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# Life Cycle Assessment by Input-Output Method

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**Abstract:**

*Mounting awareness of global environmental problems has shifted demand on industry from measures for reducing the environmental load of each industrial sector, such as pollution control and energy conservation, to measures for reducing the total environmental load of each product throughout its life cycle, including the use and disposal phases. This method for quantitatively evaluating the total environmental load of specific products is being internationally standardized under the name of life cycle assessment (LCA). LCA is expected to be a powerful tool for future technology and product development. LCA is outlined below, and application examples and problems of the input-output analysis-based LCA technique developed by the Advanced Technology Research Laboratories of Nippon Steel are reviewed.*

## 1. Introduction

With mounting awareness of global environmental problems, evaluation of industrial products has added the new coordinate axis "consideration of the environment" to the conventional coordinate axis "cost versus performance". Manufacturing industries have addressed conventional pollution problems by pipe-end treatment and management, but they have been increasingly compelled by today's environmental issues to manufacture products while paying attention to the environmental effects before the procurement of raw materials and after the shipment of finished products. The effects of products on the global environment cover a wide spectrum of issues, such as global warming, ozone layer depletion, acid rain, eutrophication, soil contamination, resource exhaustion, and animal extinction. The micro framework in which individual loads work in a chain-like manner can be understood, but distances to actual technological problems are so great that corrective measures lose their actuality. Each environmental problem covers various special regions, remedial measures, and techniques. If the load of an item is reduced, the load of another item may increase (this is called trade-off). Today's science and technology is challenged to have an accurate grasp of environmental problems that diverge in many and varied ways.

Against this background, the concept of LCA was advanced, and the International Organization for Standardization (ISO) is working to standardize LCA. This article introduces the concept of LCA and studies the feasibility of on LCA technique based on the input-output table.

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## 2. Outline of LCA and Significance of This Study

### 2.1 Definition of LCA

LCA can be defined as a technique for measuring, calculating, and evaluating the environmental effects of industrial products through their life cycle, from manufacture to disposal, and for studying measures to reduce their environmental loads. Such techniques have been traditionally called "resource and environment profile analysis", "ecobalancing", and "cradle-to-gave analysis", among other things, but they have converged to LCA in the ISO discussions. The LCA procedure studied for standardization by the ISO is shown in **Fig. 1**. The purpose of the study is defined, and the scope of the analysis is set. Quantitative data are collected and calculated (inventory analysis). Indexes for quantitatively evaluating the total effects of environmental load items are prepared (impact analysis). The results thus obtained are used to improve products or processes and to select products or raw materials to be purchased.

Inventory analysis measures and calculates the consumption of resources and the amount of emissions to the environment in the subprocesses throughout the life cycle of a product, from the extraction of raw materials to the manufacture of materials, to the fabrication and assembly of the final product, to the distribution, sale, use, and consumption of the product, to the disposal or recycling of the product (see **Fig. 2**). In an actual assessment procedure, the input (material flow) of all raw materials, parts, and members throughout the life cycle of the product are clarified, and the data sheet shown in **Fig. 3** is filled with the relevant data by using enormous time and labor. In the data sheet of **Fig. 3**, the subprocesses for which data are to be collected are each given only once, such as raw material extraction, material manufacture, fabrication, and assembly. In actual material flow, the number of subprocesses for which data are to be collected increases exponentially as one tracks down to the raw material side.

