

LCA DOMESTICATION IN TAIWAN: COMBINATION WITH THE ENVIRONMENTAL INDICATOR SYSTEM

Chien-Chung Huang* and Hwong-Wen Ma

Graduate Institute of Environmental Engineering
National Taiwan University
Taipei 106, Taiwan

Key Words: Life cycle assessment, environmental indicator, factor analysis

ABSTRACT

Life cycle assessment (LCA), the powerful environmental management tool of design for environment, could consider all stages and aspects of a specific product. Although LCA is widely recognized in environmental management, there are still some shortcomings that need to be overcome. The goal of this paper is to improve the valuation stage in LCA, by combining the LCA with the environmental indicator system through factor analysis. In the past, the valuation stage was always implemented by subjective methods to integrate the different issues into one specific eco-indicator. To reveal the environmental condition where the LCA cases occur, this study considers that the weights of different environmental issues should be based on the environmental monitor data in different regions.

For this purpose, we selected 10 environmental issues and 35 environmental indicators to characterize Taiwan's condition in this study. The weights of various environmental issues can be determined by the proposed procedure and integrated into LCA stages. The proposed methodology is expected to increase the objectivity and reflect spatial variability to enhance the reliability of the assessment results. To reveal the performance of this innovative methodology, a suppositional coffee machine is selected for the case study in this investigation.

INTRODUCTION

Based on the principle of "sustainable development", "prevention of pollution" is more important than contamination treatment. Therefore, the traditional methods of environmental protection, "End-of-Pipe" only treatment, have been considered ineffective. The significance of total environmental management has been paid more attention. To implement a comprehensive environmental management, environmental standards established on the international business are more and more important. Therefore, International organization for standardization (ISO) started to frame a series of standards for business and environmental protection, which is ISO 14000 series [1].

This series includes principles and definitions about environmental management system, environmental auditing, environmental performance evaluation, environmental labeling, environmental aspects in product standards and life cycle assessment (LCA).

LCA, the powerful environmental management tool of design for environment, could consider all stages and aspects of a specific product. The past con-

cern of environmental assessment only focused on the treatment of pollution emission during the production process, but ignored the environmental loading of resource use and the disposal stages. To complement these inadequacies, LCA had been developed gradually since 1990.

Although LCA is widely used in environmental management, there are still some shortcomings that need to be overcome. According the previous study [2], the concern regarding the impact categories typically included quality of inventory data, methodological choices in relation to time aspects, allocation, characterization, uncertainties, and weighting methods.

In this paper, an innovative frame of weighting method has been addressed. To get an integrated index in valuation stage of LCA, it needs to weight all different environmental issues and integrate them into one specific eco-indicator. Society of Environmental Toxicology and Chemistry [3] indicated that the valuation methods in common use presently are analytic hierarchy process, willingness-to-pay, multi-attribute utility theory, impact analysis matrix, contingent valuation, and fuzzy analytic hierarchy process.

*Corresponding author
Email: f87541201@ntu.edu.tw

But the methods mentioned are mostly based only on subjectivity of experts or interest groups. In fact, there are different environmental conditions in different areas. The importance of issues in different areas should not be the same.

In other words, the importance of every environmental issue should be based on the local environmental quality and the use of natural resource. Unfortunately, these factors have not been considered in traditional valuation process. For example, when the production and valuation processes are the same, the “environmental loading” of the goods produced in Taiwan is the same as that produced in Japan. But in different environmental status, the “environmental impacts” of these two goods may be different. The same concept appears in health risk assessment (RA) and environmental impact assessment (EIA). In RA, sensitive receptors (e.g., children, pregnant women, and the aged) need to be considered in the stages of exposure and consequence assessment in order to derive protective schemes. In EIA, the “environmental sensitive areas” are the emphases to be noticed. Besides, Organisation for Economic Co-operation and Development [4] claimed that the environmental data should include “Pressure-State-Response”, not only “Pressure”. Therefore, it is necessary to consider not only environmental pressure but also environmental status when we treat the environmental issues. This paper tries to combine the pressure and state indicators to obtain the more meaningful results of LCA.

