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Positive Analysis of Uncertainty in Top-Down Approach Method with Input-Output Table for Life-Cycle Inventory Analysis

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It is the purpose of Life-Cycle Inventory analysis (LCI), which is an essential component of LCA, to quantify the environmental profile of its target. This study focuses on the uncertainty of LCI which strongly affects the reliability of the whole LCA procedure. Although many studies in Japan have been performed by combination of Extended Input-Output Analysis (EIOA) and Process Analysis, almost all of them lack clear statements on uncertainty of the results. In this paper, the basic principles and inherent defects of EIOA are argued first, and then two types of their uncertainty, "precision" and "accuracy", are introduced. Their natures are investigated by positive computations on CO_2 emission caused by Japanese economic activities of 1990. In the last section, finally, statistical characteristics of Total Emission Indicators (TEI) or cumulative emission factors are discussed for the construction of a practicable and reliable LCI method.

Key words: life-cycle inventory analysis, input-output table, uncertainty, precision, hybrid analysis

1. INTRODUCTION

The reliability of whole LCA study results depends on the reliability of Life-Cycle Inventory analysis (LCI) results.

In many Japanese cases, LCI has been carried out with the combination of 2 methods, "Extended Input-Output Analysis (EIOA)" and Process Analysis. Process Analysis is a powerful method of LCI for industrial products and easy to apply to actual process improvements. EIOA, on the other hand, was established by Leontief [3] himself and has been widely used for energy analysis [4] since 1970s and also urban infrastructures in Japan.

With the 2 methods combined, it is highly expected to improve the reliability of analysis. The key is how much of high perspicuity, clearness, and consistency of EIOA should be maintained while integrating the process analysis data of high costs and value.

Table I Comparison of 2 LCI Methods

Method	Process Analysis	Extended Input-Output Analysis
Process Outline	Collect and compile research data of actual production processes and existent materials, then sum up	Combine statistical materials (Input-Output table) and environmental emissions, then calculate with the well-defined formula
Influential Factor for Reliability	・ Partial nondisclosure of calculation grounds ・ Insufficient representatives of small sampling survey ・ Difficulty in quantitative evaluation for the reliability of calculation results	・ Few classification of industrial sectors and consequent mixture of multiple products in one sector (Therefore the results are rather rough for the estimation of each product and also there are some distortions in them due to the substitution of monetary flow for material flow.)

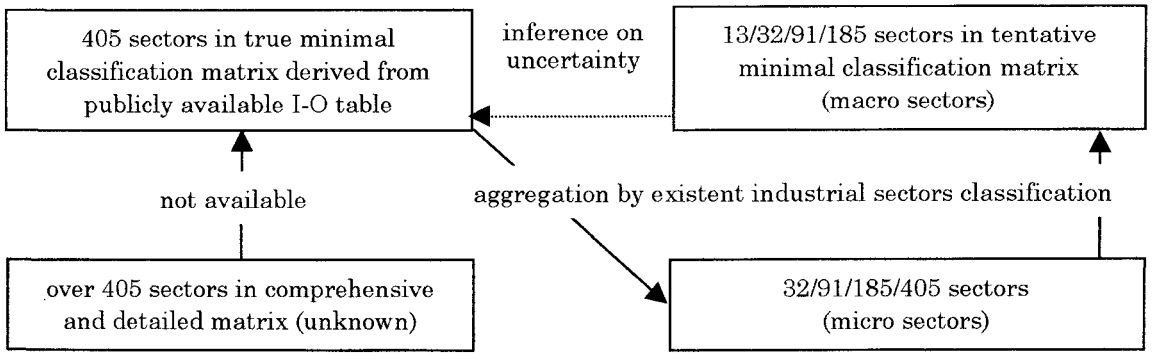

Fig.I Concept of Tentative Minimal Classification Matrix

2. METHODS AND RESULTS

2.1 Data and Definition of TEI in EIOA

With I-O Table [5] of Japan 1990, the reliability of EIOA was empirically examined by the calculation of CO_2 emission. CRIEPI estimation [6] was used for the divisional CO_2 emission amount.