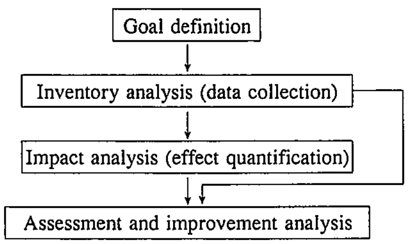


**Fig. 1** LCA procedure

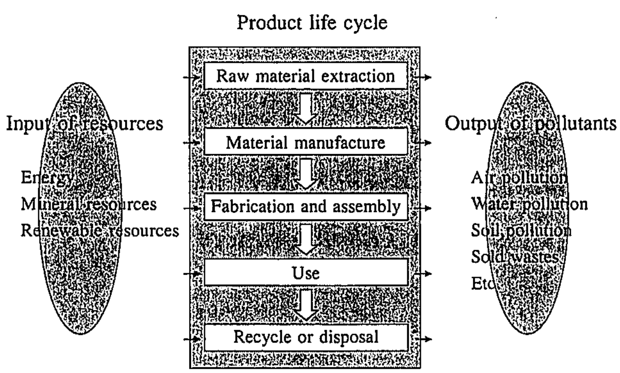


**Fig. 2** Outline of LCA

Impact analysis multiplies the calculated values of environmental load items collected in the inventory analysis phase by coefficients befitting the impact of the environmental load items and adds these values to the products. Primary effects, such as global warming, acid rain, resource consumption, human toxicity, and ecological toxicity, are first evaluated and then compiled into comprehensive indexes. Several methods are proposed, but definitive ones are not yet established because environmental values dependent on individual regional or national characteristics are inevitably inserted in the final indexing stage.

### 2.2 Manufacture of products from LCA point of view

In the light of the significance of the implementation of LCA in solving environmental problems, manufacturing industries are required not only to reduce environmental loads in product manufacturing processes but also to develop products by considering the effects the products have on the environment during their use.

When the environmental load of thermal power plant boiler steel tubes in the manufacturing process is compared with that of thermal power plant boiler steel tubes in the power generation process, for example, the load of latter is overwhelmingly high. The development of ultra-supercritical pressure thermal power plant boiler steel tubes with elevated-temperature strength high enough to increase the energy conversion efficiency in electric power generation is very significant from an LCA point of view in lessening the environmental load in the electric power generation process[1]. Adding value to steel products, as represented by high-strength steel for automotive use, coated steel, and low-core loss electrical steel, may involve increased energy consumption in the manufacturing process, but it greatly contributes to energy conservation on the whole when the products' uses in society are taken into account[2]. These steel products spearheaded product

| | | Inventory Analysis | | | | | | | | | Impact Analysis | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Raw material extraction | Material manufacture | Fabrication and assembly | Transportation | Use | Recycling | Disposal | Subtotal | | Weighting coefficient | | Subtotal |
| Air pollution | $NO_x$ | | | | | | | | | | | | |
| | $SO_x$ | | | | | | | | | | | | |
| | $CO_2$ | | | | | | | | | | | | |
| | Dust | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| Water pollution | COD | | | | | | | | | | | | |
| | SS | | | | | | | | | | | | |
| | Oil | | | | | | | | | | | | |
| | | | | | | | | | | × | | = | |
| Exhaustible resources | Oil | | | | | | | | | | | | |
| | Coal | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| Trace hazardous substances | Pb | | | | | | | | | | | | |
| | Hg | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| Energy | | | | | | | | | | | | | |
| Solid wastes | | | | | | | | | | | | | (+ |
| | | | | | | | | | | | | Total | |

**Fig. 3** Conceptual diagram of actual LCA procedure

development according to LCA.

The significance of existing steel products has been noted from the standpoint of LCA in the above example. Conversely, the LCA analysis may identify the improvements to be made to present products. For example, the ends of two-piece steel beverage cans are made of aluminum. Nearly one-third of the energy consumed to make the two-piece steel beverage cans is accounted for by the manufacture of the aluminum ends. If the aluminum is replaced by steel that can be produced with much less energy, a large energy savings will be achieved.

### 2.3 Need for LCA by input-output analysis

As discussed above, LCA is considered an effective method for solving the environmental problems. In actual analysis, however, the following problems are present in the inventory analysis stage. Some supplementary methods must also be studied.

As described in Section 2.1, the cradle-to-grave analysis of a product calls for data to be collected in so many subprocesses that the analysis is limited, some subprocesses are omitted, and analysis boundaries are arbitrarily defined. If an LCA study is to be conducted from the standpoint of an industry, for example, it becomes necessary to acquire data in processes in other industries. In this case, corporate secrecy and knowledge constraints make it extremely difficult to perform an analysis with accurate data throughout the life cycle. LCA databases are already sold commercially. Necessary data are not always available in such LCA databases, and there are problems with data accuracy and representativeness.

