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Environmental indicators for communication of life cycle impact assessment results and their applications

Seong-Rin Lim[a], Jong Moon Park[b,*]

[a] Department of Chemical Engineering and Materials Science, University of California, Davis, CA 95616, USA
[b] Advanced Environmental Biotechnology Research Center, Department of Chemical Engineering, School of Environmental Science and Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Pohang 790-784, South Korea

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ABSTRACT

Life cycle impact assessment (LCIA) is performed to quantitatively evaluate all environmental impacts from products, systems, processes and services. However, LCIA does not always provide valuable information for choosing among alternatives with different specifications, functionalities and lifetimes. The objectives of this study are (1) to propose environmental indicators to evaluate environmental efficiency and value qualitatively and quantitatively on the basis of analogies to financial and economic indicators, and (2) to present the application of the indicators. Incremental evaluation using a reference is employed to obtain the environmental indicators. The environmental efficiency indicators are conceptually based on the ratios of reduced environmental burdens returned to environmental burdens required: environmental return on investment, environmental payback period and environmental internal rate of return. The environmental value indicator is the sum of all reduced and required environmental burdens: i.e., environmental net present value. All the environmental indicators can be used to compare and rank the environmental efficiencies or values of alternatives. The environmental efficiency indicators can be applied to a new environmental labeling. The concept of eco-efficiency labeling is developed by combining the environmental efficiency indicators with financial indicators. A case study is performed to illustrate the necessity and importance of the environmental indicators. These environmental indicators can help easily communicate LCIA results in the field of environmental management.

1. Introduction

Due to the paradigm shift to sustainable development, the concepts of cleaner production, eco-design and design for environment (DfE) have been employed to improve the environmental and economic performances of products, systems, processes and services. While traditional economic and financial indicators are used to evaluate the economic performances, life cycle assessment (LCA) plays a key role in evaluating the environmental performances. LCA is an environmentally fundamental methodology which is used to comprehensively and quantitatively evaluate the significance of potential environmental impacts and to systematically identify hot spots incurring heavy environmental impacts. LCA is also applied to environmental labeling, which contributes to market-driven continuous environmental improvement by conferring a label on products meeting environmental criteria (Type I environmental labeling) and by publicly declaring the environmental performances of products (Type III environmental labeling: product environmental declaration) (Ardente et al., 2006; Gallastegui, 2002; Lavallee and Plouffe, 2004; Manzini et al., 2006; Mungkung et al., 2006). Therefore, LCA play a pivotal role in environmental management which can be represented by the ISO 14000 series (Lamprecht, 1997).

The limitations of LCA and environmental labeling are often raised in the choice of a more environmentally friendly alternative because making the functional units of alternatives congruous is difficult in comparative assessment. Life cycle impact assessment (LCIA) is performed to evaluate the significance of potential environmental impacts as a process of LCA. However, the LCIA results do not always provide decision makers with valuable and obvious information that is required to make a choice among alternatives: the different specifications, functionalities and lifetimes of alternatives make it difficult to compare and rank their environmental performances (Finnveden, 2000). The functional units of alternatives should be the same for comparing and ranking the LCIA results because LCIA results are the simple sum of environmental burdens incurred throughout the life cycle from a functional unit. However, much resource and time are required in order to make

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* Corresponding author. Tel.: +82 54 279 2275; fax: +82 54 279 8299.
E-mail address: jmpark@postech.ac.kr (J.M. Park).

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the functional units of alternatives congruous because of complicated system interpretation and allocation, even though the ISO standards for LCA are well established. Furthermore, LCIA results do not provide qualitative information on the environmental efficiencies and values of products, processes, systems and services (hereinafter, "environmental efficiency" is defined as "how much environmental burden is reduced at the expense of additional environmental burden required to enhance environmental performance"; and "environmental value" is defined as "how much environmental burden is reduced over all life cycle phases"). Type III labeling has disadvantages derived from the limitations of LCA because Type III labeling employs the characterization results of LCIA for the environmental declaration of products (Ardente et al., 2006; Gallastegui, 2002; Lavallee and Plouffe, 2004; Manzini et al., 2006), and does not provide detailed information needed to make the function units of alternatives congruous. In other words, Type III labeling cannot be used for comparing and ranking alternatives in case the functional units of alternatives are different. Type I labeling also cannot differentiate the environmental performances of products with the environmental label (Ardente et al., 2006; Gallastegui, 2002; Lavallee and Plouffe, 2004; Manzini et al., 2006). Therefore, a new environmental indicator has been required to compare the environmental performances of alternatives and to easily communicate LCIA results.

Some eco-indicators developed with the viewpoint of microecometrics have been proposed to comprehensively estimate the environmental and economic performances (Biswas et al., 1998). Return on environment (ROE) was suggested as an objective indicator to show economic returns on environmental burdens incurred from products (Hunkeler and Biswas, 2000). An eco-costs/value ratio model was developed to describe the eco-efficiency of products and services (Vogtlander et al., 2002). The ratios of environmental effect scores to a life cycle cost were used as Environmental Efficiency (EE) for DfE (Schmidt, 2003). A green productivity (GP) index was proposed to measure the ratio of productivity to environmental impacts (Hur et al., 2004). CO_2 efficiency was defined as a ratio of a producer's price to CO_2 emissions to characterize various industries (Tahara et al., 2005). Sustainable development indicators (SDIs) for sludge handling and wastewater treatment systems were formulated to reflect economic, environmental, technical and societal aspects (Palme et al., 2005). A product sustainability index was used to translate sustainability aspects in vehicle development (Schmidt and Butt, 2006). However, environmental indicators which focus only on environmental performance have not been developed, even though the environmental effect scores from the results of LCIA have been employed to estimate environmental performance. Therefore, qualitative and quantitative environmental indicators have been required to evaluate environmental performance.