Vector E for divisional total emission intensity (TEI) or cumulated emission factor was calculated by the following EIOA general definition with A for input coefficient matrix and vector L for CO_2 emission amount.

$$E = L^t \ (I - A)^{-1} \qquad (1)$$

TEI alone is equivalent to "cradle to gate" LCI results, because it represents a sub system of function provided by the LCI target. Thus TEI should be regarded as a fundamental figure of LCI.

2.2 TEI by Different Sizes of I-O Table

It is difficult to evaluate the uncertainty of TEI directly, because publicly available I-O table [5] we use in this research is the most comprehensively detailed one.

This made us turn the way of thinking around; estimation for uncertainty of the real analysis was worked out in an extrapolative manner (Fig. I). The key is the TEI calculation with each tentative minimal classification number, which is the aggregation of true minimal classification (405 sectors) of the existent table into the smaller classification with less sectors (13,32,91,185 sectors).

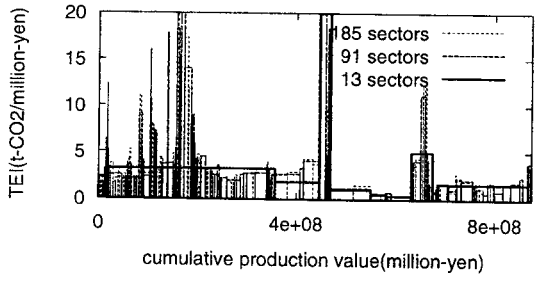

Fig.II TEIs of CO_2 for Different Sizes of I-O Tables

Fig. II shows the outline of calculation results. The thickest line shows the TEI of each sector (vertical axis) and its production value (horizontal axis) when tentative minimal classification has 13 sectors. When it has 185 sectors, there are wider distributions of TEI than 13 sectors.

Focusing on the following 2 factors, uncertainty of EIOA is then quantitatively examined.

The first one is temporarily called a problem of "precision", which looks at the distance between TEI of each micro sector and the average TEI of the group of micro sectors belonging to the same macro sector. If many TEIs are around the average, the corresponding macro sector's "precision" seems to be good and therefore the reliability of LCI is high.

The second one is also called a problem of "accuracy", which refers to the difference of results according to the size of tables used in the calculation under the same numbers of tentative minimal classification. This is because TEI of a macro sector differs from the average TEI of micro sectors (i.e. unbiased estimator) (Fig. III).

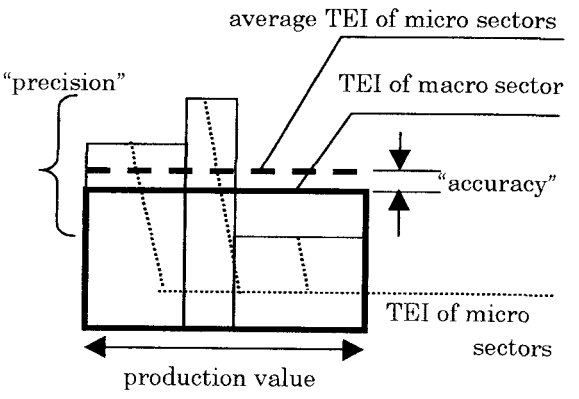

Fig. III Precision and Accuracy of a Macro Sector (ex. 3 micro sectors in 1 macro sector)

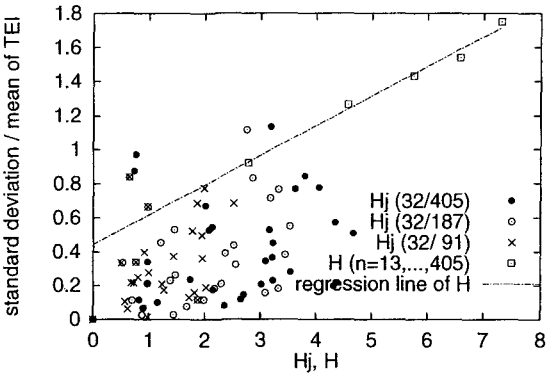

Fig. IV Precision Movement

2.3 Analysis of Precision

Points in Fig. IV (except for "square" dots) show the relationship between the precision indicator (i.e. the dispersion of TEIs) of each macro sector and the variety of its components (micro sectors) of each macro sector, when the number of a tentative minimal classification is 32.

