Study On The Advanced Technique Of Environmental Assessment Based On Life Cycle Assessment Using Matrix Method

マトリックス法を用いたライフサイクルアセスメントによる環境影響評価技術の高度化に関する研究

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Symbols

A : Coefficient matrix in the matrix-based LCI

B : Environmental load matrix in the matrix-based LCI

C : Surplus flow matrix in the matrix-based LCI

I : Unit matrix

S : Sensitivity analysis result matrix

p : Process vector in the matrix-based LCI

α : System boundary vector in the matrix-based LCI

β : Final environmental load vector in the matrix-based LCI

γ : Final surplus flow vector in the matrix-based LCI

RMA : Ratio of Matrix Analysis

Chapter 1

General Introduction

In recent years, due to the increased rates of resource depletion, land use, solid waste generation and emissions of pollutants, to preserve the environment of the earth and to avoid the exhaustion of the resources have become an urgent and unavoidable object to human being. The heightened awareness of the importance of environmental protection, and the possible environmental impact associated with products (including product and service) manufactured and consumed, has increased the attention on developing the methods to better comprehend and reduce these impacts. One of the techniques being developed for this purpose is Life Cycle Assessment (LCA).

§ 1.1 Life Cycle Assessment

LCA is a process for evaluating the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes discharged to the environment, assessing the impact on the environment of those energy and material uses and waste releases, and identifying ways for reducing the environmental impacts [1]. If a study is to be described as an LCA, it should cover the entire life cycle of the system, from extracting raw materials, through manufacturing, distribution and use, to final disposal; and in general, the life cycle is called as "from cradle to grave".

LCA can assist in [2]

- Identifying opportunities to improve the environmental aspects of products at various points in their life cycle;
- Decision-making in industry, governmental or non-governmental organizations (e.g. strategic planning, priority setting, product or process design or redesign);
- Selection of relevant indicators of environmental performance, including measurement techniques;
- Marketing (e.g. environmental claim, ecolabelling scheme or environmental product declaration).

The science of LCA methodology and procedure has grown and developed significantly since it started more than a decade ago. Parallel to the scientific development, and often integrated into it, many initiatives have been taken to harmonize LCA methodology. The harmonization efforts resulted in a series of international standards for LCA: ISO 14040-14043 [2-4], which was a milestone for LCA practice.

§ 1.1.1 Methodological framework of LCA

The general framework of LCA is composed of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation, according to the Society of Environment Toxicology and Chemistry (SETAC) guideline [5, 6] and the International Standard ISO 14040 series [2], as shown in Fig. 1.1.

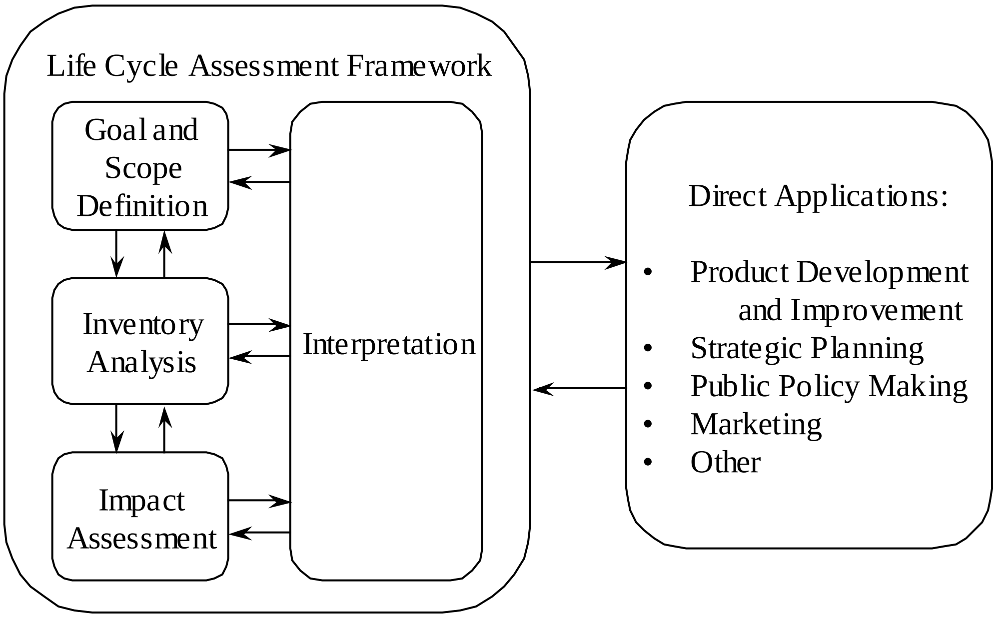

Fig. 1.1 Phases and applications of an LCA [8]

Goal and Scope Definition

The goal and scope of an LCA study shall be clearly defined and consistent with the intended application [2]. The goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated. In defining the scope of an LCA study, the items of the functions of the product system, the product system boundaries and data requirements etc. shall be considered and clearly described. LCA is an iterative technique; therefore, the scope of the study may need to be modified while the study is being conducted as additional information is collected.

Life Cycle Inventory Analysis (LCIA)

Life cycle inventory analysis in LCA involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. These inputs and outputs may include the use of resources and releases to air, water and land associated with the system. The process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. Sometimes, issues may be identified that require revisions to the goal or scope of the study. The methods of life cycle inventory analysis will be stated in detailed in section 1.1.2.

Environmental Impact Assessment

The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. The impact assessment phase may include elements such as:

- assigning of inventory data to impact categories (classification);
- modeling of the inventory data within impact categories (characterization);
- prossibly aggregating the results in very specific cases and only when meaningful (weighting).

