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UNCERTAINTIES IN LCA • METHODOLOGY

# Quantifying system uncertainty of life cycle assessment based on Monte Carlo simulation

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**Abstract**
*Background, aim, and scope* Many studies evaluate the results of applying different life cycle impact assessment (LCIA) methods to the same life cycle inventory (LCI) data and demonstrate that the assessment results would be different with different LICA methods used. Although the importance of uncertainty is recognized, most studies focus on individual stages of LCA, such as LCI and normalization and weighting stages of LCIA. However, an important question has not been answered in previous studies: Which part of the LCA processes will lead to the primary uncertainty? The understanding of the uncertainty contributions of each of the LCA components will facilitate the improvement of the credibility of LCA.
*Methodology* A methodology is proposed to systematically analyze the uncertainties involved in the entire procedure of LCA. The Monte Carlo simulation is used to analyze the uncertainties associated with LCI, LCIA, and the normalization and weighting processes. Five LCIA methods are considered in this study, i.e., Eco-indicator 99, EDIP, EPS, IMPACT 2002+, and LIME. The uncertainty of the environmental performance for individual impact categories (e.g., global warming, ecotoxicity, acidification, eutrophication, photochemical smog, human health) is also calculated and compared. The LCA of municipal solid waste management strategies in Taiwan is used as a case study to illustrate the proposed methodology.
*Results* The primary uncertainty source in the case study is the LCI stage under a given LCIA method. In comparison with various LCIA methods, EDIP has the highest uncertainty and Eco-indicator 99 the lowest uncertainty. Setting aside the uncertainty caused by LCI, the weighting step has higher uncertainty than the normalization step when Eco-indicator 99 is used. Comparing the uncertainty of various impact categories, the lowest is global warming, followed by eutrophication. Ecotoxicity, human health, and photochemical smog have higher uncertainty.
*Discussion* In this case study of municipal waste management, it is confirmed that different LCIA methods would generate different assessment results. In other words, selection of LCIA methods is an important source of uncertainty. In this study, the impacts of human health, ecotoxicity, and photochemical smog can vary a lot when the uncertainties of LCI and LCIA procedures are considered. For the purpose of reducing the errors of impact estimation because of geographic differences, it is important to determine whether and which modifications of assessment of impact categories based on local conditions are necessary.
*Conclusions* This study develops a methodology of systematically evaluating the uncertainties involved in the entire LCA procedure to identify the contributions of different assessment stages to the overall uncertainty. Which modifications of the assessment of impact categories are needed can be determined based on the comparison of uncertainty of impact categories.
*Recommendations and perspectives* Such an assessment of the system uncertainty of LCA will facilitate the improvement of LCA. If the main source of uncertainty is the LCI stage, the researchers should focus on the data quality of the LCI data. If the primary source of uncertainty is the LCIA stage, direct application of LCIA to non-LCIA software developing nations should be avoided.

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## 1 Background, aim, and scope

Uncertainty is one of the important issues of life cycle assessment (LCA). In the literature, some studies have reviewed the definition, classification, and source of uncertainty in LCA and have also explored how to deal with the uncertainty (Bjorklund 2002; Ross et al. 2002). Most studies were focused on individual stages of LCA, such as life cycle inventory (LCI), and normalization and weighting of life cycle impact assessment (LCIA), especially on LCI (Huijbregts et al. 2001; Andrae et al. 2004; Sugiyama et al. 2005; von Bahr and Steen 2004). Most of these studies considered data quality of LCI, including establishment of a data quality indicator by qualitative criteria (Weidema and Wesnaes 1996). Frischknecht et al. (2005) further transformed the qualitative criteria into statistical distributions. Besides, some studies discussed the results of impact categories affected by the uncertainty of LCI, and uncertainty factors were usually used to represent the degree of uncertainty (Geisler et al. 2005). ISO 14040 (ISO 14040 2006) and ISO 14044 (ISO 14044 2006) mentioned the problems of uncertainty in LCA and pointed out that lack of spatial and temporal dimensions in LCI will introduce uncertainty in LCIA. Fewer studies evaluated the uncertainty of the weighting procedure of LCA; Bengtsson and Steen (2000) compared the environmental burdens of using different weighting methods. Moreover, different uncertainties were rarely considered at the same time; Huijbregts et al. (2003) quantified parameter, scenario, and model uncertainty, but normalization and weighting processes were not evaluated.