The horizontal axis represents the amount of information (H_j) for details of the production share of micro sectors, which comprise a macro sector #j. The reason for the introduction of H_j is to show how detailed the component of the tentative minimal classification is.

$$Hj = -\sum_{\{i|i=c(j)\}} \frac{xi}{Xj} \log_2 \frac{xi}{Xj} \qquad (2)$$

where

X = vector of macro sector's production value, with element X_k,

x = vector of micro sector's production value, with element x_k, and function c regulates their relationship:

$$Xj = \sum_{\{i|j=c(i)\}} xi \qquad (3)$$

The vertical axis shows the value that the standard deviation of TEIs of micro sectors is divided by their average. For any macro sector, the larger the value is, the lower the precision becomes. The figure shows that the precision becomes lower if the micro sectors increase in their number (i.e. fine grained modeling).

The straight line in the figure is the regression line of relationship between the amount of information (H) for the production value of the whole macro sectors and the coefficient of variation of TEIs.

where

$$H = -\sum_{i}^{n} \frac{Xi}{\sum_j^n Xj} \log_2 \frac{Xi}{\sum_j^n Xj} \qquad (4)$$

n = number of tentative minimal classification.

Most of the points locate under the line†, that means available TEI components are in variety when division of sectors are applied for the whole economy rather than a specific industry, if the table is almost same in its size. This points out the usefulness of the analysis with such a macro viewpoint like EIOA.

2.4 Analysis of Accuracy

Fig. V shows the calculation results of TEI variations when the number of micro sectors changes within the frame of 32 macro sectors. It is confirmed that there actually happens a problem of accuracy.

The problem of accuracy has been studied as aggregation bias in economics[7]. In LCI, although it is more division-oriented than aggregation, the achievement is still applicable. For example, if the I-O table is expanded only by the information on output structure of the division target sector, its accuracy turns out not to be improved so much.

2.5 Examination for the Whole System

With the indicators representing "precision" and "accuracy" of the whole system, their characteristics are studied by calculations. The indicator for "accuracy" of the whole system is set as follows,

$$\alpha = \sum_j \left| \frac{EjXj}{\sum_{\{i|j=c(i)\}} eixi} - 1 \right| Xj / \sum_j Xj \qquad (5)$$

while the one for "precision" as below.

$$\beta = \left(\sum_j \left| \frac{\sigma j}{e_{\{i|j=c(i)\}}} \right| Xj \right) / \sum_j Xj \qquad (6)$$

J here is the index for macro sectors, i for micro sectors, and $j=c(i)$ regulates their relationship. Each of e, E, x and X represents the TEI and production value of micro or macro sector. $\sigma / \bar{e}$ is the same as the vertical axis of Fig. IV.

Fig. VI shows the example examination results; it draws the relationship of α and β with the change of micro sector numbers (a) for 2 kinds of macro sectors (A).

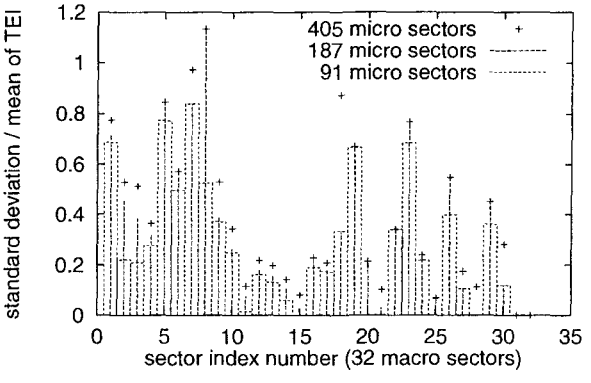

Fig. V Accuracy Movement

† Linear behavior of H and the relationship between the H regression line and H_j's are also observed not only for whole macro sectors but also for the sub-macro sectors in some large macro sectors such as "manufacture" and "service".