Moreover, if necessary, normalization is also considered as a development of the characterization step. It is to express the aggregated data in each impact category as a proportion of the total magnitude of that impact in some given area [1].

Interpretation

Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are combined together consistent with the defined goal and scope in order to reach conclusions and recommendations.

§ 1.1.2 Methods for life cycle inventory analysis

Life Cycle Inventory (LCI) analysis is the most important phase of LCA. The developed methodologies for LCI analysis so far are summarized in Table 1.1.

Table 1.1 Life Cycle Inventory Analysis methods

General LCIA method				LCIA method based on Fuzzy theorem
Process analysis method		Input-Output Analysis (IOA) method	Hybrid LCIA method	
Process flow diagram method	Matrix based LCIA method			

Each method for LCI analysis will be stated as follows, in which the matrix method for LCI analysis will be introduced in a little more detail.

Process flow diagram method

Process flow diagram method is the first LCIA method appeared in early LCA studies, and it is still widely used in LCA practices nowadays. Process flow diagrams show how processes of a product system are interconnected through commodity flows. In process flow diagrams, boxes generally represent processes and arrows the commodity flows. Each process is represented as a ratio between a number of inputs and outputs. Using plain algebra, the amount of commodities fulfilling a certain functional unit is obtained, and by multiplying the amount of environmental interventions generated to produce them, the LCI of the product system is calculated [7].

Matrix based LCIA method

The matrix based LCIA method (matrix method) was first introduced to LCI computation by Heijungs [9]. This method utilizes a system of linear equations to solve an inventory problem. Arranging the economic and environmental flows in matrix forms, the final cumulative environmental loads are calculated by matrix algebra operations.

The detailed computational methods and skills of the matrix method were developed by Heijungs later as well [10]. Compared with other methods, this method can deal with the LCA system with internally recurring unit processes better [11, 12].

Input-Output based LCIA method

An Input-Output table is used in an LCI, environmental data is added to quantify the environmental burdens for each sector per unit of money inflow to that sector. The money data as well as the environmental data are average over the whole industrial sector.

IOA method for LCI analysis will be simply reviewed in Chapter 4 of this thesis.

Hybrid LCIA method

Linking process based and Input-Output based analysis, combining the strengths of both, are generally called hybrid method [7, 18, 36, 37]. So far hybrid LCIA method has been adopted to some

LCA case studies [34, 35]. In detail, hybrid LCIA method can be distinguished as tiered hybrid analysis, IO-based hybrid analysis and integrated hybrid analysis [7].

LCIA method based on Fuzzy theorem

For LCI analysis, a great deal of data are needed to collect. In a practical LCA case study, it is difficult to collect all the necessary and there must exist some lacking data, which are in fact very important. In order to resolve the problem, fuzzy theorem [38] has ever been considered to overcome the difficulty of collecting enough data in LCI [19, 39]. And fuzzy theorem is used in the phase of environmental impact assessment of LCA as well [40-42].

§ 1.1.3 LCA database

In the general LCA studies, Life Cycle Inventory Analysis (LCIA) is the most important stage. Most of the time and efforts taken in LCIA are concentrated in the necessary data collection. Therefore, in order to support the easy and reliable LCA studies in our societies, it has been started to develop LCA databases in many nations in the world [16, 43-52]. Some of the databases are general ones [45-47] and some of them are limited to some special product categories [49, 50].

In Japan, a five-year national LCA project was initiated in 1998 with support from the Ministry of Economy, Trade, and Industry (METI) and New Energy and Industrial Technology Development Organization (NEDO) [47]. The purpose of the project is to develop common LCA methodology as well as a highly reliable database that can be shared in Japan [47, 48]. Activities over these five years have resulted in the supply of LCI data on some 250 products. In Switzerland, an ecoinvent database is developed by the Swiss Centre for Life Cycle Inventories. The database accommodates more than 2500 background processes often required in LCA case studies [46].

LCA has also been emphasized in some developing countries and the LCA databases are under development. For instance, in China, accompanying with the rapid development of economy, the environmental problem has become one of the most important and serious problems. Therefore, some LCA databases have begun to be developed in China as well [51, 52].

§ 1.1.4 LCA software

There have been many commercial LCA software in many countries, such as "NIRE-LCA/JEMAI-LCA" [16, 22, 23], "LCASUPPORT" [24, 25], "EcoAssist" [26, 27], "Easy-LCA" [17, 28, 29] and "Quick LCA" [30] in Japan, "SimaPro (Netherlands)" [31], "TEAM

(France)” [32] and “GaBi (Germany)” [33] in Europe.

Some of the software are based on the process analysis method [13, 16], and some of them adopt the Input-Output analysis method [17] or hybrid analysis method [18]. There are some software as well, which are based on the fuzzy theorem [19]. Many LCA software are developed for a particular category of products, such as constructions, ships, etc [20, 21].

Most of the LCA software adopts the Process flow diagram method, while not the matrix method for LCI analysis. CMLCA is one of the general purpose LCA software, which adopts the matrix method [13]. However, in CMLCA much information is needed and it is somewhat complicated and delicate to use. The details about CMLCA will be stated again in Chapter 5.

§ 1.2 Problem setting

The science of LCA methodology and procedure has grown and developed significantly since it started more than a decade ago. However, there are still some problems unsolved in it.

The major disadvantage of quantitative LCAs is their complexity and effort required. The life cycle inventory phase usually takes a great deal of time and effort and mistakes are easily made. The matrix method for LCI analysis has been proved to be an effective method. However, in practical LCA case studies or the conventional LCA software, it is rarely used due to the difficulty to establish an appropriate matrix model for the product system and compose the necessary matrices.