In addition, many studies have evaluated the results of different LCIA methods that are applied to the same LCI data (Bovea and Gallardo 2006; Raluy et al. 2004, 2005; Seo et al. 2004). In a comparison of ecological scarcity, environmental theme, and EPS LCIA methods, Baumann and Rydberg (1994) pointed out that the different calculation outcomes resulted from differences of computation algorithms and background data. Brent and Hietkamp (2003) studied CML, Ecopoints, Eco-indicator 95, Eco-indicator 99, and EPS, organized the difference in terms of classification, characterization, normalization, and weighting of the five methods, and investigated the contribution of various pollutants to environmental impacts with empirical cases. It was discovered that different evaluation methods produce different results, and it is incorrect to directly apply normalization and weighting of the LCIA method without modification. The establishment of normalization and weighting for local conditions is necessary to make the evaluation meaningful. Dreyer et al. (2003) also compared EDIP97, CML2001, and Eco-indicator 99 and discovered that in the same impact category, especially for human toxicity, different pollutants were identified as major contributors for different LCIA methods. The results led to the advice that a proper LCIA method should be selected based on professional judgment on the reasonableness of assessment results.

However, an important question has not been answered from those studies: Which part of the LCA processes will lead to the main uncertainty? The understanding of the uncertainty contributions of each of the LCA components will facilitate the improvement of the credibility of LCA. To address this question, a novel methodology is proposed to systematically analyze the uncertainties involved in the whole procedure of LCA.

## 2 Methodology

In order to understand of the uncertainty contribution of each of the LCA components, a methodology is developed in this study to systematically analyze the uncertainties involved in the whole procedure of LCA. The methodology not only deals with the uncertainty contributions of the LCA components but also explores the degree of uncertainty of various impact categories. The proposed procedure is described as follows:

### 2.1 Identification of the uncertainty contributions of the LCA components

(a) *Assignment of LCI results*. Conduct LCI of the alternative scenarios. The detail of the LCI procedure is described in ISO 14044 (2006).
(b) *Selection of LCIA methods*. Select the LCIA methods that can integrate the impact categories into a single score. In this phase, the LCI results are translated into contributions to the single score, such as Eco-indicator 99, IMPACT 2002+, LIME, etc. To this end, it is necessary to identify relevant impact categories and select an LCIA method for calculating the effects of the inventory.
(c) *Calculation and ranking results of the final score by different LCA procedures*. Perform LCA calculations and rank the results under the following five situations:
   - Consider uncertainty of LCI only: except where the data in the LCI step is subject to change, all the

other LCA steps are fixed under a chosen LCIA method.

- Consider uncertainties related to LCI and normalization of LCIA: the data in the LCI step and the normalization value are subject to change; the weighting process of LCA is fixed under a chosen LCIA method.
- Consider uncertainties of the stages of LCI and normalization and weighting of LCIA: the data in the LCI stage, and the normalization value and weighting, are subject to change under a chosen LCIA method.
- Consider uncertainties of LCI and LCIA stages: the data in the LCI step, the normalization value and weighting are subject to change. In addition, different LCIA methods can be chosen.
- Consider uncertainty associated with the LCIA stage: the normalization value, the weighting, and the LCIA method are subject to change, but deterministic LCI data are used.

(d) *Evaluation of system uncertainty by Monte Carlo simulation*. The rankings of alternatives based on overall performance of LCA assessed by distributions of LCI, different LCIA methods, normalization, and weighting are then compared. An uncertainty index is derived to determine which parts of the LCA processes are primary contributors of uncertainty. The Monte Carlo simulation is used to analyze the uncertainties associated with LCI, LCIA, and the normalization and weighting processes. The difference of modeling performance is represented by the deviation of the rank of individual alternative scenarios among various LCA processes. An uncertainty index of single score (denoted as $UI_s$) for LCA is defined as the sum of the deviation of the rank of alternative scenarios between the compared LCA methods, as shown in Eq. 1. A larger uncertainty index indicates higher uncertainty involved in the assessment (see Eq. 1).

$$UI_s = \sum_i sd_{ij} \quad (1)$$

where $sd_{ij}$ is the standard deviation of the ranks of the single score for alternative $i$ with selected LCIA methods $j$.