The objective of this study is (1) to propose environmental indicators to evaluate, differentiate and easily communicate the environmental efficiencies or values of products, systems, processes and services, and (2) to present the applications of the indicators. The environmental indicators are presented on the basis of analogies to financial and economic indicators: environmental return on investment (EROI), environmental net present value (ENPV), environmental payback period (EPP) and environmental internal rate of return (EIRR). The main application of the environmental indicators is presented: communication of qualitative and quantitative information on environmental performance, and comparative evaluation of alternatives. The extended application of the environmental indicators is also examined: new environmental labeling for differentiating environmental performances of products, and development of eco-efficiency labeling. A case study is performed on the environmental evaluation of alternative water systems with different system boundaries for LCA to illustrate the necessities and importance for the environmental indicators.

2. Environmental indicators

The proposed environmental indicators are conceptually based on traditional economic and financial evaluation. Table 1 shows the analogy between the environmental indicators and economic and financial indicators. The environmental efficiency indicators (i.e., EROI, EPP and EIRR) are developed to estimate the reduced environmental burdens returned on the additional environmental burdens required to enhance environmental performance, in the same manner as the financial indicators (i.e., ROI, PP and IRR) estimate economic profits returned on investment costs. The environmental value indicator (i.e., ENPV) is conceptually based on how much net environmental burden is incurred during the life cycle with respect to all the reduced and additional environmental burdens, as economic indicators such as NPV evaluate net profits by comparing costs and revenues. Therefore, the environmental indicators have qualitative as well as quantitative information, which can augment LCIA results and LCA. Also, the environmental indicators can be used as goals and criteria in designing and producing more environmentally efficient and valuable products, systems, processes and services.

Incremental evaluation is used for the environmental indicators to compare and rank the environmental performances of alternatives. The environmental burdens of products, systems, processes and services are expressed with environmental effect scores obtained from the characterization results of LCIA. However, the environmental efficiencies and values of alternatives are not always differentiated with the environmental effect scores because of their different specifications, functionalities and lifetimes. Therefore, incremental evaluation is required in order to compare the environmental performances of alternatives. This incremental approach can be applied to rank mutually exclusive products, systems, processes and services (for example, an air conditioner and a refrigerator), or to rank mutually exclusive alternatives of the same product, system, process and service (for example, "A" and "B" branded cars) (Hajdasinski, 2004). The environmental indicators are calculated by using incremental environmental burdens which are the difference between the environmental effect scores of an alternative estimated and those of a reference. The incremental environmental burdens are incurred over total life cycle phases such as production or construction, use or operations and maintenance (O&M), and disposal. The flow of the incremental environmental burdens over the lifetime is defined as an incremental environmental effect flow (IEEF), in the same way as cash flow is used for financial and economic evaluation. Equations for the IEEF in each life cycle phase are as follows:

$$\mathrm{IEEF}_c^{pro} = E_{alt,c}^{pro} - E_{ref,c}^{pro} \tag{1}$$

$$\mathrm{IEEF}_c^{use,dis} = E_{alt,c}^{use,dis} - E_{ref,c}^{use,dis} \tag{2}$$

where $E_{alt,c}$ and $E_{ref,c}$ are the environmental effect scores of an alternative estimated and a reference obtained from the characterization results of the LCIA, respectively, and c represents each environmental impact category. Superscripts *pro*, *use* and *dis* represent the life cycle phases: production, use and disposal.

The reference used to calculate the IEEF for the environmental efficiency indicators is limited to the alternative which generates the lowest environmental burdens in the production stage and the highest ones in the use phase among alternatives. If the IEEF of a product in the production stage is negative, the environmental

Table 1
Analogy between the economic and financial indicators and the environmental indicators.

Economic and financial indicators (Hajdasinski, 2004; Peters and Timmerhaus, 1991; Pintaric and Kravanja, 2006; Tang and Tang, 2003)		Proposed environmental indicators
Return on investment (ROI)	- A ratio of profits before taxes to total capital investment costs - Financial indicator	Environmental return on investment (EROI)
Net present value (NPV)	- The sum of the present values of all cash flows over the life cycle - Economic indicator	Environmental net present value (ENPV)
Payback period (PP)	- A time period required to pay off initial capital investment costs with profits returned - Financial indicator	Environmental payback period (EPP)
Internal rate of return (IRR)	- A discount rate at which the NPV of a project is equal to zero - Financial indicator	Environmental internal rate of return (EIRR)

efficiency indicators cannot be evaluated because the indicators mean how much environmental benefit can be obtained on an investment of environmental burdens, i.e., environmental sacrifice. In contrast, the reference for the environmental value indicator is unlimited because the environmental value indicator represents the net environmental burdens of an alternative, i.e., the sum of the IEEFs in the life cycle stages. With increasing application of cleaner production, eco-design, DfE, and environmental labeling to products, systems, processes and services, the most conventional and old-model alternative can be employed as the reference for the environmental efficiency indicators. This is because new alternatives are improved to enhance consumption efficiencies for resources and energy in the use phase incurring the heaviest environmental burdens, while in the production phase, more resource and energy are required to increase their functionalities and efficiencies; however, there can be exceptions not to meet the conditions needed to be the reference. The buildup of database on the LCIA results of products, systems, processes and services enables choosing the reference of a given category for the environmental efficiency indicators. It should be mentioned that the financial indicators analogous to the environmental efficiency indicators are useful for the economic evaluation of alternatives despite the same limitation on choosing a reference.