The above problems may be solved by the use of input-output tables. The input-output table is a compilation of all monetary transactions among industries in a country. All materials flows among the industries can be calculated backward from the monetary values. The input-output table approach has been traditionally used in analysis of the energy consumption structure[3] and can be exploited in LCA analysis to grasp material flows among all products in the country throughout their life cycle in a coherent manner. The authors have reported the study results of the applications and limitations of the LCA technique based on the input-output table approach[4,5]. The input-output analysis-based LCA technique is reviewed here.

## 3. LCA by Input-Output Method

### 3.1 Methodology

#### 3.1.1 Basic framework of input-output table and focus of study

The input-output method is essentially based on the theory of input-output analysis[6] as an area of econometrics. The Japanese input-output table as the basis for the input-output analysis is a tabular compilation of all monetary transactions among industries for one year in Japan. Because the flows of products can be estimated from the flows of money, material flows from the acquisition of raw materials to the final assembly of products can be estimated for all domestic industrial products. Because the inputs of energy producing products like oil and coal can also be known, total energy consumption and $CO_2$ emissions in the entire process from raw material extraction to final product assembly can be estimated. The input-output analysis, energy analysis, and $CO_2$ emission analysis techniques are summarized in the appendix.

The framework of the above-mentioned input-output table is discussed in somewhat greater detail. The Japanese input-output table consists of a monetary transaction matrix among 529 categories (rows) and 408 categories (columns)[7]. In other words, Japan is taken as the analytical boundary, and the inter-product network within the Japanese industrial system is described by a 408×529 matrix. In the Japanese industrial system, an industry $k$ is described as a subprocess as shown in **Fig. 4**. The industry $k$ receives as raw materials 529 categories of products from 529 industries and supplies a product $k$ to 408 industries. Because the activities of all industries can be tracked one by one from the 529×408 matrix, the flows of all parts, members, materials, and raw materials required in the manufacturing stages of all products can be determined.

The above input-output table is useful not only in the macroanalysis of money, energy, and $CO_2$ but also in the supply of material flow data most basic to the LCA analysis. In that case, the size of the mesh used to describe the material flows is problematic. The 529×408 mesh of the Japanese input-output table is the outcome of five years of work by 13 Japanese government ministries and agencies and is detailed enough to be unrivaled in the world. The purpose of this study is to investigate the quality of the material flow data furnished by the Japanese input-output table, to ascertain the degree of accuracy to be achieved by the LCA analysis based on this table, and to identify problems with the development of a LCA database from the table.

#### 3.1.2 Outline of newly developed technique

The above aims were not seen in traditional macroanalyses starting with the framework of existing input-output tables. The features of the present analytical study may be summarized as follows:

(1)Analysis with 531-category format

The conventional input-output method was based on 408 columns or categories and analyzed in 406 categories by combining electric power companies into one sector. In matrix calculation, a square matrix is first composed from a basic table, and an inverse matrix calculation or other operations are then performed. The 406×406 square matrix is the only matrix that can be built from the 529×408 basic table without self-contradiction. The present study prepared and analyzed a 531×531 square matrix, which is described below.

(i)One input row, the electric power industry, was subdivided into three subsectors to increase the 529 rows of the basic table to 531 rows. The total input of the original electric power industry was proportionately distributed among the three subsectors.

(ii)Each output column was subdivided into two to nine subsectors to expand the 408 columns of the basic table to 531 columns. The total production of each original column was proportionately distributed among the subsectors.

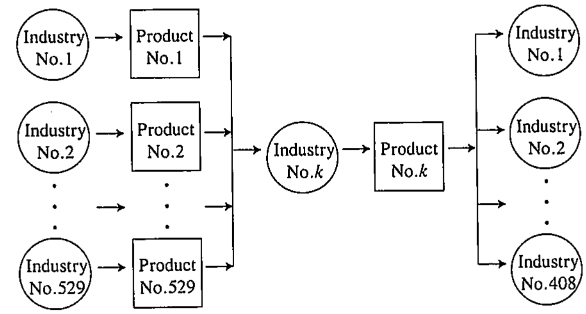


**Fig. 4** Definition of industry $k$ in input-output table

The advantages and problems of the analysis with the 531-category format will be described later.