Moreover, in the conventional LCA studies, since it is difficult to compose all the relevant processes, the composition of a product system for LCA is limited to the possibly derived processes. In some cases, the product system is composed subjectively to some extent, which makes LCA suffer low-reliability and low-objectivity. Therefore, herein, an objective method for composing an appropriate product system in LCA studies becomes urgently needed.

In addition, some other problems in LCA have been shown in the past literatures as well. Since the LCA methodology develops rapidly, the international standards for LCA (ISO 14040-14043) becomes outdated fairly quickly [14]. It became clear that different LCAs carried through by different consultants resulted in different and sometimes conflicting conclusions. Many efforts have been taken to harmonize LCA methodology. However, most of the methodological guidelines are valid for a specific geographical area, a particular category of products, or a particular application of LCA [15].

§ 1.3 Aim and structure of the thesis

In this thesis, we are aiming to develop a complete, practical and effective matrix method for LCI analysis, which is very convenient to use in a practical LCA case study. Based on the matrix method, the algorithms from the environmental load calculation to the sensitivity and uncertainty analysis in LCI are connected and generalized. By using the matrix-based LCA methodologies, we attempt to develop a general purpose LCA system and apply it to practical LCA case studies. Furthermore, we hope to popularize the matrix-based LCA methodologies and software in society.

The thesis is composed of total 6 chapters. The outline of each chapter is shown as follows.

In Chapter 2, the basic algorithm of the matrix method for LCI analysis is reviewed and the problems in the conventional matrix method are discussed. After that, a new general and practical approach for matrix-based LCI analysis is proposed and the algorithm of the matrix method is generalized. In the practical approach, the necessary matrices can be composed easily by specifying some process data. All the operations and calculations for LCI analysis are fully based on matrix algebra. As a result, the matrix method for LCI analysis becomes more appropriate to deal the complex product system with many recursive loops and recycling loops. It is more practicable and easier to use, especially for the practitioners, who has a few LCA experiences and knowledge. Moreover, this practical approach can be easily carried out by computer program. It is the most basic algorithm of the studies in this thesis. Based on the basic matrix method for LCI analysis, further studies on LCI analysis methods are carried out in Chapter 2 and Chapter 3.

In Chapter 3, based on the matrix method proposed in Chapter 2, the algorithm of sensitivity and uncertainty analysis in matrix-based LCI is generalized. The sensitivity analysis adopts the rate sensitivity and quantitatively studies the influence of each process datum on the final cumulative environmental loads. The uncertainty analysis studies the uncertainties of the final environmental loads, which are propagated from the uncertainties of process data. In this chapter, after completing the matrix-base sensitivity analysis, a simplified method for uncertainty analysis, which is based on the central limit theorem, and a detailed method, which is based on the Monte Carlo simulation, are generalized based on the matrix method. Moreover, a general procedure for uncertainty analysis from the simplified method to the detailed method is proposed. As a result, based on the matrix method, the operations from LCI analysis to sensitivity and uncertainty analysis are connected to facilitate the LCA analysis.

In Chapter 4, the matrix method for LCI analysis proposed in Chapter 2 is combined with the Input-Output Analysis (IOA) method by using the final surplus flow vector $\boldsymbol{\gamma}$. Consequently, all the direct and indirect environmental loads associated with a product can be taken into account and the LCI analysis is completed. Continuatively, considering the cost performance and the result's accuracy in practical LCA case studies, a general and consistent method about how to define the product system boundary is proposed. As a result, by using the method for system boundary definition based on the matrix method and IOA method, the accuracy of LCI result is improved. The problem of compromise between practicality and completeness in LCA is resolved.

In Chapter 5, the matrix-based LCA methodologies developed in Chapter 2, 3, and 4 are practically used. In the first place, using the methodologies, a general purpose LCA system (EMLCA) is established on the spreadsheet of Excel. In EMLCA, all the operations and calculations of LCA analysis are based the matrix algebra and all the matrices are shown on sheet. It is greatly easy to carry out the Monte Carlo simulation for uncertainty analysis in EMLCA.

Continuatively, an LCA case study of copier is carried out. In the case study of copier, how the matrix-based LCA methodologies are made good use of are demonstrated. The practicability and effectiveness of the methodologies and software in a practical case study of a product are examined and confirmed. The developed matrix-based LCA methodologies and software can also be applied to the LCA case study of services, if the operations of service are expresses to be a series of processes. As an LCA case study of service, the environmental assessment of the maintenance system of railway track is carried out. By establishing the matrix model of railway track maintenance system, the environmental loads associated with one year's railroad maintenance are calculated. By carrying out sensitivity analysis, the opportunities to obtain environmental improvements are identified and evaluated.

In Chapter 6, the studies and results stated and interpreted in the above chapters are summarized, and the conclusions are drawn. Moreover, the possible directions of future research on LCA are discussed.

All the studies are based on the matrix method. The development of matrix-based LCA methodologies, the development of general purpose LCA software and the practical usage of the methodologies and software are all covered in the thesis.

The structure of this thesis is shown in Fig. 1.2.