To present the different environmental states, a lot of environmental indicator systems have been developed around the world. Although the selection of indicator items still depends on expert panels, the basis of indicators is objective environmental monitor data and scientific methodology. In addition, most environmental indicators correspond to the environmental issues. Consequently, this study established an environmental indicator system and integrated the indicators into the corresponding weighting value in the valuation stage. Finally, the sensitivities of different issues in different regions will be apparent and the results of LCA will be more significant.

METHODOLOGY

The goal of this paper is to improve the valuation stage in LCA. The investigation process is shown as Fig. 1.

First, we collected the data for the case study and processed the first two steps of conventional LCA methodology (“goal and scope definition” and “inventory analysis”). In this study, the coffee machine and three regions in Taiwan were selected for the case study. After the characterization stage, the environmental loadings of issues (or called ELs in Eq. 1) were obtained. The issues include global warming, ozone layer depletion, acidification, eutrophication, heavy

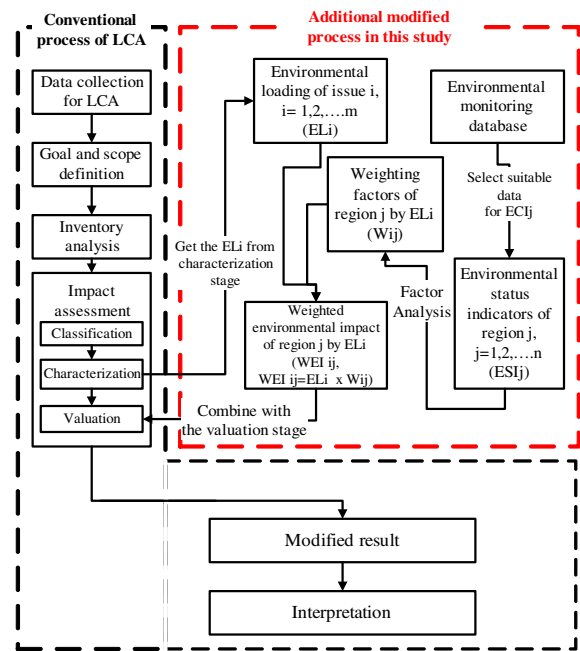


Fig. 1. Investigation process.

metal pollution, carcinogenic substance, winter smog, summer smog, and energy consumption. The ELs were derived from Sigmapro, the LCA software developed by Pre consultants B.V. (The Netherlands) [5]. Separately, the weighting factors (W) were obtained by factor analysis from environmental status indicators (see content below). Then, the weighted environmental impact (WEI) could be obtained from EL and W.

$$WEI_{ij} = EL_i \times W_{ij} \quad (1)$$

where WEI_{ij} is WEI of region j by EL_i ; EL_i is environmental loading of issue i , $i = 1, 2, \dots, m$; W_{ij} is weighting factors of region j by EL_i .

After integrating the WEI and valuation stage, the modified result was derived. The modified result included environmental pressure and state considerations. This innovative methodology consists of mainly three concepts: LCA, environmental indicators, and factor analysis. The introductions of these concepts and the detail calculating processes are described below.

APPLICATIONS OF LCA

According to ISO 14040 [6], LCA shall include four phases: goal and scope definition, inventory analysis, impact assessment and interpretation of results. ISO 14042 [7] suggested that the steps of impact assessment could be divided into mandatory and optional elements. The mandatory elements include selection of impact categories, classification, and characterization. Normalization, grouping, weighting, and data quality assessment are categorized into the optional elements.

Table 1. The environmental issues and corresponding indicator groups in this study.