(2)Analysis of environmental load structure along material flows

A usual input-output analysis calculates the total contribution of directly and indirectly related products to the manufacture of a given product. It does not address such problems as material flows, or what raw materials and parts are inputted in the manufacturing processes of the product and raw materials, or the environmental load structure, or each stage's environmental load. The present study developed a technique for deriving the environmental load structure along the material flows.

Assume that a unit environmental load $w_k$ (for example, unit $CO_2$ emission) in the final manufacturing stage of a product $k$ is known. To calculate the environmental load of product $k$ throughout its life cycle, it is necessary to total the environmental loads of raw materials and parts required to manufacture product $k$ and the environmental loads of raw materials and parts required to manufacture product $k$'s raw materials and parts. For example, the input of the raw materials and parts required to manufacture product $k$ is the element $a_{ik}$ of the input coefficient matrix $A$ (see the Appendix). The environmental load in the manufacturing stage is given by

$$w_i a_{ik}$$

The environmental load of product $i$ required to manufacture product $k$ and the environmental load of product $j$ required to manufacture product $i$ are given by

$$w_j a_{ji} a_{ik}$$

Let part of the material flow of product $i$ required to manufacture product $k$ be denoted by $i \to k$. The above equation can be generalized and used to calculate the environmental load in $m$ manufacturing steps in the material flow $m \to l \to \cdots j \to i \to k$ as given by

$$w_m a_{ml} \cdots a_{ji} a_{ik}$$

Similarly, the sum of production in the $m$ manufacturing steps in the material flow $m \to l \to \cdots j \to i \to k$ is given by

$$b_{pm} a_{ml} \cdots a_{ji} a_{ik} \ (p{:}1, \cdots n)$$

The total environmental load is calculated by

$$\sum_p w_p b_{pm} a_{ml} \cdots a_{ji} a_{ik}$$

The above calculations can be repeated for all portions of the material flows of a product to extract raw materials and parts with large percentage contributions along the material flows, for example (see **Fig. 5**).

The present study analyzed the $CO_2$ emission structure. The unit $CO_2$ emission of each industry was obtained from the transaction basic table of the 1985 Japanese input-output table[7], the material quantity table attached thereto[7], and the energy balance table[8] (see the Appendix), according to the method of Moriguchi et al.[9] Industries such as electric power, oil products, coal products, and basic petrochemical products (for example, ethylene and propylene) were specially treated as exceptions to the above procedure to avoid double counting primary and secondary energy products.