A discount rate is employed to evaluate the environmental indicators by taking into consideration the time values of environmental burdens. This is because many feasibility estimations of projects and policies having environmental and societal effects have used the discount rates in line with ecological and environmental economics, even though discounting environmental burdens is still controversial (Spitzley et al., 2005). A two-step discounting procedure has been proposed to estimate environmental projects by selecting different discount rates for short and long terms (Rabl, 1996). Dual-rate discounting has been suggested in dynamic economic and environmental modeling by employing an economic discount rate for private cash flows and by selecting a lower environmental discount rate for environmental cash flows (Yang, 2003; Weikard and Zhu, 2005). Discount rates used in environmental evaluations were lower than ones used in economic evaluations (Rambaud and Torrecillas, 2005).

2.1. Environmental return on investment

The EROI is defined as a ratio of the reduced environmental burdens occurring over the service life to the additional environmental burdens initially required to enhance environmental performance. This indicator can be used as an environmental efficiency indicator. When the additional environmental burdens in the production phase are incurred at year 0 and the reduced environmental burdens in the use and disposal phases occur regularly at the end of each year, an equation for the EROI is as follows:

$$\mathrm{EROI}_c = -\frac{\sum_{t=1}^{n} \frac{\mathrm{IEEF}_{c,t}^{use,dis}}{(1+r)^n}}{\mathrm{IEEF}_{c,t=0}^{pro}} \tag{3}$$

where r is a discount rate and t is a discrete time over the service life, and n is the service life. The greater the EROI is, the more environmentally efficient the alternative is. The choice of a discount rate should be significantly taken into account because the value of a discount rate can have significant effect on the EROI, even though the appropriate value of a discount rate is still controversial (Spitzley et al., 2005).

2.2. Environmental net present value

The ENPV is defined as the arithmetic sum of discounted IEEFs throughout the life cycle. This indicator can be used as an environmental value indicator to determine which alternative can reduce more environmental burdens. When the additional environmental burdens in the production phase are incurred at year 0 and the reduced environmental burdens from the use and disposal phases occur regularly at the end of each year, an equation for the ENPV is as follows:

$$\mathrm{ENPV}_c = \sum_{t=1}^{n} \frac{\mathrm{IEEF}_{c,t}^{use,dis}}{(1+r)^n} + \mathrm{IEEF}_{c,t=0}^{pro} \tag{4}$$

A negative ENPV means that an alternative is more environmentally valuable than a reference, because the reduced environmental burdens are expressed as a negative IEEF. The smaller the ENPV is, the less environmental burdens from the choice of the alternative are.

2.3. Environmental payback period

The EPP is defined as the period of time required to pay off the environmental burdens incurred with the environmental burdens reduced from the choice of an alternative. The EPP is obtained from equation (4) when the ENPV is set to zero and the discount rate is given. An alternative with a shorter EPP is preferred, in order to earlier offset the additional environmental burdens. This indicator can be used to evaluate the environmental efficiencies of alternatives. However, the comparison of alternatives by using their EPPs does not always guarantee the choice of the most environmentally efficient alternative because the indicator does not take into account IEEFs after the payback. In other words, this indicator does not include all the additional and reduced environmental burdens throughout the life cycle.

2.4. Environmental internal rate of return

The EIRR is defined as a discount rate at which the ENPV is equal to zero. The EIRR is obtained from equation (4) when the ENPV is set to zero and the service life is given. The EIRR should be higher than a discount rate used for environmental evaluation to show that an alternative is more environmentally efficient than the reference. The greater the EIRR is, the more environmentally efficient the alternative is. This indicator can be used as an environmental efficiency indicator.

3. Main application of the environmental indicators

The environmental indicators can be used for (1) providing qualitative and quantitative information on environmental performance, and (2) comparing and ranking the environmental performances of alternatives with different specifications, functionalities and lifetimes.

3.1. Communication of qualitative and quantitative information

The environmental indicators can be used to easily communicate LCIA results because the indicators include qualitative and quantitative information, i.e., environmental efficiency and value. The environmental indicators have essential characteristics which LCIA results and environmental labeling (Type I or III) lack: simplicity, comparability, quality, quantity and easy communicability. These characteristics of the environmental indicators can be supported by their analogies to traditional financial and economic indicators and will be shown in the case study.