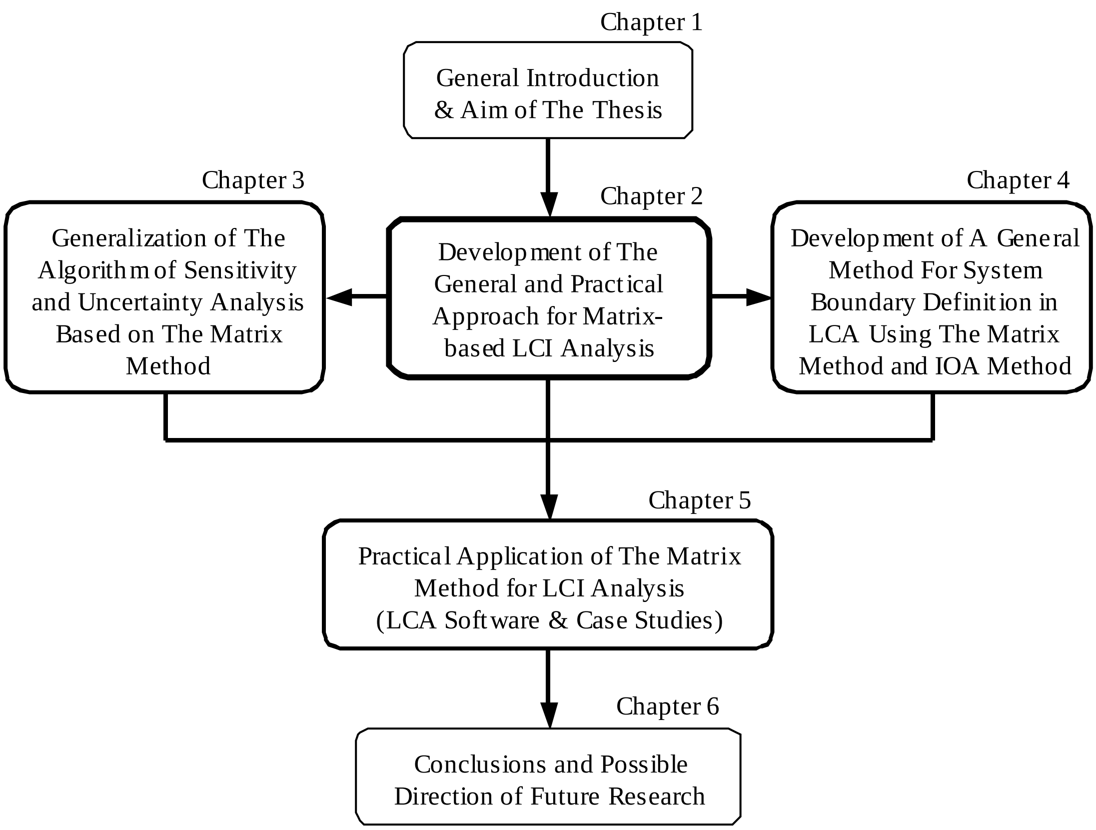

Fig. 1.2 Flow chart of the thesis

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Chapter 2

Development of A Practical Approach for Matrix-based LCI Analysis

Although the matrix method in LCA has been proposed for many years, there are still some unsolved problems, which result in that matrix method is rarely used in the practical LCA case studies. In this chapter, firstly, the basic algorithm of the matrix method for LCI analysis is reviewed and the problems in the conventional matrix method are discussed. After that, a new practical approach for matrix-based LCI analysis is proposed. In the practical approach, the necessary matrices can be composed easily by specifying some process data. Especially, the coefficient matrix, which is the most important one, is composed of the functional flows, each of which is defined in each unit processes. As a result, the coefficient matrix is assured to be a square one. The allocation in the matrix method is carried out, after confirming that the byproducts etc. are assuredly cross the system boundary and allocation is really needed based on the surplus flow vector. Consequently, the efficiency of the matrix method for LCI analysis is further improved. Furthermore, the general procedure of the matrix method is summarized as well.

Finally, an extend example of LCA case study is carried out by using the conventional matrix method and the present one respectively. The practicability and effectiveness of the latter one are examined. By comparing the two kinds of analysis, the merits of the present matrix method for LCI analysis is shown clearly as well.

As a result, the matrix method for LCI analysis becomes more appropriate to deal the complex product system with many recursive loops and recycling loops. It is more practicable and easier to use, especially for the practitioners who have few LCA experience and knowledge. Moreover, this practical approach can be easily carried out by computer program.

Key words: Functional Flow; LCI Analysis; Matrix Method; Practical Approach.

§ 2.1 Introduction

In the Life Cycle Inventory (LCI) stage of Life Cycle Assessment (LCA), the main feature is to collect data to compile the unit processes and calculate the final cumulative environmental loads by summing up every contribution from each unit process from the "cradle" to the "grave" [1, 2]. The matrix method [3, 4], which is one of the effective process analysis methods for LCI analysis, has been proposed to establish a matrix model for the product system and calculate the final environmental loads associated with the defined functional unit.

Compared with other LCI analysis methods, the matrix method has the merits as shown in following:

1. In practical LCA case studies, the products outputted from the downstream processes are often inputted into the upstream processes as the necessary materials or parts. In LCA, such loops are generally called as recursive loops, and the flows of the products are generally called as recursive flows. Compared with the other process analysis method-process flow diagram method, the matrix method is easier and more appropriate to deal with the product systems with recursive flows, since it is not necessary to analyze the unit processes one by one to calculate the practical environmental loads in each process and it is not needed to analyze the same process many times although the outputs from the process are used in many other processes [5, 6]. For example, in general when producing light oil, electricity is needed; and in order to produce the electricity, light oil should be imported. It is obvious that electricity and light oil are recursive between the two processes. The matrix method can calculate all the environmental loads in the recursive loop, while the process flow diagram method cannot. In practical LCA case studies, there are much more such recursive loops, which make the product systems more complicated. Therefore, the matrix method is more appropriate to LCI analysis, and the LCI result by the matrix method is more correct. Suh and Huppes have compared all kinds of methods for LCI, and pointed out that matrix representation of product systems is clearly superior to the flow diagram method for all LCA systems except for the most simplified ones [7].
2. The Input-Output Analysis (IOA) method for LCI, which is based on the input-output table of a country or a region, adopts matrix form as well. Therefore, the hybrid analysis for LCI, which combines the process analysis method and the IOA method, can be realized easily by introducing the matrix method [7-9].
3. Based on the matrix model of the product system, it is easier to realize the sensitivity analysis and uncertainty analysis than other methods. Heijungs [10] has ever discussed the