### 3.2 Results and discussion

#### 3.2.1 Study of product types

It has already been noted that the conventional input-output

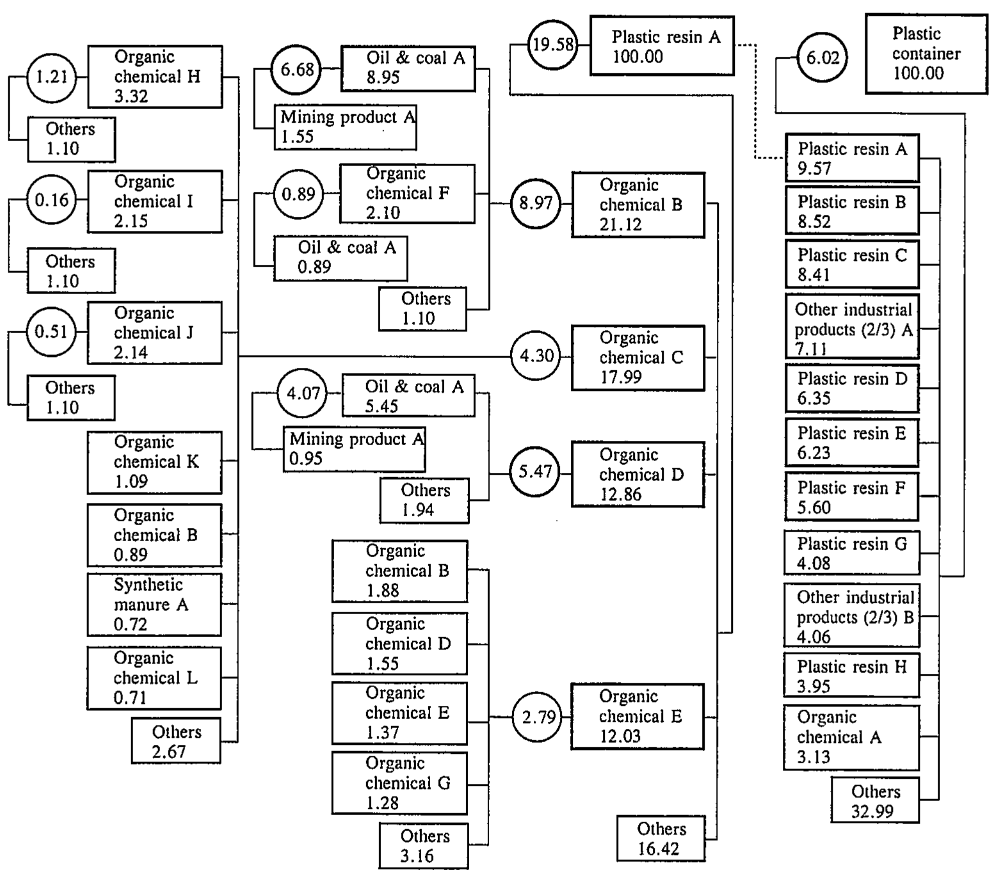


**Fig. 5** $CO_2$ emission structure of plastic containers

**Table 1** Differences in number of product types between 408-category format and 531-category format

| 408-category format | → 531 -category format |
|---|---|
| Nonferrous metal minerals | → Copper, lead, zinc, and other nonferrous metal minerals |
| Soda industry products | → Soda ash, caustic soda, liquefied chlorine, and other soda industry products |
| Basic petrochemical products | → Ethylene, propylene, and other basic petrochemical products |
| Petrochemical aromatic products | → Pure benzol, pure toluol, xylol, and other petrochemical aromatic products |
| Aliphatic intermediates | → Synthetic alcohol, acetic acid, ethylene dichloride, vinyl acetate monomer, and other aliphatic intermediates |
| Cyclic intermediates | → Styrene monomer, synthetic phenol, high-purity terephthalic acid, caprolactam, and other cyclic intermediates |
| Thermoplastic resins | → Low-density polyethylene, high-density polyethylene, polystyrene, polypropylene, and vinyl chloride resin |
| Petroleum products | → Gasoline, jet fuel oil, kerosene, gas oil, fuel oil A, fuel oil B, fuel oil C, naphtha, liquefied petroleum gas, and other petroleum products |
| Hot-rolled steel | → Carbon steel shapes, carbon steel plates, carbon steel strip, carbon steel bars, other hot-rolled carbon steel products, and hot-rolled special steel products |
| Aluminum | → Aluminum and recycled aluminum |

method analyzed the input-output relations among industries with 406 input categories by considering electric power generation as one sector and that the present study tries to analyze the input-output relations with 531 input categories by subdividing the electric power industry into three subsectors. The differences in the product names between the 406-category format and the 531-category format are shown in **Table 1**. The thermoplastic resin category in the 406-category format combines the five categories of low-density polyethylene, high-density polyethylene, polystyrene, polypropylene, and vinyl chloride resin in the 531-category format. The mesh of the 406-category format is too coarse for the raw materials in particular. The 531-category format covers more than 300 industrial products, excluding agriculture and service industries. This number is greater than 100 to 200 products covered in the LCA data bases of Simapro, RIPA, and Franklin that are widely used in the United States and Europe and means that material flows can be described with a finer mesh than possible with these databases.

3.2.2 Results of analysis of $CO_2$ emission structure along material flows

Packaging and containers constitute an area where LCA is most advanced. The analyzed results of the $CO_2$ emission structure in the manufacturing stages of plastic containers are shown in **Fig. 5**. In **Fig. 5**, a circle denotes an industry, and a square denotes a product. The data are normalized by taking the total amount of $CO_2$ emitted in the manufacturing stages of plastic containers as 100%. The number in each circle indicates the amount of $CO_2$ emitted by the industry, and the number in each square indicates the total amount of $CO_2$ emitted in upstream stages until the manufacture of the product. The industries and products that have $CO_2$ emissions of 5% or more are enclosed in thick-lined circles and squares, respectively. In this report, product names are not given, but products are distinguished by alphabetic labels. For example, plastic resins are classified into "plastic resin A", "plastic resin B", "plastic resin C", and so forth.

