis on the EPE criteria related to the environmental condition indicators (i.e., ECIs), such as factory wastewater treatment, GHG management, and the CO_2-absorption efficacy of factory afforested areas.

However, the improvement of environmental performance should first embarked on enhancing management performance indicators (i.e., MPIs), such as applying for corporate environmental prizes, complying with environmental regulations, implementing pollution prevention, and obtaining environmental labels. The TFT-LCD panel manufacturers were further advised to promote their design and operations for operations system including factories, equipment, materials, and energy supply, which can be evaluated by the relevant operational performance indicators (i.e., OPIs), such as increasing eco-design products, reducing CO_2 emissions, and adopting renewable energy.

Interestingly, the top five key EPE criteria belonged to the OPIs and ECIs dimensions, and all three of the evaluation criteria of the ECIs dimension, were included. Through a cross-reference of the DEMATEL analyses, the causal relationship of the EPE dimensions (Fig. 4) suggests that the environmental condition was an important evaluation dimension and was affected by management performance and operational performance. In other words, a cross-reference of the DEMATEL analyses identified a correspondence between the results of the ANP and DEMATEL analyses, because the ANP normalization had been incorporated into the influential strength among the dimensions obtained by DEMATEL. Therefore, such a combination of DEMATEL and ANP (i.e., DANP) used by the proposed model, would be considered to be more rational than the common use of either alone in a real situation.

Lastly, three well-known Taiwanese TFT-LCD panel display industry manufacturers were analyzed by GRA to verify the established evaluation model of environmental performance at the fourth stage. As previously delineated, environmental performance evaluation, like most of practical problems, is considered too complicate to be appropriately assessed by a single criterion or indicator. Therefore, the proposed model adopted a MCDM approach to perform environmental performance evaluation. However, when comparing between sites (e.g., organizations, factories), an aggregation method to summate multiple relevant criteria/indicators with data of various sources as a composite score is better to represent specific performance considered at the same time (Koschke et al., 2012; Perotto et al., 2008). Furthermore, GRA is applied in allowing for analyses with small sample size (Deng, 1982, 1985, 1989). Thus, for these reasons, GRA was employed to aggregate the performances of the three dimensions: MPIs, OPIs, and ECIs, where aggregation contains criteria/indicators (e.g., air, water, waste) referring to each dimension. The aggregate values (i.e., composite scores) can not only provide succinct and comprehensible information, but also relatively valuable sense in directing attention (Atkinson et al., 1997; Perotto et al., 2008). As shown in Table 11, with the synthesized performance analysis (i.e., composite scores) of GRA, Company B (0.9540) presented the best environmental performance, followed by Company C and Company A. The performances of Company A (0.4034) and Company C (0.5349) were closest to each other.

According to the gap analysis (calculating the distances from the highest performance against each environmental performance criterion and determining the largest gap among criteria for each company.), the EPE indicator most needed to be improved and/or enhanced for each company is identified. For example, it is found that for Company A, the gap of greenhouse gas (GHG) emissions (ECI1) (0.1526 - 0.0509 =

0.10170) as indicated by “d” in Table 11 is the largest one of all environmental performance criteria. Reducing GHG emissions should be the focal points in its environmental performance improvement. The major emission source of GHG emissions in TFT-LCD manufacturing processes is electric consumption. Company A is encouraged to be energy efficient, production operations and process improvement effectively and adopt innovative environmental technologies such as the use of clean and renewable energy to reduce energy consumption as well as GHG emissions. More specifically, Company A can conduct LCA to evaluate the product’s environmental impacts and calculate the carbon footprint and the main environmental impacts of TFT-LCD screens from the raw materials to the end use of the product, then cooperated with its suppliers to improve environmental performance and make it an essential part of production.

Although Company B exhibits the best environmental performance out of the three case companies, for achieving better environmental performance Company B is advised to increase the number of pollution prevention implementation (MPI1) by launching more pollution prevention projects to fulfil its environmental policy, goals, and objectives. For example, in addition to investing more in pollution-prevention research and development, Company B can intimately promote cleaner production (CP) including systematic programs of pollution reduction and resource reduction, and environmental impacts assessment programs and so on (Liu et al., 2015).