### 2.2 Comparison of the uncertainty degree of impact categories

The same procedure as described above is also used to compare the degree of uncertainty of various impact categories, except that the performance for individual impact categories is calculated instead of the single score. The uncertainties of all stages are considered simultaneously without separating the assessment conditions into five situations as in 1.1(c). Finally, the ranking of alternatives based on individual impact categories of LCA assessed by distribution of LCI, the different LCIA methods, normalization, and weighting are compared. An uncertainty index of impact categories performance (denoted as $UI_i$) for LCA is defined as the standard deviation of the ranks of alternative scenarios under a selected impact category for a given LCIA method, as shown in Eq. 2.

$$UI_i = sd_{ijk} \quad (2)$$

where $sd_{ijk}$ is the standard deviation of the ranks of alternative $i$ under a selected impact category $k$ for the LCIA methods $j$.

## 3 Case study

The LCA of municipal waste management strategies in Taiwan is used as a case study to illustrate the proposed methodology. To properly manage the municipal waste, the Taiwan central government planned to build 27 incineration plants, and 24 of them have been built. However, due to implementation of the Resource Recycling and Reuse Act and Policy of Mandatory Garbage Sorting, the amount of waste is presently less than the total effective capacity of the existing incinerators; whether to build another three new incineration plants or not is therefore subject to discussion. There are eight regional management alternatives as shown in Table 1. Figure 1 displays the siting of these incinerators in Taiwan. Waste management activities generally include collection, transportation, treatment, and final disposal stages. For a given amount of waste, the impact at the stage of waste collection stage as well as the amount of ash production in each scenario would be the same. Therefore, this case study focuses on the environmental impacts of waste transportation and incineration. The system boundary was sketched as Fig. 2, and the functional unit is defined as the amount of municipal wastes that need to be incinerated a day in Taiwan. Transportation is the process to transfer the collected wastes from a county/city to another county/city for incineration. Main input in this stage is the amount of diesel oil used for cross-area transportation of waste. Output is the air pollutants produced by burning diesel oil during transportation. Incineration is the stage whereby waste gets into the treatment process in the destined county/city incineration plant after waste flows. The major inputs in this stage are the waste amounts entering into the destined incinerator and the energy provided by electric power. The outputs are the

**Table 1** The description of the eight alternative scenarios in this case study

| Alternative strategy | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Construction numbers of new incineration plants | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 0 |
| Construction plans | Continue to build all 3 new incineration plants | Continue to build 2 new incineration plants, but stop the Hsinchu plant | Continue to build 2 new incineration plants, but stop the Miaoli plant | Continue to build 2 new incineration plant, but stop the Yunlin plant | Continue to build the Hsinchu plant, but stop the other two | Continue to build the Yunlin plant, but stop the other two | Continue to build the Miaoli plant, but stop the other two | Stop building all three new plants |
| Total number of incineration plants | 27 | 26 | 26 | 26 | 25 | 25 | 25 | 24 |
| Number of cities and counties involved | 21 | 20 | 20 | 20 | 19 | 19 | 19 | 18 |

amount of air pollutants emitted by incineration and the recovered electricity. The emission factor of each process used in this study is listed in Table 2. When the approach stated in Section 2 is applied to the case study, the Monte Carlo method is used to combine individual probability distributions of LCI parameters and variant methods of normalization, weighting, and LCIA models to produce probability distributions of impact performance estimates. The setting of assumption of Monte Carlo simulation in this study consists of the data used to calculate LCI (e.g., the emission factors of $NO_x$, $SO_x$, CO, HCl, Dust, $CO_2$, and emission rate, etc.) and the choice of LCIA methods, normalization, and weighting procedure. The setting of forecast consists of two parts: one is ranking results of the alternative scenarios under different LCIA methods; the other is the ranks of alternative scenarios under a selected impact category for a given LCIA method. One thousand sets of simulations are conducted. Because Eco-indicator 99, EDIP, EPS, IMPACT 2002+, and LIME can estimate environmental performance of the single indicator as well as the individual impact categories, the five LCIA methods are considered in selecting the LCIA methods.

## 4 Results and discussion

### 4.1 The uncertainty contributions of each of the LCA components

Table 3 shows the example of ranking results of the alternative scenarios under different LCIA methods (there are 1,000 such ranking results produced by Monte Carlo simulations). The results of the uncertainty contributions of each of the LCA components are shown in Fig. 3. The primary source of uncertainty is the LCI stage under a given LCIA method. When different LCIA methods are compared, EDIP has the highest total uncertainty ($UI_s$ is equal to 11.69), and Eco-indicator 99 ($UI_s$ is equal to 3.34) has the lowest total uncertainty in this case study. When the differences between the five LCIA methods are incorporated into the uncertainty assessment, it is estimated that the overall uncertainty, $UI_s$, is equal to 10.54.