The findings obtained from the analytical results of **Fig. 5** are discussed here. First, subprocesses and raw materials with high environmental loads can be known. According to **Fig. 5**, for example, the final process to manufacture plastic containers contributes a mere 6%, and most of the remaining $CO_2$ emissions are contributed by the raw material manufacturing processes "plastic resin A" to "plastic resin H". From these results, the use of alternative raw materials with less $CO_2$ emissions is derived as an effective guideline for product improvement. When the present raw material or part is replaced, the number in the square is replaced by that of the new raw material or part. The manufacturing process of one raw material or "plastic resin A" is newly analyzed, and the results are included in **Fig. 5**. The manufacturing processes of "organic chemical B" and "organic chemical C" (specifically, monomer and plasticizer) and "oil & coal A" (naphtha) emit large amounts of $CO_2$. These $CO_2$ emissions can be effectively reduced by improving the processes.

3.2.3 Problems

The 531 product categories defined in the 531-category format are analyzed for the $CO_2$ emission structure, and the problems of this technique are identified.

(1)There are products that produce the wrong material flow.

The analytical results of polystyrene, for example, show that ethylene, propylene, and other raw materials are inputted to the polystyrene manufacturing process. When the 408 columns were increased to 531, the thermoplastic region sector was subdivided into five subsectors of low-density polyethylene, high-density polyethylene, polystyrene, polypropylene, and vinyl chloride resin. At that time, these five resin types were all assumed to be inputted as raw materials for the manufacture of thermoplastic resins, and four of the five resin types were assigned as raw materials for polystyrene. This caused the above-mentioned error. When expanding the input columns to the 531 categories, it is necessary to consider findings about the synthesis of essential raw materials and to incorporate data from other sources.

(2)There are products that do not fit the description of material flow.

The analytical results of cans show that the manufacturing process of sheared and slit steel sheet products makes a large contribution to $CO_2$ emissions. Actually, however, can products account for a mere 13.3% of the applications for the sheared and slit steel sheet products. This points to the possibility that the raw material mix assumed for analytical purposes is considerably different from the actual raw material mix of the sheared and slit steel sheet products for the manufacture of the cans. It is necessary to abolish this sector and to reassign the material flow of this sector to another sector.

(3)It is necessary to consider the environmental loads of imported products in their country of manufacture.

The $CO_2$ emissions of imported products should be correctly evaluated and added to the $CO_2$ emission calculations. Today's $CO_2$ emission calculations assume that the $CO_2$ emissions of imported products are zero. Compare aluminum and steel, for example. Japan depends on foreign sources for close to 100% of new aluminum ingots refined. Aluminum takes a large amount of energy to produce on a global basis, but it is assessed very favorably in Japan compared with steel. In this case, it is theoretically justified to handle imported products and domestic products completely separately and to calculate $CO_2$ emissions with 531×2 products.

## 4. Conclusions

The use of the 531-category format on the basis of the Japanese input-output table makes it possible to raw material flows of such detail as to compare favorably with LCA databases in the United States and Europe. To overcome the problems described in section 3.2.3, it is necessary to modify the Japanese input-output table to some degree and to incorporate information from other sources.

Material flow data are most basic to LCA. Once the material flow in Japan is described, various unit environmental load data can be compiled without contradiction, and a database of good quality can be built. The authors are presently accumulating know-how to modify the Japanese input-output table and to incorporate external data into the table.