use of matrix theory for sensitivity and uncertainty issues in LCA, also he indicated that in sensitivity analysis the analytical way based on the algebraic manipulation is easier and more time saving than the one by one numerical way. Sakai and Yokoyama [11] proposed a matrix-based method for the efficient sensitivity analysis by introducing the perturbation method. This will enable one to evaluate the degree of the influence of each element on the total sum of environmental loads. By this sensitivity analysis method based on matrix algebra, all sensitivities can be calculated easily, even if the number of processes becomes larger.

4. Furthermore, since all the data are stored in matrix forms in the matrix-based LCI, the management and the modification of the data will become convenient. And it is also easy to grasp all the data as a whole.

Therefore, constructing a matrix model in LCI can help the LCA practitioners to calculate the environmental loads, and assist in sensitivity analysis and uncertainty analysis as well.

However, the matrix method is rarely used in practical LCA case studies and most available LCA software tools are all based on the process flow diagram method due to some problems, which have not resolved yet. For instance, there is yet no general and consistent method for matrices composition in LCI analysis. Therefore, it results that it is somewhat difficult and delicate to compose the proper matrices for the LCI analysis in practical LCA case studies, especially when the product system becomes large and complicated. It is unclear that how to deal with the flows, which are relative with the product system but are cut off from the product system. Therefore, a practical approach for matrix composition in the matrix method became very imperative.

For this purpose, in this chapter, the basic algorithm of the matrix method for LCI analysis is reviewed first. Then, the problems in the conventional matrix method are investigated, and a new practical approach for matrix-based LCI analysis is proposed to solve the problems.

The new approach is compared with the general formulation of the matrix model for LCI analysis proposed by Heijungs [4], and the merits of the former are shown. Finally, using an example of LCA case study, the new practical approach is demonstrated and the applicability is examined. In the practical approach, the necessary matrices can be composed easily by specifying some process data. The allocation in the matrix method is carried out, after confirming that the byproducts etc. are assuredly cross the system boundary and allocation is really needed based on the surplus flow vector. Consequently, the efficiency of the matrix method for LCI analysis is further improved. As a result, the matrix method for LCI analysis becomes more appropriate to deal the complex product system with many recursive loops and recycling loops. It is more practicable and easier to use, especially for the practitioners who has few LCA experiences and knowledge. Moreover, this practical approach can be easily carried out by computer program.

§ 2.2 Review of the conventional matrix method for LCI analysis

The matrix based LCI analysis method (matrix method) is based on linear assumption, which means that in each unit process the economic flows (e.g. materials, products and co-products etc.) and the environmental flows (e.g. consumed energy and resources, emitted pollutant etc.) will be amplified with the same degree as the process function does. The main idea in the matrix method is the systematic construction of a set of linear balance equations for the economic flows in the product system. By the matrix method, all the economic flows and the environmental flows are compiled in matrix forms. And the matrix model represents the whole product system. According to the convention [3, 4, 11], the economic flows are arranged in the coefficient matrix **A**, and the environmental flows in the environmental load matrix **B**. Both in the matrix **A** and **B**, columns represent the processes and rows represent the flows. The inputted flows are expressed by negative coefficients and outputted flows by positive ones. In the meantime, the boundary condition for the economic flows at the product system boundary is expressed by the vector $\boldsymbol{\alpha}$. Then, the process vector **p** can be derived as:

$$\mathbf{A}\mathbf{p} = \boldsymbol{\alpha} \tag{2.1}$$

$$\mathbf{p} = \mathbf{A}^{-1}\boldsymbol{\alpha} \tag{2.2}$$

A is a square matrix, and $\mathbf{A}^{-1}$ is the inverse matrix of **A**. Items in the system boundary vector $\boldsymbol{\alpha}$ are the absolute values of the economic flows, which cross the system boundary. Each item in the vector **p** is the scaling factor corresponding to one unit process. Then, the final environmental load vector $\boldsymbol{\beta}$ can be obtained by using the environmental load matrix **B** as:

$$\boldsymbol{\beta} = \mathbf{B}\mathbf{p} \tag{2.3}$$

$$\boldsymbol{\beta} = \mathbf{B}\mathbf{A}^{-1}\boldsymbol{\alpha}\ . \tag{2.4}$$

All the economic flows are also called as materials in this thesis. By Heijungs *et al*. [4], matrices **A** and **B** are also called as technology matrix and intervention matrix, vectors $\boldsymbol{\alpha}$, **p** and $\boldsymbol{\beta}$ are also called as final demand vector, scaling vector and inventory vector, respectively.

The largest advantage of the matrix method for LCI is that it can appropriately deal with the product systems with internally recurring unit processes and recursive flows.

§ 2.3 Discussion about the problems in the conventional matrix method

The concept and principle of the matrix method for LCI analysis has been proposed for many years. It helps to calculate the environmental loads associated with the defined functional unit of the product system, and it is competent to support the sensitivity analysis and uncertainty analysis etc. in LCI as well. However, in practical LCA case studies so far, the matrix method is rarely used, since there is no a general and convenient matrix for composing the proper matrices for LCI analysis. The concrete problems, which make it difficult to compose the proper matrices, are discussed as follows.

(1) From Eq. (2,2), it is known that in order to calculate the process vector **p**, the composed coefficient matrix **A** must be a square one. However, in a practical LCA case study, it is somewhat difficult and delicate to compose a square coefficient matrix.