Figure 4 shows the relative uncertainty contributions of each of the LCA components when the LCI is set as deterministic. Only Eco-indicator 99 has the $UI_s$ value when normalization and weighting procedures are considered; setting aside the uncertainty caused by LCI, the weighting step has higher uncertainty than the normalization step. $UI_s$ is substantially increased to 9.31 when the differences between LCIA methods are incorporated. In other words, selection of LCIA methods is an important source of uncertainty.

### 4.2 Comparison of the uncertainty degree of impact categories

The impact categories assessed in this study include global warming potential, acidification, eutrophication, photochemical smog, human toxicity, ecotoxicity, and resource use. Figure 5 shows the comparison of the uncertainty index of individual impact categories. In comparison of the $UI_i$ values of various impact categories, the lowest is global warming, followed by eutrophication and acidification; human health and photochemical smog have the highest uncertainty. According to the results, the impacts of human health, ecotoxicity, and photochemical smog can vary a lot

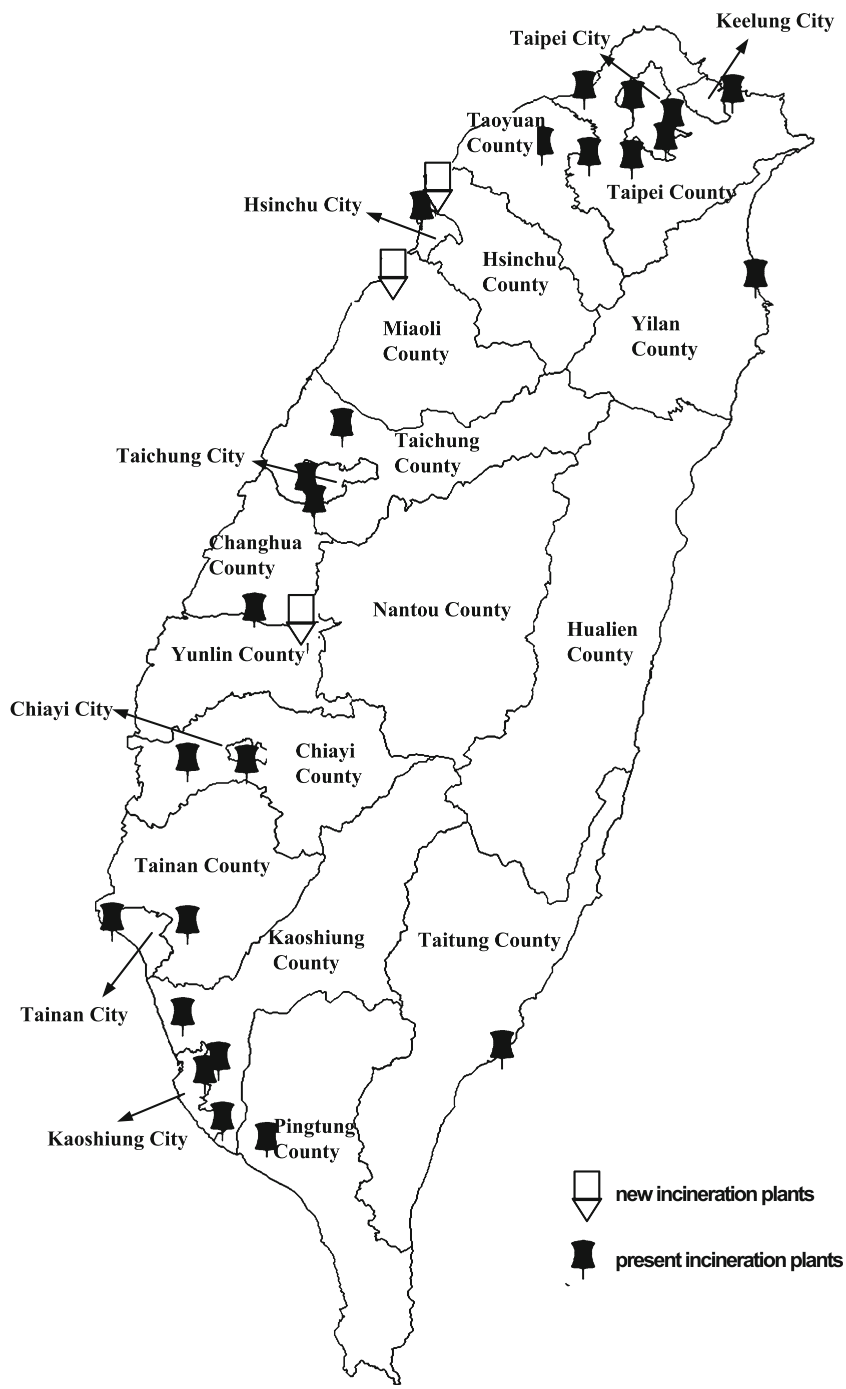


**Fig. 1** Siting of incinerators in Taiwan

when the uncertainties of LCI and LCIA procedures are considered. This also verifies the aforementioned finding that different LCA methods designed for their own regions may produce different assessment results even if they are applied to the same case. For the purpose of reducing the errors of impact estimation due to geographic differences, it is important to determine whether and which modifications of assessment of impact categories are necessary based on local conditions.

## 5 Conclusions and recommendations

By combining Monte Carlo simulations with the selection of various LCA processes, this study develops a methodology of systematically evaluating the uncertainties involved in the entire LCA procedure to identify the contributions of different assessment stages to the overall uncertainty. In this case study of municipal waste management, it is confirmed that different