Environmental issues	Corresponding indicator groups	Environmental issues	Corresponding indicator groups
Ozone layer depletion	Average sunshine time Entire day light radiant energy	Energy consumption	Sold electric quantity
Acidification	SO _x conc. NO _x conc. pH value of rain	Air pollution	PM ₁₀ conc. SO ₂ conc. CO conc. NO ₂ conc.
Solid waste	Trash amount Ratio of non-recycling resources Ratio of illegal dumping Complained cases about waste pollution		O ₃ conc. NMHC conc. Days of PSI > 100 Complained cases about air pollution Complained cases about odor pollution
Water consumption	Effective rainfall amount Water quantity for industrial use Water quantity for civil use	Noise	Unqualified proportion of transportation interval Unqualified proportion of normal interval Complained cases about noise
Water pollution	Water quantity for agricultural use BOD Unqualified rate of tap water Unqualified rate of non-tap water Complained cases about water pollution	Soil pollution	Areas of heavy metal pollution in level 5 Amount of cadmium pollution
		Eutrophication	N P Reservoir eutrophication index

In this study, the focus is on the valuation (weighting) stage, the third step in impact assessment. Generally speaking, technologies of valuing could be divided into three groups [5]. They are expert panel method, distance to target method, and monetarisation. But these methods all have difficulties [5]. For example, it is difficult to explain to a panel the meaning of the impact category indicators and the number of indicators. And policy targets cannot reflect the “real” need to reduce environmental impacts.

Thus it can be seen that there are various values in our society. Many methods could be used to solve the weighting problem. In this investigation, factor analysis is applied to build an environmental indicator system and yield the weight of different environmental issues.

ENVIRONMENTAL INDICATORS

2.1 Definition of Environmental Indicators

Environmental indicators, which could help us to know the current environmental condition, comprise important phenomenon or factors. But the process of data mining in environmental monitoring database would simplify the real circumstance. U.S. EPA [8] claimed “Environmental indicators are scientific measurements that track environmental conditionals over time. Indicators help measure the state of our air, water and land resources, the pressures on them, and the resulting effects on ecological and human health.”

To build a reasonable and meaningful indicator system and avoid the neglect of important information, some principle need to be noticed [9]:

- Easily understood by the public
- Include major pollutants and be capable of including future pollutants
- Calculated in a simple manner using reasonable assumptions
- Based on a reasonable scientific premise
- Spatially meaningful
- Can be forecasted a day in advance

2.2 Environmental Indicators in This Study

To correspond to the environmental issues in different levels, appropriate environmental indicator must be selected. In this case, the different impact of environmental loading is the compared target, so the relative monitoring data issued by the government are the major information LCA resources. After comparing the different current LCA software and considering the feasibility, some environmental issues and indicators are selected as Table 1.

Take “eutrophication” for example. This study select nitrogen concentration, phosphorous concentration and reservoir eutrophication index to be the corresponding indicator group. Factor analysis was used to integrate this indicator group into one index of eutrophication issue in this step.

FACTOR ANALYSIS

3.1 Applications of Factor Analysis

Hair et al. [10] claimed “factor analysis is a generic name given to a class of multivariate statistical methods whose primary purpose is to define the un-

derlying structure in a data matrix.” And as Comrey and Lee [11] supposed, “Factor analytic methods can also help these scientists to gain a better understanding of the complex and poorly defined interrelationships among large numbers of imprecisely measured variables.” Briefly speaking, factor analysis is a process that could find meaningful inter-relationships among variables and factors. In this paper, the “communality”, which is obtained in factor analysis process, is used to be the weight to integrate the variables (corresponding indicator group) to one index for a specific environmental issue.