3.2. Comparative evaluation of alternatives

The environmental indicators can be used to compare and rank the environmental efficiency or value of alternatives with different specifications, functionalities and lifetimes. The environmental indicators are useful and practical in case comparative LCA requires too much resource and time in making the functional units of alternatives congruous because of complicated system interpretation and allocation, or in case obtaining the same functional unit is impossible because of the completely different characteristics of alternatives. In other words, the environmental indicators can differentiate the environmental performances of mutually exclusive products, systems, processes, services, projects and policies, as well as mutually exclusive alternatives of the same product, system, process, project and policy because the environmental indicators mean how much incremental environmental benefit can be obtained from investment on an alternative, i.e., incremental environmental burdens, regardless of functional units and system boundaries. Normalization and weighting can be used to integrate and simplify the environmental indicators in environmental impact categories by using the reference values and weighting factors established in the field of LCA; the methods for the EROI, EPP and EIRR are suggested in the following section, while the normalization and weighting for the ENPV can be performed by dividing by reference values, multiplying by weighting factors and summing because the ENPV is expressed as in the characterization results of LCIA. It should be mentioned that the choice of different sets of weighting factors and reference values can have effects on the absolute values of the environmental indicators and result in a different ranking of alternatives.

4. Extended application of the environmental indicators

The application of the environmental indicators can be extended to (1) new environmental labeling for differentiating environmental performances of products, and (2) development of eco-efficiency labeling.

4.1. New environmental labeling for differentiating environmental performances of products

The environmental efficiency indicators can be applied to new environmental labeling which can compare and rank the environmental performances of products. The concept of the new labeling is extended from the environmental evaluation of alternatives. In other words, the environmental performances of products can be ranked by comparing the values of the environmental efficiency indicators on their labels which are ratios of the reduced environmental burdens obtained from the choice of the product to the additional environmental burdens required for the choice of the product. Once a reference is identified to evaluate the environmental efficiencies of other products in the same product category, the EROI, EPP and EIRR can quantify the environmental efficiencies of the other products, and can provide valuable information required to select the most environmentally efficient one.

The evaluation of the environmental efficiency indicators for the new environmental labeling is used as a substitute for the normalization in LCIA. In other words, the environmental efficiency indicators obtained using the characterization results of the LCIA are the normalized results, because the concept of the environmental efficiency indicators is a ratio of reduced environmental burdens to the additional environmental burdens required to enhance environmental performance. This is reasonable, because the aim of the normalization is to better understand the relative importance and magnitude of the characterization results (Guinee, 2001). This characteristic of the environmental efficiency indicators can avoid confusion incurred in choosing reference information required to normalize the characterization results of products for international trade (Mungkung et al., 2006; Finnveden, 2000): the normalization reference is generally based on a given country (Guinee, 2001).

A weighted average method is employed for the new environmental labeling in order to aggregate and simplify the environmental efficiency indicators in environmental impact categories. Single indicators are obtained from the weighted average of each of EROI_c, EPP_c and EIRR_c by taking into account the relative importance of the environmental impact categories and the characteristics of the environmental efficiency indicators, i.e., ratios. Equations for the single indicators are as follows:

$$\text{EROI}_w = \sum_{c=1}^{n}\left[\text{EROI}_c\cdot\left(w_c/w^t\right)\right] \tag{5}$$

$$\text{EPP}_w = \sum_{c=1}^{n}\left[\text{EPP}_c\cdot\left(w_c/w^t\right)\right] \tag{6}$$

$$\text{EIRR}_w = \sum_{c=1}^{n}\left[\text{EIRR}_c\cdot\left(w_c/w^t\right)\right] \tag{7}$$

where w_c is a weighting factor for each environmental impact category and w^t is the sum of all the weighting factors. The weighting factors can be the same as used for weighting in LCIA. The single indicators obtained from the above equations are still quantitative and qualitative, and they can be used to compare and rank the environmental efficiencies of products. The new environmental labeling using these single indicators could accelerate market-driven continuous environmental improvement. Furthermore, these single indicators can be applied to supplement Type I and Type III environmental labeling. These single indicators could give comparability and quantification to Type I environmental labeling to help differentiate the efficiencies of environmental friendly products and could confer simplicity, easy communicability and comparability to Type III environmental labeling.

4.2. Development of eco-efficiency labeling

The environmental efficiency indicators could also be applied to develop eco-efficiency labeling to classify products on the basis of their environmental and economic performances. This eco-efficiency labeling is conceptually similar to Type I environmental labeling. To estimate the eco-efficiency of a product, one of the environmental efficiency indicators is combined with one of the financial indicators showing its economic efficiency: EROI vs. ROI, EPP vs. PP, or EIRR vs. IRR. The environmental efficiency and financial indicators are based on incremental evaluation using a reference product to compare and rank products in the same product category. Fig. 1 shows the concept of the eco-efficiency labeling and a portfolio where products are classified by their environmental efficiency and financial indicators; for instance, the eco-efficiency levels of products can be classified into the three parts with differently shaded colors. The eco-efficiency labeling employs the environmental and financial indicators independently, rather than integrating them into a new single indicator. This is because it is difficult to objectively evaluate the relative importance of the environmental and economic efficiencies. Many data on the environmental efficiency and financial indicators of products in the same product category are needed to classify their eco-efficiency levels. The interfaces between the different eco-efficiency levels are inversely plotted because of tradeoffs between environmental and economic efficiencies. More eco-efficient products are positioned on top right in the portfolio. The "minimum values" in Fig. 1 are criteria required to be environmentally or economically efficient products; for example, the EROI and ROI should be greater than 1, and the EIRR and IRR should be higher than discount rates required, which means that the choice of an alternative can obtain environmental benefits greater than environmental burdens additionally required. Therefore, the eco-efficiency labeling can differentiate the eco-efficiency levels of products, systems, processes and services to help non-experts purchase more eco-efficient ones.