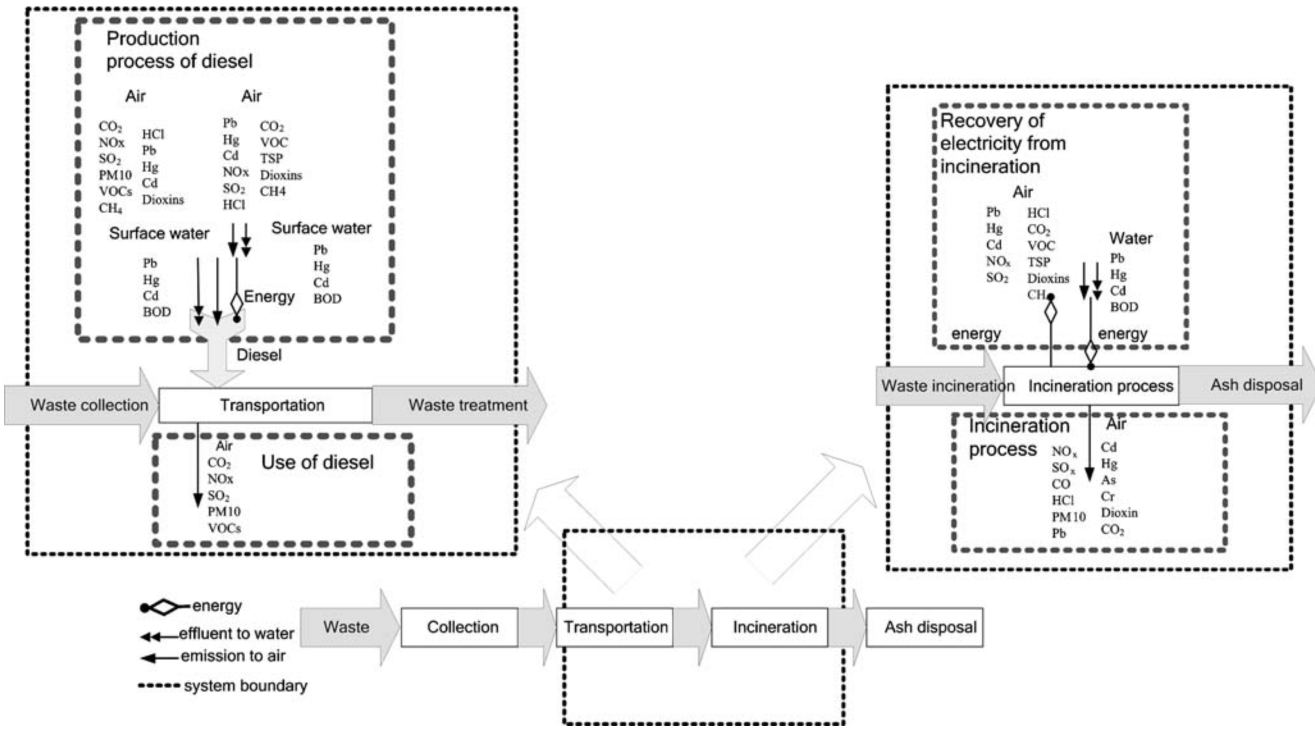


**Fig. 2** System boundary in this study

**Table 2** The emission factor of each process used in this study

| Process | Production process of diesel | Use of diesel | Electricity production | Incineration process[b] |
|---|---|---|---|---|
| Emission to air | | | | |
| $CO_2$[a] | 4.16E−01 kg/L | 2.70E+00 kg/L | 1.83E+02 kg/GJ | |
| $NO_x$ | 2.55E−03 kg/L | 2.39E−02 kg/L | 4.62E−01 kg/GJ | 2.63E+05~6.26E+05 mg/ton |
| $SO_2$ | 2.65E−03 kg/L | 4.32E−03 kg/L | 7.17E−01 kg/GJ | 1.82E+04~1.18E+05 mg/ton |
| PM10 | 1.33E−03 kg/L | 3.60E−03 kg/L | 3.51E−01 kg/GJ | 3.28E+03~4.46E+04 mg/ton |
| VOCs | 7.59E−03 kg/L | 4.56E−03 kg/L | 4.36E−02 kg/GJ | |
| $CH_4$ | 3.89E−03 kg/L | | 7.32E−01 kg/GJ | |
| HCl | 1.62E−05 kg/L | | 4.72E−02 kg/GJ | 3.43E+04~1.16E+05 mg/ton |
| Pb | 1.39E−07 kg/L | | 3.63E−05 kg/GJ | 1.99E+01~1.12E+02 mg/ton |
| Hg | 4.61E−09 kg/L | | 6.36E−06 kg/GJ | 1.86E+00~4.58E+01 mg/ton |
| Cd | 3.31E−08 kg/L | | 1.35E−06 kg/GJ | 1.98E+00~9.40E+00 mg/ton |
| As | | | | 5.15E+00~2.12E+01 mg/ton |
| Cr | | | | 1.50E+01~1.00E+02 mg/ton |
| Dioxins | 4.26E−12 kg/L | | 7.98E−12 kg/GJ | 3.21E+02~2.97E+03 ng I-TEQ/ton |
| CO | | | | 1.60E+04−9.34E+04 mg/ton |
| Emission to surface water | | | | |
| BOD | 4.35E−06 kg/L | | 3.38E−05 kg/GJ | |
| Pb | 5.13E−07 kg/L | | 8.30E−04 kg/GJ | |
| Hg | 5.31E−10 kg/L | | 2.45E−07 kg/GJ | |
| Cd | 5.57E−08 kg/L | | 8.37E−06 kg/GJ | |
| Others | | | | |
| Energy consumption | 6.62E−03 GJ/L | | | 3.23E−01−7.20E−01 GJ/ton |