3.2 The Mathematical Model of Factor Analysis

The q -factor mode can be represented as:

$$\begin{aligned} x_1 &= \mu_1 + l_{11}f_1 + l_{12}f_2 + \dots + l_{1q}f_q + \varepsilon_1 \\ x_2 &= \mu_2 + l_{21}f_1 + l_{22}f_2 + \dots + l_{2q}f_q + \varepsilon_2 \\ &\vdots \\ x_p &= \mu_p + l_{p1}f_1 + l_{p2}f_2 + \dots + l_{pq}f_q + \varepsilon_p, \end{aligned} \quad (2)$$

where f_j is the common factor held by all variables χ_i . And ε_i is unique factor that are only held by the i^{th} variable, χ_i .

In these equations, the inter-correlation among the p variables is being explained by the q common factors. It is assumed that the number of q is much less than the number, p . In other words, the inter-correlation among the p variables is due to a small a small number, q ($q < p$), of common factors.

μ_i is the mean of χ_i . l_{ij} is the χ_i 's factor loading for common factor f_j . When χ_i are the standard data or correlation matrix is applied to analysis, the next equation will come into existence.

$$\sum_{j=1}^q l_{ij}^2 = h_i^2 \quad (3)$$

where h_i^2 is called the “communality” of χ_i . Comrey and Lee [11] considered “the communalities represent the extent of overlap between the variables and factors.” Therefore, in this study, h_i^2 is used to the weighting factor of region j by EL_i . In other words, h_i^2 is the W_{ij} in this paper.

PROCESS OF WEIGHTS INTEGRATION

The process of weights integration depends on the number of variables and factors. There are three pathways to obtain the weights (see Fig. 2). The variables are the environmental indicators corresponding to the specific environmental issues.

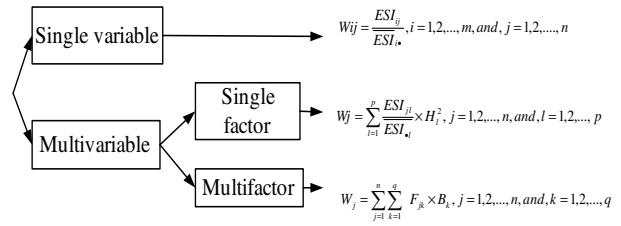


Fig. 2. The process of weights integration.

1. When there is only one corresponding environmental indicator for the environmental issue, the calculating process is listed as Eq. 4. The W_{ij} is the weight.

$$W_{ij} = \frac{\overline{ESI}_{ij}}{\overline{ESI}_i}, \quad i = 1, 2, \dots, m \quad \text{and} \quad j = 1, 2, \dots, n \quad (4)$$

where i is the amount of environmental issues which have only one corresponding indicator (the total number of issues is m), and n is the number of evaluated areas (alternatives). \overline{ESI}_i means the average of all indicator data for all evaluated areas regarding this specific indicator. In other words, the average indicator data of all alternatives are the baseline, and then the single indicator could convert into an equivalent for weight.

2. When there are several corresponding environmental indicators for the environmental issue, the factor analysis is used to get the communality for every indicator. Then, let the sum of communalities equal one and integrate the indicators into one weight. The detailed steps are described as following:

Step 1.

For the consistent unit, the raw data should be transferred to correlative matrix “R” and then the factor analysis is performed. Next, according to the Kaiser criterion [12], select the factors whose eigenvalue is more than one.

Step 2.

Estimate the parameter through principal component analysis, and calculate the factor loadings and uniqueness.

Step 3.

To select one solution from many feasible ones, the Varimax method is applied to process the factor rotation. The factor loadings of selected solution must be close to zero or one.

Step 4.

- 1). If one factor is sufficient for the analysis result, p communalities h_i^2 were obtained. Let the summary of communalities equal to one, and we can get the proportion of communalities “ H_i^2 ”.

$$H_l^2 = \frac{h_l^2}{\sum_{l=1}^p h_l^2}, l = 1, 2, \dots, p \quad (5)$$

Next, obtain the single weight W_j from integrating the H_l^2 .

$$W_j = \sum_{l=1}^p \frac{ESI_{jl}}{ESI_{\bullet l}} \times H_l^2, j = 1, 2, \dots, n, \quad (6)$$

$$l = 1, 2, \dots, p$$

where n is the number of evaluated areas, and p is the number of indicators corresponding to the same environmental issue.