Generally, there are a great number of input and output flows in a practical process of the product system. For example, in the process of the digital monochrome copier manufacture in JLCA database [13], there are more than one hundred economic and environmental flows. According to the regulation of the conventional matrix method, if all the economic flows in a product system are arranged in the coefficient matrix **A**, it will result in a huge coefficient matrix. Moreover, in practical LCA case studies, due to the limitation of time and cost, it is difficult or even impossible to compile all the relative processes. It means that process data are unknown for certain processes. Then, the coefficient matrix **A** composed of all the economic flows will not necessarily be a square matrix. Therefore, the process vector **p** cannot be obtained and the environmental load cannot be calculated using Eq. (2.2 – 2.4).

For example, a product system of aluminum can is shown in Fig. 2.1. In this case study, CO_2 and solid waste are considered to be environmental loads, and the other flows are all considered as economic flows. The functional unit is given by '1 used can', and the finally cumulative solid waste and CO_2 are expected to calculate.

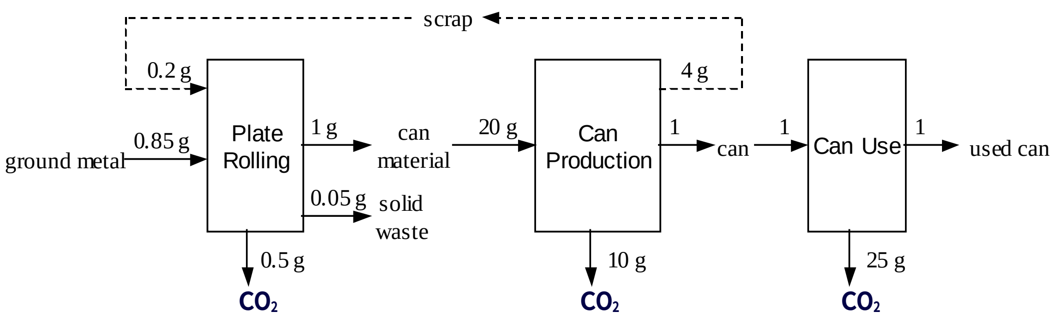

Fig. 2. 1 Flow chart for aluminum can's life cycle

Depending the practitioner's judgment, checking the upstream flows from 'used can', it is known that the process values are determined by the requirements of the flows of 'used can', 'can' and 'can material' respectively. Then, in order to calculate the process vector **p**, it is only needed to solve the balance equations of the three flows. So that, the coefficient matrix **A** is only composed these three flows:

$$\mathbf{A} = \begin{matrix} \text{can material} \\ \text{can} \\ \text{used can} \end{matrix} \begin{pmatrix} 1 & -20 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix} \tag{2.5}$$

However, in a practical LCA case study, since there are a great number of processes and flows, and many recursive and recycling loops, which make the product system very complex, it is difficult even impossible to choose all the necessary economic flows one by one depending on the practitioner's judgment. Therefore, this operation should be performed using computer program and a generalized procedure to compose the matrices becomes necessary.

In this LCA case study of aluminum can, if the coefficient matrix is composed of all of the economic flows according to the regulation of the conventional matrix method, then, it will be derived as:

$$\mathbf{A}' = \begin{matrix} \text{ground metal} \\ \text{scrap} \\ \text{can material} \\ \text{can} \\ \text{used can} \end{matrix} \begin{pmatrix} -0.85 & 0 & 0 \\ -0.2 & 4 & 0 \\ 1 & -20 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix} \tag{2.6}$$

Obviously, in this matrix, the number of rows is larger than that of columns and it is not a square matrix. As the resolving method, Heijungs [4] suggest to add hollow processes to the matrix, so as to make it to be a square one, as follows.

$$\mathbf{A}'' = \begin{matrix} \text{ground metal} \\ \text{scrap} \\ \text{can material} \\ \text{can} \\ \text{used can} \end{matrix} \begin{pmatrix} -0.85 & 0 & 0 & 1 & 0 \\ -0.2 & 4 & 0 & 0 & 1 \\ 1 & -20 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{pmatrix} \tag{2.7}$$

In Eq. (2.7), the fourth and the fifth columns are the added hollow processes. The problem in this method is, in the two columns, why the value 1 is given to ground metal and scrap, while not can or can material. How to select the flows of ground metal and scrap has not ever stated. Therefore, it is difficult to determine the correct position to add hollow processes in the non-single matrix.

It has been mentioned above, in a product system of LCA, not all the economic flows are needed in calculating the process vector **p**. Then, which of them should be selected to compose the coefficient matrix and which should not? In Fig. 2.1 and Eq. (2.6), some flows in the matrix are useless in calculating the absolute values of the processes; therefore, they are needed to be cut off from the product system and be moved from the matrix. Then, how could it be dealt with? In order to distinguish the cut-off flows, whose process data are not concluded in the product system, a criterion of automatic cut-off has been defined as [4]: *a good i is cut-off when it is the input of one (or more) process j and not the output of any process, and a waste i is cut-off when it is the output of one (or more) process j and not the input of any process.* This criterion surely can distinguish the cut-off flows, whose corresponding processes do not exist in the product system, and removed them from the matrix **A**. However, when there is a closed recycling loop in the product system, the matrix **A** cannot be guaranteed to be a square one yet.