| Energy recovery | | | | 1.33E+00−1.99E+00 GJ/ton |
| Emission rate | | | | 1.90E+03−3.77E+03 $Nm^3$/ton |

[a] The emission quantity of $CO_2$ from incinerators is derived from the carbon content of waste

[b] The data displayed in the incineration process is minimum value to maximum value and is the setting of assumption of Monte Carlo simulation

**Table 3** An example of ranking results of alternative scenarios under different LCIA methods

| | | alt1 | alt2 | alt3 | alt4 | alt5 | alt6 | alt7 | alt8 |
|---|---|---|---|---|---|---|---|---|---|
| Eco-99 | | | | | | | | | |
| LCI | EA[a] | 2 | 4 | 7 | 1 | 5 | 6 | 3 | 8 |
| | EE[a] | 2 | 4 | 7 | 1 | 5 | 6 | 3 | 8 |
| | HA[a] | 2 | 4 | 7 | 1 | 5 | 6 | 3 | 8 |
| | HH[a] | 2 | 4 | 7 | 1 | 5 | 6 | 3 | 8 |
| | IA[a] | 2 | 4 | 7 | 1 | 5 | 6 | 3 | 8 |
| | II[a] | 2 | 4 | 6 | 1 | 5 | 7 | 3 | 8 |
| LCI + N | | 2 | 4 | 7 | 1 | 5 | 6 | 3 | 8 |
| LCI + N + W | | 2 | 4 | 7 | 1 | 5 | 6 | 3 | 8 |
| LIME | | | | | | | | | |
| LCI | 3.1[b] | 1 | 3 | 5 | 2 | 7 | 6 | 4 | 8 |
| | 3.2[b] | 1 | 3 | 5 | 2 | 7 | 6 | 4 | 8 |
| | 3.3[b] | 1 | 3 | 5 | 2 | 7 | 6 | 4 | 8 |
| LCI + N | | 1 | 3 | 5 | 2 | 7 | 6 | 4 | 8 |
| LCI + N + W | | 1 | 3 | 5 | 2 | 7 | 6 | 4 | 8 |
| EDIP | | | | | | | | | |
| LCI | Dk[c] | 8 | 7 | 4 | 1 | 5 | 2 | 3 | 6 |
| | China[c] | 8 | 7 | 4 | 1 | 5 | 2 | 3 | 6 |
| LCI + N | | 8 | 7 | 4 | 1 | 5 | 2 | 3 | 6 |
| LCI + N + W | | 8 | 7 | 4 | 1 | 5 | 2 | 3 | 6 |
| EPS | | 1 | 3 | 5 | 2 | 7 | 6 | 4 | 8 |
| IMPACT 2002 + | | 2 | 4 | 5 | 1 | 7 | 6 | 3 | 8 |
| LCIA[d] | | 2 | 4 | 5 | 1 | 7 | 6 | 3 | 8 |