TFT-LCD industry is high demands for water. Therefore, especially, for Company C, with relatively low performance in factory sewage discharge (ECI3), it is recommended to primarily focus on water conservation for the facilities during manufacturing process and water management in order to reduce the risks of water resource shortages as well as sewage discharge. Company C could better manage the collection, treatment and recycling or safe disposal of sewage. For instance, Company C could upgrade wastewater treatment system, such as adding the “organic wastewater membrane replacement” in the wastewater processing facility and using “non-organic system recycling and processing” facility. In addition, fundamentally, some actions to be considered could be using recyclable materials, selecting non-hazardous materials, and using reusable parts and components to prevent sewage pollution (Bereketli and Genevois, 2013).

The results of the analysis by the proposed model can help direct the efforts of an organization towards improving a few vital environmental problems under limited resources.

5. Conclusions

Environmental performance has become the main concern of internally and externally interested parties of enterprises and environmental indicators have been developed to measure the environmental performance of an enterprise. Nonetheless, it is difficult to evaluate the environmental management of enterprises, because of the complexity of environmental problems. The study aimed to provide enterprises with an effective, convenient, and rapid basis for the self-diagnoses of green management. The quantified environmental evaluation model based on a hybrid MCDM approach identified ten environmental indictors categorized into three evaluation dimensions (i.e., MPIs, OPIs, and ECIs) of the ISO14031 EPE standard for TFT-LCD industry. Against the established evaluation criteria and weights, the related secondary environmental data of the three comparable TFT-LCD panel manufacturers in Taiwan were substituted to assess the environmental performance.

This study makes a major contribution to performing objective and quantitative evaluation on the integration of EPE indicator weights and environmental performance with simple and accessible data from secondary sources. In sum, rather than focusing on the selection of environmental indicators, one of relevant topics in the field of environmental evaluation research, which has been widely and thoroughly discussed, the presented hybrid approach of combining the MCDM tools, DANP and GRA, is a novel idea to put the main focus of proposing a generic framework of environmental performance evaluation taking into account the complex interdependence (i.e., influential directions and strengths of causal links) between and among the environmental indicators.

5.1. Managerial implications

Some managerial implications are briefly addressed as below. First, the assessment results by the proposed evaluation model indicate that organizations cannot only efficiently allocate resources to the aspects of environmental management that need the most improvements, but also must effectively prioritize their implementations. Second, organizations related to governmental environmental protection could refer to analytical results for policy adjustment of environmental quality standard requirements of other relevant industries. Third, related industries could refer to the proposed evaluation model to identify environmental management problems within their businesses, develop environmental performance improvement strategies, and formulate action plans of environmental management. Finally, to respond to governmental environmental policies, enterprises should select proper environmental indicators for different environmental strategies to better improve their key environmental quality.

5.2. Suggestions for further research

The established environmental indicators were primarily on the basis of ISO14031 structure and on the basis of data availability through an extensive literature review. Pertinent data gathered from related environmental information websites and corporate reports were organized to select the common key quantifiable indicators for the case companies of this study, which might not be suitable for other cases. Therefore, according to the limitations of this study, some important recommendations for future work are made as follows.

First, it is suggested that other industrial characteristics and environmental conditions be included in the various evaluation dimensions and criteria, so as to correspond to the environmental management requirements for the particular industry. Second, in cases where the environmental criteria are numerous, it is advisable to reduce the data with some other tools such as factor analysis, trough sets theory, or other professional questionnaire surveys (e.g., Delphi method) to abstract most relevant key environmental indicators.

Third, following the quantitative analyses of the proposed evaluation model, future research could complement the method with uncertainty and sensitivity analysis and/or pursue qualitative analyses, such as in-depth case studies, and further develop environmental management strategies as a basis for promoting environmental performance. Finally, the proposed environmental performance evaluation model can be further adapted to sustainability assessment by including more relevant social and economic criteria.