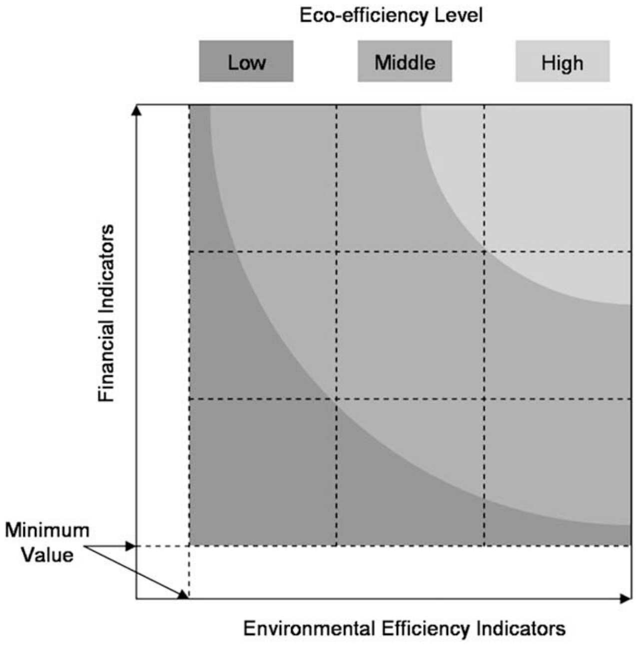

Fig. 1. Eco-efficiency portfolio for the eco-efficiency labeling.

5. Case study

The proposed qualitative and quantitative indicators were employed to compare the environmental efficiencies and values of alternative water systems with different system boundaries. An iron and steel plant in Korea needs to determine which alternative water network system design using water reuse (WNS 1 or WNS 2) is more environmentally efficient and valuable (detailed design methods are presented in Supplementary data). The same functional units for alternative comparison cannot be easily obtained because of their complex systems. The water network systems are composed of different combinations of water-using operations; for instance, WNS 1 uses the operations 1, 2, 3 and 4, while WNS 2 uses the operations 1, 3, 4 and 5. To evaluate the environmental indicators, a conventional water system (CWS) using only freshwater was employed as the reference: CWS uses the operations 1, 2, 3 and 4. The three systems are depicted in Fig. 2. LCA was performed to evaluate the environmental burdens, i.e., LCIA results, of each water system, which followed the ISO 14040 series of standards as in the study (Lim and Park, 2007).

The characterization results of LCIA performed to evaluate total environmental burdens from each water system did not provide enough information to determine which system was more environmentally efficient or valuable. The characterization results of the LCIA are presented in Table 2. It should be noted that the environmental performances of WNS 2 cannot be compared to those of WNS 1 because of their different system boundaries for the LCA, even though normalization and weighting are employed for the LCIA to easily compare the characterization results in the environmental impact categories. Even LCA experts cannot select more environmentally efficient system using these results.

The proposed environmental efficiency indicators differentiated the environmental performances of the alternative water systems. The environmental efficiency indicators of WNS 1 and WNS 2 are summarized in Table 3. CWS was used as a reference for the incremental evaluation because it had the lowest environmental burdens in the construction phase and the highest in the O&M phases. The discount rates were set to zero or 1.5% to estimate the effects of discount rates on the environmental indicators (Rabl, 1996). The weighting factors and normalization reference values for Korea were obtained from the literature (Hur et al., 2004; IKP and PE Europe GMBH, 2004). EROI, EPP and EIRR showed consistent results for the comparison of the environmental efficiencies of the two water network systems. The $EROI_c$ and $EIRR_c$ in all environmental impact categories and their weighted averages of WNS 1 were greater than those of WNS 2, and the EPP_c in all environmental impact categories and their weighted average of WNS 1 was less than those of WNS 2, regardless of the discount rates. As a result, WNS 1 was more environmentally efficient than WNS 2. This was because WNS 1 reduced more environmental burdens in the O&M stage than WNS 2 at the expense of the same amount of additional environmental burdens in the construction stage. The weighted averages of the $EROI_c$, EPP_c and $EIRR_c$ as single indicators showed their simplicity, quantification, easy communication and comparability, which is also required for the new environmental and eco-efficiency labeling and for compensating for the weakness of Type I or III environmental labeling.