[a] There are six normalization and weighting methods (the first letter: adjusted for damage assessment. *E* egalitarian version, *H* hierarchist version, *I* individualist version. The second letter: 'A' refers to the average weighting set; 'E' refers to the weighting set belonging to the egalitarian perspective; 'H' refers to the weighting set belonging to the hierarchist perspective; 'I' refers to the weighting set belonging to the individualist perspective) in Eco—indicator 99 (Goedkoop and Spriensma 1999)
[b] There are three weighting methods in LIME (3.1: willingness to pay; 3.2: dimensionless; 3.3: AHP; Itsubo et al. 2004)
[c] There are two normalization methods (Word/Demark, Word/China) in EDIP (Hauschild and Wenzel 1998)
[d] LCIA is one of the ranking results of different LCIA methods (In this example, Impact 2002+ is selected)

LCIA methods would generate different assessment results; the stage of LCI is also identified as the most significant source of uncertainty. In addition, the differences between various LCIA methods introduce a large degree of uncertainty.

Such an assessment of the system uncertainty of LCA will facilitate the improvement of LCA. If the main source of uncertainty is the LCI stage, the researchers should focus on the data quality of the LCI data. If the primary source of

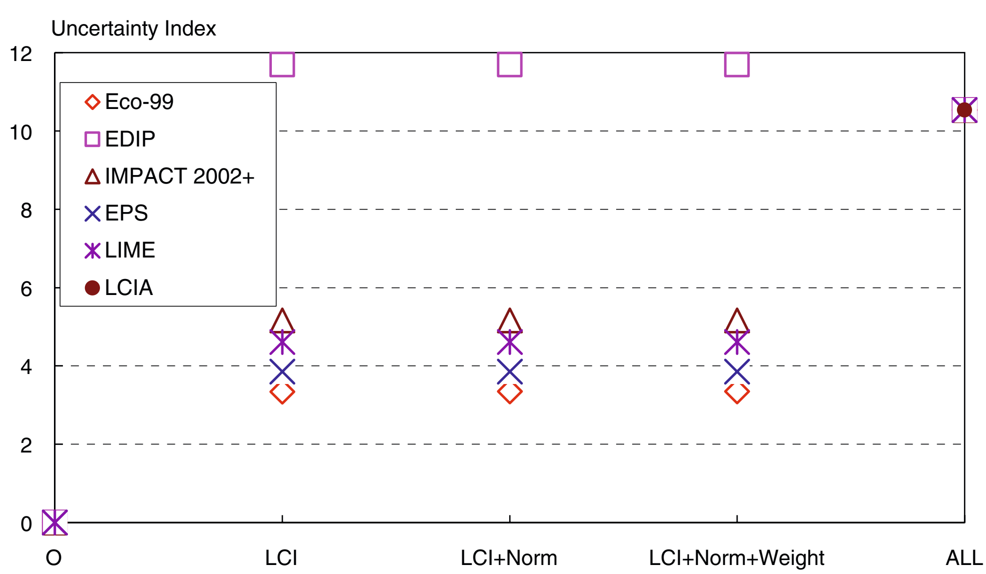


**Fig. 3** The uncertainty contributions of each of the LCA components

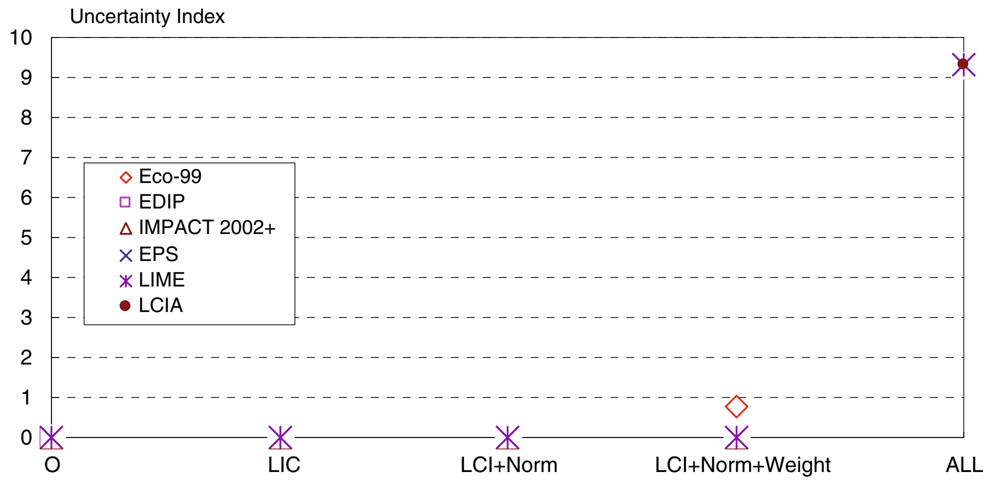


**Fig. 4** The uncertainty contributions of each of the LCA components (excluding the LCI procedure)

uncertainty is the LCIA stage, direct application of LCIA to non-LCIA software developing nations should be avoided. Many LCIA models have been developed to support the execution of LCA. In the present practice, a country that attempts to conduct LCA usually selects one of the existing models and applies the model directly to the country's concerned issues. Since the