### References


1) Shibata, K. et al.: CAMP-ISIJ. 8 (4), 1147 (1995)
2) Shinohara, Y.: Tekkokai. (9), 40 (1995)
3) Hrendeen, R.A. et al.: Energy Impact of Consumption Decisions. Proc. IEEE. 63,3 (1976)
Kaya, Y.: Energy Analysis. First edition. Tokyo, Denryoku Shinposha, 1980
Resources Council, Science and Technology Agency: Food, Clothing, and Housing Life Cycle Energy. 1979
4) Dohnomae, H. et al.: Advanced Materials 93, V/A: Ecomaterials. 1994, p. 97
5) Dohnomae, H. et al.: Proceedings of International Conference on EcoBalance. 1994, p. 137
6) Management and Coordination Agency: 1985 Input-Output Tables
7) Leontief, W.: Input-Output Economics. Oxford University Press, New York, 1936
8) Agency of Natural Resources and Energy: Comprehensive Energy Statistics. 1994 edition
9) Moriguchi, Y. et al.: Energy and Resources. 14,32 (1993)


### Appendix

"Techniques for Input-Output, Energy, and $CO_2$ Analyses"

Input-output analysis is an econometric theory widely used for forecasting business trends by using input-output tables. Wassily Leontief advocated the input-output method for the economic analysis of the United States in 1936. In 1973, he was awarded the Nobel Prize in Economics for devising the technique. The input-output tables that summarize monetary transactions among industries in individual countries in matrix format are now compiled and announced every several years by the governments of many countries. The analysis of environmental loads by the input-output method was used by R.A. Hrendeen of Britain in his energy analysis for the first time in 1973[3]. Since then, many researchers have conducted energy analysis and environmental load analysis in Japan as well, basically utilizing the framework of input-output analysis devised by Leontief. The input-output analysis is described below.

Let $x_k$ be the total annual production of an industry $k$ manufacturing a product $k$. Industry $k$ supplies product $k$ as a raw material to other industries and as a final product to the market. Let these outputs be denoted by $x_{k1}, \cdots xk_j, \cdots x_{kn}$, and $f_k$. Conversely, industry $k$ requires the inputs $x_{1k}, \cdots x_{nk}$ from other industries as raw materials (for example, parts and fuels) required for the production $x_k$.

When the input coefficient matrix $A$ is defined as

$$A = \begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & a_{kj} & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} = \begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \frac{x_{kj}}{x_j} & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$$

and $X$ and $F$ are given by

$$X = \begin{pmatrix} \cdot \\ x_k \\ \cdot \end{pmatrix},\ F = \begin{pmatrix} \cdot \\ f_k \\ \cdot \end{pmatrix}$$

the following relation holds:

$$X = AX + F$$

Thus,

$$X = BF$$

where $B = (1 - A)^{-1}$ (inverse matrix of Leontief).

If $A$ is known, the total $X$ of product inputs directly and indirectly required for the production $F$ can be calculated by the above equation.

The inverse matrix $B$ of Leontief may also be developed as given by

$$B = A^0 + A^1 + A^2 + A^3 + \cdots$$

The first item on the right side is the input of the final product, the second item is the input of the raw material required to manufacture the final product, and the third item is the input of the raw material required to manufacture the raw material in the second item, and so on. When a product is manufactured in a unit amount, it has an impact on various other industries that are the manufacturers of raw materials required to manufacture the product. The total impact to an infinitely far point can be uniquely determined by obtaining the inverse matrix $B$. This is the greatest characteristic of the input-output analysis. For example, the effect a public investment in a civil engineering project has on demand in other industries can be analyzed by the input-output method.

The input-output analysis can calculate the total amounts of energy consumed and $CO_2$ released until a product is manufactured. The total monetary value of energy products (crude oil, petroleum products, coal, coal products, natural gas, and electricity) inputted into each industry $k$ can be obtained from the basic table of the input-output table. From the energy (heat) content and carbon content per unit price and unit quantity, the amounts of energy consumed and carbon released per unit production of each product in each industry, or unit energy consumption and unit carbon emission, can be determined for all industries $k$. For example, the unit energy consumption in the industry $k$ is denoted by $w_{energy,k}$. Because $w_{energy,k}$ is known for all industries $k$,

$$W_{energy} = (w_{energy,1} \ldots w_{energy,n})$$

The total of environment loads as to $m$ at production $F$ is given by

$$W_{energy} X$$

where $X = BF$.

Assume that the unit environmental load for all industries is known for $m$ environmental load items, except for energy and $CO_2$, for example. If the unit environmental load is

$$W_{load} = (w_{load,1} \cdots w_{load,n})$$

the total of environmental loads as to $m$ at production $F$ is given by

$$W_{load} X$$

where $X = BF$.