2). If the analysis result requires q factors to be selected, the communalities " h_{lk}^2 " and the proportion of communalities " H_{lk}^2 " of p indicators corresponding to q factors should be obtained at first.

$$H_{lk}^2 = \frac{h_{lk}^2}{\sum_{l=1}^p h_{lk}^2}, l = 1, 2, \dots, p, k = 1, 2, \dots, q \quad (7)$$

where q is the number of selected factors.

Afterwards, the proportion of factor B_k , the explanation for communality of one factor among all factors, is obtained.

$$B_k = \frac{\sum_{l=1}^p h_{lk}^2}{\sum_{l=1}^p \sum_{k=1}^q h_{lk}^2}, l = 1, 2, \dots, p, k = 1, 2, \dots, q \quad (8)$$

The integrating value of factors F_{jk} is obtained simultaneously. F_{jk} is the value obtained from equivalent of indicators multiplied by the proportion of communalities.

$$F_{jk} = \sum_{l=1}^p \frac{ESI_{jlk}}{ESI_{j\bullet k}} \times H_{lk}^2, j = 1, 2, \dots, n,$$

$$l = 1, 2, \dots, p, k = 1, 2, \dots, q \quad (9)$$

Finally, the single weight " W_j " could be derived from the integrating value of factors multiplied by the proportion of factor.

$$W_j = \sum_{k=1}^q \sum_{l=1}^p F_{jlk} \times B_k, j = 1, 2, \dots, n,$$

$$k = 1, 2, \dots, q \quad (10)$$

Step 5.

To evaluate the fitness of model, the study applied the MSA criterion and Bartlett ball test. If the

Kaiser-Meyer-Olkin (KMO) value is higher than 0.5 or the significant level of Bartlett test is less than 0.05, the process of factor analysis is applicable.

CASE STUDY

The LCA software, Simapro 4.0, includes a case-coffee machine. In this study, we also took it as the example. The coffee machine consists of 0.1 kg aluminum, 1 kg polystyrene, 0.3 kg steel, and 0.4 kg glass. The manufacturing process includes 0.1 kg aluminum extrusion, 1 kg injection moulding of polystyrene, as well as the 4 MJ energy of the refine of glass. The materials and processes are shown in Fig. 3. The Simapro's database provided all information of inventory analysis of coffee machine.

To present the effect of the incorporation of an indicator system, this case selected three administrative areas in Taiwan as the example. Then, the identical product (coffee machine) was compared under the dissimilar environment regions. Taipei, Changhua County, and Taitung County were chosen. Taipei is the largest city in Taiwan. Changhua County is the traditional agricultural region but also has some manufacture industries. Taitung County is located in the eastern Taiwan and is considered the least-polluted among all administrative areas in Taiwan. The locations of these three regions are presented in Fig. 4. The regions differ significantly in their locations, environmental conditions, even the status of development.

But it should be noticed that there is a supposition: The transfer of pollution between regions was not to be considered in this investigation. Therefore, some global scale issues were excluded in this investigation (e.g., ozone layer depletion).

The weighting values for those regions with more serious environmental problems in this issue are higher. The mean value of Taiwan 22 various administrative areas is the baseline.

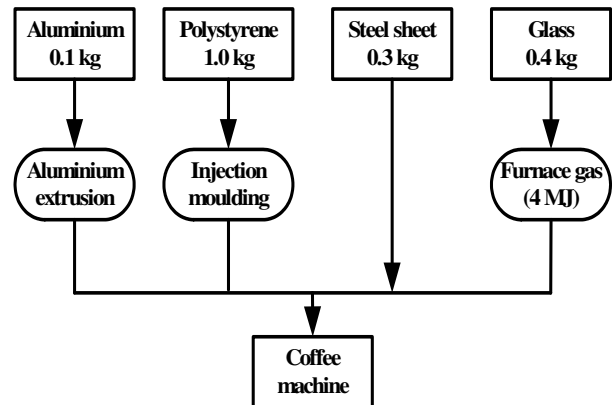


Fig. 3. The materials and processes of coffee machine in this study.