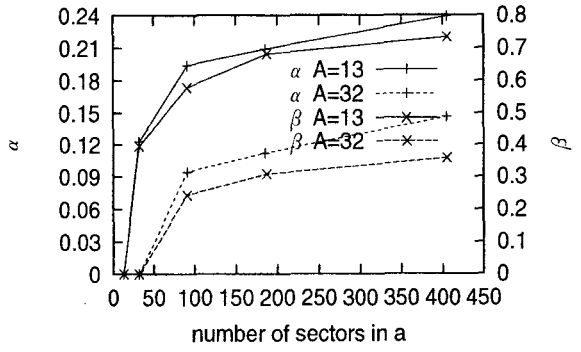

Fig. VI Relationship between "Precision" and "Accuracy" for the Whole System

These results show the followings;

1) For each sector, there is no relationship between "accuracy" and "precision" no matter they are high or low.
2) As a whole system, if "precision" is low, "accuracy" is accordingly low.
3) "Precision" is more influential overall.

3. DISCUSSION

3.1 The Superiority of Table Expansion Method

In order to maintain EIOA's good points and improve its rough estimation, Table Expansion Method seems worthy to take. Table Expansion Method is a simple combination of EIOA with individual research for its supplement. Studying the process, which has the close relationship with its analysis target, and adding its data, equivalent sectors of I-O table are divided. This division is done recursively, the table is gradually expanded, and the uncertainty is preferably reduced.

This idea shows the similar top-down approach to Hybrid Analysis presented by Bullard et al.[4] and preliminary LCA [8]. It also follows the idea Dohnomae et al.[9] claimed that I-O table should be used as a container of LCA database.

If uncertainty, especially precision, is evaluated with some forehand information like production value of analysis targets, target sectors for individual research can be effectively chosen and the reliability of results can also be evaluated according to the degree of detailed analysis. (It is based on the idea that when the inventory results of "whole plastic" is adopted as an inventory of "whole polyethylene", the reliability of its results is differently evaluated from those of the case when it is adopted as an inventory of "polyethylene made in the factory A".)

3.2 The Relationship between the Production Share of Micro Sectors in a Macro Sector and the Distribution of TEI

In each macro sector, micro sectors of a predefined range of production share are regarded as a group and a histogram has been made for each group (Fig. VII is an example). These results lead us to know that the distribution of TEI can be modeled by logarithmic normal distribution.

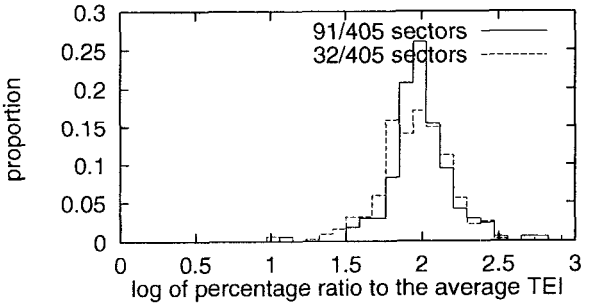

Fig. VII Histograms of Different Tentative Minimal Classifications (Product Share: 0—10% groups)

The distribution parameter is likely to change according to the following factors;
1) Number of micro sectors in the whole system
2) Number of macro sectors in the whole system
3) Production share structure in each macro sector

These factors are studied by AIC test of whether variances and/or averages are the same or not between groups. Then the results show;
1) If the production share is under certain level, the variance does not change.
2) If the number of macro sectors increases, the variance obviously decreases.
3) It is not confirmed yet though, the increment of the variance is relatively stable for the expansion of numbers of micro sectors.

These factors all support the usefulness of Table Expansion Method.

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