For example, in the product system shown in Fig. 2.1, when applying the criterion of automatic cut-off to Eq. (2.6), the coefficient matrix **A** will be recomposed as:

$$\mathbf{A}''' = \begin{matrix} \text{scrap} \\ \text{an material} \\ \text{can} \\ \text{used can} \end{matrix} \begin{pmatrix} -0.2 & 4 & 0 \\ 1 & -20 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix} \tag{2.8}$$

In Eq. (2.8), ground metal is automatically cut-off since it is only inputted into the process of ‘Plate Rolling’, while outputted from none of the processes. However, scrap remains in the matrix yet, since it is outputted from ‘Can Production’ and inputted into ‘Plate Rolling’. As a result, the matrix **A** is still a non-singular.

Finally, Heijungs developed a general formulation of the refined model, which can deal with all kinds of problems in matrix-based LCI analysis [4]. In this formulation, as the preparation of matrix composition, the following operations are obliged.

Firstly, all the flows are divided into economic flows and environmental flows, and all the economic flows are divided into two categories: goods and waste.

Secondly, allocation operation is carried out to each multifunctional process, either the byproduct is in open-loop or closed-loop.

Finally, a criterion of automatic cut-off is applied to the composed non-singular to convert it to be a square one.

However, separating all the economic flows into goods and waste depends on practitioner’s subjective judgment, and it is very time and labor consuming since there are a great deal of process data in a practical LCA case study. It is pointed out by ISO series [2] that the need for allocation is avoided in such cases, in which the byproducts from the multi-functional processes are completely recycled in the product system, which means that they are in closed-loop recycling. Therefore, the model and the software by Heijungs are so complicated that they are not appropriate to the practitioners, who have a few LCA knowledge or experience.

Moreover, Halada has ever had a discussion about the matrix-based LCI analysis and proposed a method for the matrix-based LCI analysis [25, 26]. In the discussion, a description rule, which can easily connect to a matrix of process flow, is proposed. In the method for the matrix-based LCI analysis, in order to resolve the problem of the existence of the superfluous flows in the coefficient matrix, the concept of "stock"s of material as variables is introduced. In the product system, assumed processes of "stock" are added to the superfluous flows so as to make the coefficient matrix to be a square one. However, which flows are the superfluous ones still depends on the LCA practitioner's judgments. Therefore, the approach of matrix-based LCI analysis proposed by Halada will become very complicated when many processes, recursive loops and recycled loops are included in the product system. Certainly, the approach cannot be easily carried out by computer program. This method is somewhat similar to the method of adding hollow processes proposed by Heijungs, which is shown in Eq. (2.7) above. As a result, the coefficient matrix is expanded and the burden of calculation in LCI analysis is increased as well.

(2) In the conventional matrix method, when determining the boundary condition for the economic flows at the product system boundary, it is assumed that all boundary condition values of the economic flows are zero except for the one, which is defined as the functional unit. However, besides the functional unit, there are also other non-zero ones in the practical case. What are inputted into and outputted from the product system are not only the functional unit but also some inputted parts or some outputted byproducts, whose boundary conditions are unknown. So, how should the system boundary condition be determined?

(3) It has been mentioned above that there are a great number of flows in the product system of a practical LCA case study and many of them are useless in calculating the process vector **p**, which means they will not affect the final cumulative environmental loads based on the product system. Then, how should these trivial flows be dealt with? So far, based on the matrix method for LCI analysis, this problem has not been resolved reasonably and clearly.

Except for the method of composing the square coefficient matrix to calculate the quantitative occurrences of unit processes, another way of dealing with the balance equations of materials goes back to the problem of having an over-determined system of equations. Heijungs [4] has ever stated the method of using pseudo-inverse matrix to calculate the process vector, as shown in the following equations:

$$\mathbf{Ap} = \boldsymbol{\alpha} \tag{2.1}$$

$$\mathbf{A}^{\mathrm{T}}\mathbf{Ap} = \mathbf{A}^{\mathrm{T}}\boldsymbol{\alpha} \tag{2.9}$$

$$\mathbf{p} = \left(\mathbf{A}^{\mathrm{T}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{T}}\boldsymbol{\alpha} \tag{2.10}$$

If the coefficient matrix **A** is composed of all the economic flows, it will not be a square matrix necessarily. Consequently, the system boundary vector **α** cannot be determined surely, since the absolute values of some flows are unknown at this stage. For instance, with regard to the coefficient matrix in Eq. (2.6), the absolute values of the flows of 'ground metal' and 'scrap' cannot be known before the LCI analysis. That means how much 'ground metal' is needed and how much 'scrap' is outputted in the product system are unknown. Therefore, the system boundary vector corresponding to the coefficient matrix cannot be determined.

On the other hand, if the system boundary vector **α** is determined by using the conventional method: the system boundary conditions of the flows, which are defined as the functional unit of the product system, are given values, and the others are set to be zero, a solution of the balance equations will be worked out. However, in this case, this method is to find the process vector that makes a best fit to the balance equations of materials, while not to calculate the exact process vector. Therefore, the method of using pseudo-inverse matrix cannot provide a correct and reliable result of LCI analysis.

Due to the problems shown above, the matrix method for LCI analysis is rarely used in practical LCA case studies. In this chapter, aiming to solve those problems, a new practical approach for matrix based LCI is proposed.

§ 2.4 Development of the practical approach for matrix-based LCI analysis

In order to make the matrix method for LCI analysis more practicable and appropriate to the LCA practitioners with little LCA knowledge, a practical approach for the matrix method is proposed here. By this approach, few judgments by LCA experts are needed in this practical approach, which fits computer program.

§ 2.4.1 Composition of the square coefficient matrix

It has been stated above that the main idea in the matrix method for LCI analysis is the systematic construction of a set of linear balance equations of materials in the product system as shown in Eq.