Table 2. The calculating process of weighted environmental impact of heavy metal pollution

	$EL_{heavy\ metal}^a$	Raw data		ECI ^d		W^g	WEI ^h
		A^b	W_{Cd}^c	A_{eq}^e	$W_{cd,eq}^f$		
Taipei city	1.23×10^{-4}	18	9.35×10^{-4}	0.4125	0.2785	0.3455	4.25×10^{-5}
Changhua county	1.23×10^{-4}	534	9.37×10^{-5}	12.24	2.789	7.5133	9.24×10^{-4}
Taitung county	1.23×10^{-4}	1	5.37×10^{-4}	2.291×10^{-2}	0.1599	9.142×10^{-2}	1.12×10^{-5}

^aEnvironmental loading of heavy metal, (drived from LCA software).

^bThe area of heavy metal pollution in level 5 (ha).

^cThe amount of cadmium pollution (kg).

^dEnvironmental conditional indicators

^eThe equivalent of the area of heavy metal pollution in level 5.

^f The equivalent of the amount of cadmium pollution.

^gWeighting factors, W (derived from $ECI_{heavy\ metal}$ by factor analysis).

^hWeighted environmental impact ($EL \times W$).

RESULTS AND DISCUSSION

The original results of conventional LCA methods are shown in Fig. 4. (the row of the original value). "Acidification" and "summer smog" are the highest potential environmental impact among all issues. Eutrophication is estimated the least harmful issue.

But in the conventional LCA method, the spatial variability was not considered. The result only represented the amount of pollution emission, but could not show the degree of environmental damage caused by pollution emission in different regions.

To overcome this defect and get the more meaningful results, combination of the indicator system to reveal the individual environmental condition was adopted in this study. Therefore, the spatial variability was considered in this study. The new frame of valuation led to different results. The estimated results of coffee machine in the three regions are also included in Fig. 4.

It was found that the same environmental loading will cause different environmental impacts (or called WEI in this paper) in different regions. The original value of LCA point was derived from the conventional LCA process. It does not change wherever the environmental loading is occurring. In this investigation, the modified environmental impact based on the individual environmental condition was obtained.

Among the three regions, the environmental impact is higher in Taipei and Changhua County, especially for heavy metals, energy consumption, and air pollution (summer smog and winter smog).

When we reviewed the corresponding indicators of these issues, we could find the correlation among indicators and final WEIs. Take "heavy metal" for example, the LCA points out that metals in Changhua County is much higher than those in others. According the raw data of environmental condition (Table 2), the area of heavy metal pollution in level 5 of Changhua County, was 30 and 534 times higher than in Taipei and Taitung County, respectively. The amount of

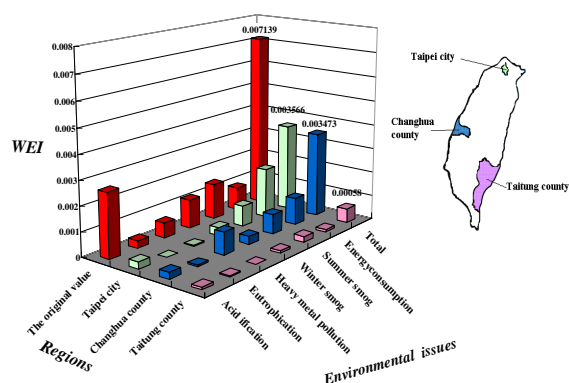


Fig. 4. The estimated results of coffee machine in the three regions.

cadmium pollution in Changhua County was also the greatest.