List of abbreviations and acronyms

Abbreviation/ Acronym	*Terminology/Full name*	*Abbreviation/ Acronym*	*Terminology/Full name*
ANP	Analytic Network Process	ISO	International Organization for Standardization
CO_2	Carbon Dioxide	ISO/TC	International Organization for Standardization/ Technical Committee
CARs	Corporate Annual Reports	ISM	Interpretive Structural Modeling
CSR	Corporate Social Responsibility	LCA	Lifecycle Assessment
CEPD	Council For Economic Planning And Development	MPIs	Management Performance Indicators
CP	Cleaner Production	MOEA	Ministry of Economic Affairs
DEMATEL	Decision Making Trial and Evaluation Laboratory	MCDM	Multi-Criteria Decision Making
DANP	DEMATEL-based ANP	OPIs	Operational Performance Indicators
ECIs	Environmental Condition Indicators	OECD	Organization for Economic Cooperation and Development
EMSs	Environmental Management Systems	PSR	Pressure State Response
EPE	Environmental Performance Evaluation	ROC	Republic of China
EPIs	Environmental Performance Indicators	SEM	Structural Equation Modeling
EPA	Environmental Protection Administration	TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
ESI	Environmental Sustainability Index	TFT-LCD	Thin Film Transistor-Liquid Crystal Display
FGD	Focus Group Discussion	VIKOR	Vlsekriterijumska Optimizacija I Kompromisno Resenje
GHG	Greenhouse Gas	RoHS	Restriction of Hazardous Substances
GRA	Grey Relational Analysis	WEEE	Waste Electrical and Electronic Equipment
IDB	Industrial Development Bureau	WEF	World Economic Forum

Appendix A. Sample of most commonly used environmental performance indicators

Table A.1. Sample of most commonly used environmental performance indicators

Dimension	*Criteria*	*Sub-criteria*
Management Performance Indicators (MPIs)	Implementation of environmental policies and programs	Number of achieved objectives and targets
		Number of organizational units achieving environmental objectives and targets
		Number of pollution prevention projects
		Number of levels of management with specific environmental responsibilities
		Number of employees participating in environmental programs (e.g. suggestion, recycle, clean-up initiatives, reward and recognition, or others)
	Conformity	Degree of compliance with regulations;
		number of audits completed versus planned
		Number of or costs attributable to fines and penalties
		Number of suppliers and contractors queried about environmental issues
		Number of contracted service providers with an implemented or a certified environmental management system

	Financial performance	Costs (operational and capital) that are associated with a product's or process environmental aspects
		Return on investment for environmental improvement projects
		Research and development funds applied to projects with environmental significance
		Cost of environmental training
		Savings achieved through reductions in resource usage, prevention of pollution or waste recycling
	Community/Public relations	Number of inquiries or comments about environmentally related matters
		Number of press reports on the organization's environmental performance
		Number of local cleanup or recycling initiatives, sponsored or self-implemented
		Number of environmental labelings
		Number of received environmental protection prizes
Operational Performance Indicators (OPIs)	Materials	Quantity of materials used per unit of product
		Quantity of processed, recycled or reused materials
	Energy	Quantity of energy used per year or per unit of product
		Quantity of energy units saved due to energy conservation programs
	Products	Number of products which can be reused or recycled
		Number of units of by-products generated per unit
		Number of products introduced in the market with reduced hazardous properties
		Number of products with instructions regarding environmentally safe use and disposal
	Outputs of solid waste	Quantity of waste per year or per unit of product
		Quantity of hazardous waste reduced by using substitutes
		Quantity of hazardous, recyclable or reusable waste produced per year
		Total waste for disposal
		Quantity of waste converted to reusable material per year
	Outputs of air emissions	Quantity of specific emissions per year or per unit of product
		Quantity of specific emissions per year
		Quantity of Greenhouse gas (GHG) emissions reduced per year
	Outputs of waste water	Quantity of waste water per year or per unit of product
		Quantity of specific water pollutants per unit of product
	Noise/Radiation	Noise measured at a certain location
		Quantity of radiation reduced at a certain location
Environmental Condition Indicator (ECIs)	Air	Contaminant concentrations in ambient air within a monitored area
		Frequency of photochemical smog events a specific
	Water	Turbidity of factory sewage in vicinity of outlets
		Change in groundwater level
	Land	Contaminant concentration in surface soil
		Area of contaminated land rehabilitated within a defined area
	Plant	Quantity of harvest of crops in the farmland nearby factory
		Quantity of plants within a monitored area
	Animal	Concentration of a contaminant in the tissue of a specific local species
		Population of an specific animal species within a defined area

Source: Adapted from IDB (2000).

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