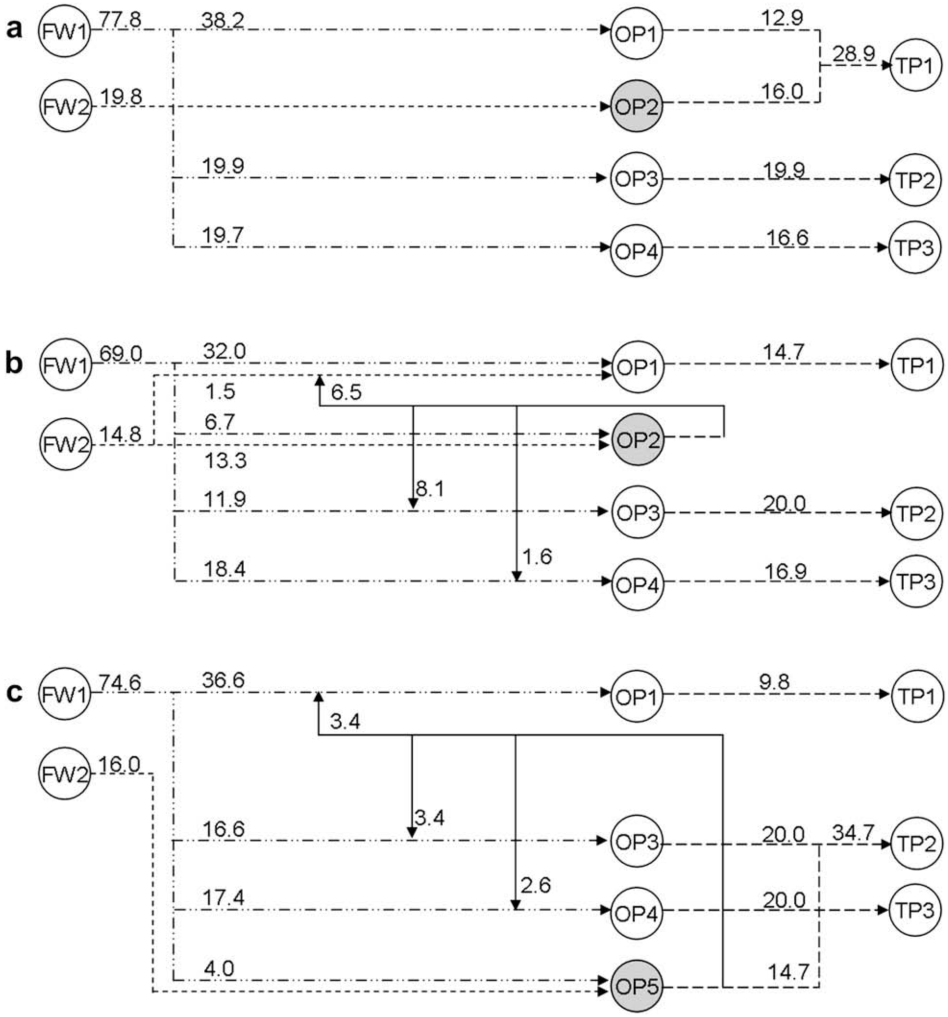

Fig. 2. Water systems: (a) conventional water system (CWS); (b) water network system using the operations 1, 2, 3 and 4 (WNS 1); and (c) water network system using the operations 1, 3, 4 and 5 (WNS 2). Industrial water (FW1) and deionized water (FW2) are supplied to water-using operations for production. Wastewater from operations is discharged to local wastewater treatment plants or is supplied to operations for water reuse in case the wastewater quality meets the water quality requirement for the operations (FW: Freshwater, OP: Water-using operation, TP: Local wastewater treatment plant, the values represent the flowrates of freshwater or wastewater (unit: m^3/hr)).

The environmental value indicators showed which system could reduce more environmental burdens. The environmental value indicators of WNS 1 and WNS 2 are summarized in Table 3. All the $ENPV_c$ values were negative, indicating that the two water network systems could reduce environmental burdens during their life cycle by displacing CWS. The $ENPV_c$ in the environmental impact categories did not provide consistent results for the comparison of the water network systems. The $ENPV_c$ of WNS 2 in the ADP, GWP,

Table 2
Characterization results of the conventional water system (CWS) and water network systems (WNS 1 and WNS 2) in LCIA (ADP: abiotic depletion potential [kg Sb-equivalents]; AP: acidification potential [kg SO_2-equivalents]; EP: eutrophication potential [kg phosphate-equivalents]; FAETP: freshwater aquatic ecotoxicity potential [kg DCB-equivalents]; GWP: global warming potential (100 years) [kg CO_2-equivalents]; HTP: human toxicity potential [kg DCB-equivalents]; MAETP: marine aquatic ecotoxicity potential [kg DCB-equivalents]; OLDP: ozone layer depletion potential (steady state) [kg R11-equivalents]; POCP: photochemical ozone creation potential [kg ethene-equivalents]; TETP: terrestrial ecotoxicity potential [kg DCB-equivalents]; DCB: 1,4 dichlorobenzene).

	Life cycle stage	ADP	AP	EP	FAETP	GWP	HTP	MAETP	OLDP	POCP	TETP
CWS	Construction	3.24E+02	1.82E+02	4.51E+01	2.06E+04	4.35E+04	1.32E+05	2.44E+07	4.03E-03	4.59E+01	3.20E+02
	O&M	4.82E+04	3.51E+04	5.36E+03	1.28E+06	9.07E+06	5.55E+06	4.36E+09	1.82E+00	3.45E+03	1.01E+05
	Disposal	1.04E+03	4.87E+02	4.07E+01	4.59E+04	1.11E+05	6.77E+04	3.96E+07	7.79E-03	7.30E+01	3.64E+01
	Total	4.96E+04	3.58E+04	5.45E+03	1.35E+06	9.22E+06	5.75E+06	4.42E+09	1.83E+00	3.57E+03	1.01E+05
WNS 1	Construction	3.45E+02	1.96E+02	4.88E+01	2.18E+04	4.66E+04	1.40E+05	2.58E+07	4.28E-03	4.87E+01	3.40E+02
	O&M	4.71E+04	3.13E+04	4.70E+03	1.17E+06	8.70E+06	5.05E+06	4.17E+09	1.42E+00	3.08E+03	9.90E+04
	Disposal	1.10E+03	5.18E+02	4.32E+01	5.82E+04	1.17E+05	7.16E+04	4.38E+07	8.25E-03	7.73E+01	3.86E+01
	Total	4.85E+04	3.20E+04	4.79E+03	1.25E+06	8.86E+06	5.26E+06	4.24E+09	1.43E+00	3.21E+03	9.94E+04
WNS 2	Construction	4.59E+02	2.55E+02	6.14E+01	2.93E+04	6.08E+04	1.88E+05	3.46E+07	5.70E-03	6.50E+01	4.54E+02
	O&M	4.61E+04	3.25E+04	4.96E+03	1.20E+06	8.58E+06	5.20E+06	4.14E+09	1.52E+00	3.21E+03	9.58E+04
	Disposal	1.48E+03	6.92E+02	5.73E+01	6.06E+04	1.57E+05	9.64E+04	5.53E+07	1.11E-02	1.04E+02	5.14E+01
	Total	4.80E+04	3.34E+04	5.08E+03	1.29E+06	8.80E+06	5.48E+06	4.23E+09	1.54E+00	3.38E+03	9.63E+04