Thus, because the manufacturing process is the same, the environmental loading of coffee machine is the same in different regions. But the environmental condition are different, the WEI in different regions is distinct (Table 2). The WEI of Changhua County is much higher than others. In the same way, the other WEI of issues could be explained.

Furthermore, when we focus on the total WEI of Taipei, we can find that 57% of the environmental impact in Taipei comes from the energy consumption. Consequently, if the decision is to establish the coffee machine factory in Taipei, reducing the energy consumption should be the first priority for environmental management of production. Similarly, reducing the emission of heavy metal pollution and improving the prevention of air pollution have high priority in Changhua and Taitung, respectively.

CONCLUSIONS

In the conventional LCA method, the spatial variability is not concerned. In other words, the environmental impact is always the same wherever the environmental loading occurs. To modify the unreason-

able process, this study designed an innovative frame to derive the different LCA results when the regional environmental condition is considered.

To reach this goal, this study attempted to combine the environmental conditional indicator system and LCA through factor analysis, a kind of multiple-variable statistic technology. This innovative method could simplify the objective environmental indicator system to one single weight. The case study of coffee machine production revealed the difference between the innovative method and the conventional one. The result showed that the coffee machine production will bring the most environmental impact in Taipei than the other regions in the present environmental condition.

To compare with the past LCA cases applied by weights of European areas, this method could not only obtain different weights in different areas to stress the spatial variation, but also estimate different impact in different time.

Relatively, the modified results could provide more information than the original one. They could indicate what the most potential environmental issues are in different regions, and show the different total environmental impact for regions with the production processes. The results suggest the importance of arranging "green supply chain" in location selection.

But there are still some limits and further works that need to be studied. For example: the transfer of pollution between regions had not been considered; the consideration of economical aspects was not included; and the change with time had not been incorporated.

ACKNOWLEDGMENTS

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 90-2621-Z-002-027.

REFERENCES

1. International Organization for Standardization (ISO), The ISO 14000 Model. <http://www.iso.org/iso/en/prods-services/otherpubs/iso14000/index.html> (Jul. 2006).
2. Finnveden, G., On the limitations of life cycle assessment and environmental system analysis tools in general. *Int. J. Life Cycle Ass.*, 5(4), 229-238 (2000).
3. Society of Environmental Toxicology and Chemistry (SETAC), A Conceptual Framework for Life-cycle Impact Assessment. SETAC Foundation for Environmental Education, Inc., FL, pp. 87-97(1993).
4. Organisation for Economic Co-operation and Development (OECD), OECD Environmental Data. OECD Environment Directorate, France, p. 8 (2002).
5. Goedkoop, M. and M. Oele, User Manual, Introduction into LCA, Methodology and Practice with SimaPro 5. Pre Consultants, The Netherlands, p. 21 (2001).
6. International Organization for Standardization (ISO), ISO 14040, Geneva, Switzerland (1997).
7. International Organization for Standardization (ISO), ISO 14042, Geneva, Switzerland (2000).
8. U.S. EPA, <http://www.epa.gov/Envindicators/abouteei.htm> (Jul. 2006)
9. Ott, W.R., Environmental Indices: Theory and Practice. Ann Arbor Sciences, Ann Arbor, MI (1978).
10. Hair, J.F., R.E. Anderson, R.L. Tatham, and W.C. Black, Multivariate Data Analysis. 4th Ed., Prentice-Hall, Englewood Cliffs, NJ (1995).
11. Comrey A.L. and H.B. Lee, A First Course in Factor Analysis. 2nd Ed., Lawrence Erlbaum Associates, Hillsdale, NJ (1992).
12. Kaiser, H.F., A second generation Little Jiffy. *Psychometrika*, 35(4), 401-415 (1970).

Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-Chief within six months of publication.

Manuscript Received: April 7, 2005
Revision Received: November 14, 2005
and Accepted: November 17, 2005