differences of the assessment results of different LCIA methods have been recognized, a few countries are considering developing their own LCIA methods. The study has verified that use of different LCIA models would produce different rankings of the management alternatives, which would in turn lead to different decisions. While further incorporation of scientific knowledge is needed to develop more accurate assessment algorithms and resolve the differences of various models, the modification of existing models based on local conditions, in the mean time, may prove to be more cost-effective. The comparison of uncertainty in each impact category could facilitate the determination on whether and which modification is needed.

## 6 Perspectives

This paper does not aim to discuss the cause of the different results observed through different LCIA methods. Instead, the goal of this paper is to develop a methodology to quantify the uncertainty degree of each LCA component systematically and to identify the relative contribution of the components to the overall uncertainty. It is recognized that different LCIA methods produce different results even when the same LCI data are used due to different methodological choices. Faced with this fact, quantitative uncertainty information would be helpful for decision makers to use the assessment results and to pinpoint the direction of improvement of the assessment method. LCA is normally used to compare environmental performance of alternative scenarios. The ranking of the alternatives is a very important assessment goal for decision making. The uncertainty, no matter what the sources are, is particularly important when it affects the ranking. The ranking is therefore suitable to serve as an uncertainty measure.

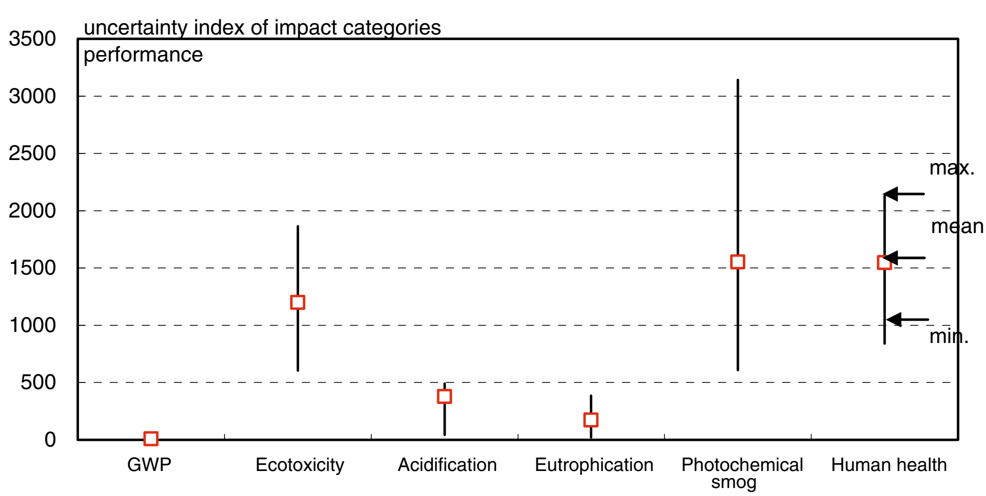


**Fig. 5** Comparison of ranking results of impact categories from different LCIA methods

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