Table 3

Evaluation of the environmental indicators for the conventional water system (CWS) and water network systems (WNS 1 and WNS 2) (EROI: Environmental Return on Investment; ENPV: Environmental Net Present Value; EPP: Environmental Payback Period; EIRR: Environmental Internal Rate of Return; r: Discount rate, ADP: Abiotic Depletion Potential [kg Sb-equivalents]; AP: Acidification Potential [kg SO_2-equivalents]; EP: Eutrophication Potential [kg Phosphate-equivalents]; FAETP : Freshwater Aquatic Ecotoxicity Potential [kg DCB-equivalents]; GWP : Global Warming Potential (100 years) [kg CO_2-equivalents]; HTP: Human Toxicity Potential [kg DCB-equivalents]; MAETP: Marine Aquatic Ecotoxicity Potential [kg DCB-equivalents]; OLDP : Ozone Layer Depletion Potential (steady state) [kg R11-equivalents]; POCP: Photochemical Ozone Creation Potential [kg Ethene-equivalents]; TETP: Terrestrial Ecotoxicity Potential [kg DCB-equivalents]; DCB: 1, 4 dichlorobenzene).

			ADP	AP	EP	FAETP	GWP	HTP	MAETP	OLDP	POCP	TETP	Weighting Results
Weighting Factor (Hur et al., 2004)			2.42E-01	6.40E-02	6.00E-02	9.90E-02	2.11E-01	1.05E-01	9.90E-02	1.72E-01	4.70E-02	9.90E-02	-
Normalization Reference Value (IKP and PE Europe GMBH, 2004)			2.14E+09	4.04E+09	1.77E+09	4.24E+10	6.32E+11	8.14E+11	1E+13	8641781	8.06E+08	4.69E+09	-
EROI	r = 0	WNS 1	50	269	178	81	117	62	133	1598	131	100	382
		WNS 2	12	33	24	8	26	6	20	178	11	39	50
	r = 0.015	WNS 1	44	240	158	73	105	55	118	1422	116	89	340
		WNS 2	11	29	21	7	23	5	18	158	10	34	45
ENPV	r = 0	WNS 1	-1.02E+03	-3.76E+03	-6.54E+02	-9.65E+04	-3.61E+05	-4.88E+05	-1.84E+08	-3.99E-01	-3.63E+02	-1.98E+03	-2.49E-06
		WNS 2	-1.53E+03	-2.32E+03	-3.67E+02	-5.66E+04	-4.27E+05	-2.65E+05	-1.94E+08	-2.95E-01	-1.90E+02	-5.05E+03	-2.57E-06
	r = 0.015	WNS 1	-9.10E+02	-3.34E+03	-5.81E+02	-8.68E+04	-3.21E+05	-4.34E+05	-1.64E+08	-3.55E-01	-3.23E+02	-1.76E+03	-2.22E-06
		WNS 2	-1.38E+03	-2.08E+03	-3.26E+02	-5.07E+04	-3.82E+05	-2.32E+05	-1.73E+08	-2.63E-01	-1.70E+02	-4.48E+03	-2.29E-06
EPP	r = 0	WNS 1	0.29	0.06	0.08	0.16	0.13	0.24	0.11	0.01	0.11	0.15	0.17
		WNS 2	0.96	0.42	0.61	1.63	0.53	2.40	0.70	0.08	1.19	0.39	0.98
	r = 0.015	WNS 1	0.29	0.06	0.09	0.17	0.13	0.24	0.11	0.01	0.12	0.15	0.18
		WNS 2	0.98	0.43	0.62	1.66	0.54	2.44	0.71	0.08	1.21	0.39	1.00
EIRR (%)		WNS 1	349	1810	1189	611	796	417	905	10667	881	667	2569
		WNS 2	104	237	164	61	189	41	144	1198	84	259	348

MAETP and TETP categories were less than those of WNS 1 while those of WNS 2 in the other categories were greater than those of WNS 1. When the $ENPV_c$ were normalized and weighted to obtain single indicators, WNS 2 was found to be able to reduce greater environmental burdens throughout the life cycle. Therefore, it should be noted that the ENPV was suitable for evaluating the absolute amount of the environmental burdens reduced during the life cycle.

6. Conclusions

The environmental indicators enable easy communication of LCIA results without respect to the specifications, functionalities and lifetimes of alternatives and so can improve and augment LCA which has limitation on the difficult interpretation of LCIA results. The environmental indicators can be evaluated from diverse LCIA methods, even though the LCIA methods can differently affect the absolute values of the environmental indicators on the basis of inherent characteristics of impact assessment methodologies. The environmental indicators can help consumers, manufacturers, designers and managers easily choose more environmentally efficient products, systems, processes and services and can be employed for the new environmental or eco-efficiency labeling. Therefore, the environmental indicators can contribute to the environmental management represented by the ISO 14000 series including the ISO 14040s (life cycle assessment), ISO 14062 (design for environment), the ISO 14020s (environmental labels and declarations), ISO 14063 (environmental communication) and the ISO 14030s (environmental performance evaluation).

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.jenvman.2009.05.003.

References

Ardente, F., Beccali, G., Cellura, M., 2006. POEMS: a case study of an Italian wine-producing firm. Environmental Management 38, 350–364.

Biswas, G., Clift, R., Davis, G., Ehrenfeld, J., Forster, R., Jolliet, O., Knoepfel, I., Luterbacher, U., Russell, D., Hunkeler, D., 1998. Ecometrics. International Journal of Life Cycle Assessment 4, 184–190.

Finnveden, G., 2000. On the limitations of life cycle assessment and environmental systems analysis tools in general. International Journal of Life Cycle Assessment 5, 229–238.

Gallastegui, I.G., 2002. The use of eco-labels: a review of the literature. European Environment 12, 316–331.

Guinee, I., 2001. Life Cycle Assessment: an Operational Guide to the ISO Standards; LCA in Perspective; Guide; Operations Annex to Guide. Center for Environmental Science, Leiden University, The Netherlands.

Hajdasinski, M.M., 2004. The internal rate of return (IRR) as a financial indicator. Engineering Economist 49, 185–197.

Hunkeler, D., Biswas, G., 2000. Return on environment. International Journal of Life Cycle Assessment 6, 358–362.

Hur, T., Kim, I., Yamamoto, R., 2004. Measurement of green productivity and its improvement. Journal of Cleaner Production 12, 673–683.

IKP and PE Europe GMBH, 2004. Gabi 4.0.

Lamprecht. J.L., 1997. ISO 14000 Issues & Implementation Guidelines for Responsible Environmental Management, New York.

Lavallee, S., Plouffe, S., 2004. The ecolabel and sustainable development. International Journal of Life Cycle Assessment 9, 349–354.

Lim, S.-R., Park, J.M., 2007. Environmental and economic analysis of a water network system using LCA and LCC. AIChE Journal 53, 3253–3262.

Manzini, R., Noci, G., Ostinelli, M., Pizzurno, E., 2006. Assessing environmental product declaration opportunities: a reference framework. Business Strategy and the Environment 15, 118–134.

Mungkung, R.T., Haes, H., Clift, R., 2006. Potentials and limitations of life cycle assessment in setting ecolabeling criteria: a case study of Thai shrimp aquaculture product. International Journal of Life Cycle Assessment 11, 55–59.

Palme, U., Lundin, M., Tillman, A., Molander, S., 2005. Sustainable development indicators for wastewater systems – researchers and indicator users in a co-operative case study. Resources, Conservation and Recycling 43, 293–311.

Peters, M.S., Timmerhaus, K.D., 1991. Plant Design and Economics for Chemical Engineers. McGraw-Hill, New York.

Pintaric, Z.N., Kravanja, Z., 2006. Selection of the economic objective function for the optimization of process flow sheets. Industrial and Engineering Chemistry Research 45, 4222–4232.

Rabl, A., 1996. Discounting of long-term costs: what would future generations prefer us to do. Ecological Economics 17, 137–145.

Rambaud, S.C., Torrecillas, M., 2005. Some considerations on the social discount rate. Environmental Science and Policy 8, 343–355.

Schmidt, W.P., 2003. Life cycle costing as part of design for environment. International Journal of Life Cycle Assessment 8, 167–174.

Schmidt, W.P., Butt, F., 2006. Life cycle tools within Ford of Europe's product sustainability index. International Journal of Life Cycle Assesssment 11, 315–322.

Spitzley, D.V., Grande, D.E., Keoleian, G.A., Kim, H.C., 2005. Life cycle optimization of ownership costs and emissions reduction in US vehicle retirement decisions. Transportation Research. Part D: Transport and Environment 10, 161–175.

Tahara, K., Sagisaka, M., Ozawa, T., Yamaguchi, K., Inaba, A., 2005. Comparison of "CO2 efficiency" between company and industry. Journal of Cleaner Production 13, 1301–1308.

Tang, S.L., Tang, H.J., 2003. The variable financial indicator IRR and the constant economic indicator NPV. Engineering Economist 48, 69–78.

Vogtlander, J.G., Bijma, A., Brezet, H.C., 2002. Communicating the eco-efficiency of products and services by means of the eco-costs/value model. Journal of Cleaner Production 10, 57–67.

Weikard, H.-P., Zhu, X., 2005. Discounting and environmental quality: when should dual rates be used. Economic Modelling 22, 868–878.

Yang, Z., 2003. Dual-rate discounting in dynamic economic environmental modeling. Economic Modelling 20, 941–957.