(2.11). By solving the balance equations, the quantitative occurrence of each unit process to meet the product system function is derived, namely, the process vector **p** is calculated.

$$\mathbf{Ap} = \boldsymbol{\alpha} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \\ \\ p_m \end{pmatrix} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \\ \alpha_m \end{pmatrix} \tag{2.11}$$

In the matrix method, each balance equation is corresponding to one material, and each scaling factor p_i in the process vector **p** is corresponding to one unit process. In general, if there is only one solution of linear simultaneous equations, the number of the materials is equal to that of the scaling factors, namely $m = n$. From Eq. (2.2), it can also be known that matrix **A** should be a square matrix. Therefore, in order to obtain the process vector p, only n balance equations of the materials are needed, but not all of the materials in the product system. Then, how the necessary materials could be selected to compose the coefficient matrix **A** and the set of balance equations?

In a unit process, the quantitative occurrence of the process is determined by the condition of one economic flow only, which is the most important flow and makes the process linked with another one or ones decisively. If this flow could be determined in advance based on each of the unit processes, then, the coefficient matrix **A** may be composed of these flows and matrix method will become easy. In practical LCA case studies, fortunately, it is easy to determine these flows when compiling the unit processes by making the purpose of introducing the processes into product system clear.

[Definition 1] The flow, which determines the quantitative occurrence of a unit process in the product system, is defined as the functional flow of the unit process.

The functional flow in each unit process is defined based on the individual process but not the product system, therefore, the recursive loops or the recycling loops in the product system will not make trouble in matrix composition.

In the practical approach of the matrix method proposed in this thesis, it is assumed that each of the unit processes of the product system mainly operates for one economic flow, which is defined as functional flow. Then, the scaling factor is determined by the only functional flow of each unit process, and the coefficient matrix is composed of all the defined functional flows in the product system. So that, the coefficient matrix **A** can be composed as:

$$\mathbf{A} = \begin{bmatrix} f_1 & a_{12} & \cdots & a_{1n} \\ a_{21} & f_2 & & \vdots \\ \vdots & & \ddots & \vdots \\ a_{n1} & \cdots & \cdots & f_n \end{bmatrix} \tag{2.12}$$

Here, f_i is the value of the functional flow in the *i*th process, and f_i is not zero. So, it is obvious that **A** is a square matrix and Eq. (2.2) has a unique solution. Moreover, since there are no two same processes in the product system and all the processes are different from each other, any of the columns in the coefficient matrix **A** cannot be eliminate by linear transformation. Therefore, matrix A is also guaranteed to be a non-singular. In real case, f_i does not always exist on diagonal position of the matrix **A**, but there is no any influence on LCI analysis.

Therefore, what is the most important in the practical approach is to define the functional flow for each unit process clearly. Then, how it should be defined?

(a) If there is only one outputted economic flow (including product and service), it is easy to define the functional flow by the outputted economic flow. Therefore, when compiling a unit process, it is strongly recommended that all the data should be compiled corresponding to only one function in the unit process. In some of the LCA databases, each unit process is compiled to operate for only one product or service, such as most of the processes in JLCA database [13].

(b) However, in practice, there are still many multifunctional processes, which output more than one valuable products or services. Then, how could the main functional flow be defined? We can define the functional flow by the most important material by making clear the main purpose of introducing the multifunctional process into the product system for LCA. In general, the main product of the multifunctional process is defined as the functional flow, and the other products are overlooked at this stage. The definition of the functional flow in a multifunctional process does not mean to do allocation in the process; it is just to define the flow, which could determine the quantitative occurrence of the process in the product system. As to the byproduct etc. in a multifunctional process, allocation operation will be carried out in this stage of matrix composition; it will be done in the following stage of surplus flows' treatment after confirming that the byproduct is exported out of the system boundary. Although the byproduct is not defined as the functional flow in this multifunctional process, it does not mean that it will be removed from the coefficient matrix. If it is defined as the functional flows in any other unit process, it will still exist in the coefficient matrix.

(c) Moreover, in order to compose a square coefficient, it is needed to guarantee that only one functional flow is defined in each unit process, and all the defined functional flows are different from each other. The most important characteristics of functional flow are summarized as:

- The functional flow is the most important flow in a unit process and it represents the purpose of introducing the process to the product system.

For example, the purpose of electricity production process is to produce electricity, so the outputted flow of electricity is defined as the functional flow for the process. In some cases, the determination of the functional flow depends on the product system. Therefore, to clarify the purpose of introducing each process to the product system is extremely important. For example, in the incineration process of wastepaper, electricity is often produced. This process has two functions: wastepaper incineration and electricity production. Since the purpose of introducing this process into the product system is to dispose the wastepaper, the inputted wastepaper is defined as the functional flow. Therefore, the functional flow is not always the outputted flow; in some cases, it is the inputted flow.

- The functional flow of a unit process is always be used out in the product system, or it is defined as the functional unit of the product system.

Therefore, to check if a flow is used out in the product system or if it is defined as the functional unit of the product system could help to define the functional flow. Making clear these two characteristics, it is easy to define the functional flows of unit processes and compose the coefficient matrix in practical LCA case studies.

In the product system shown in Fig. 2.1, 'used can' is defined as the functional unit of the product system and the purposes of the processes of 'Can Production' and 'Plate Rolling' are to product 'can' and 'can material', therefore, the flows of 'used can', 'can' and 'can material' are defined as the functional flows respectively. Then, the coefficient matrix **A** is composed of these flows, which is the same as Eq. (2.5) and it is a square matrix necessarily.

$$\mathbf{A} = \begin{matrix} \text{can material} \\ \text{can} \\ \text{used can} \end{matrix} \begin{pmatrix} 1 & -20 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix} \tag{2.5}$$

As shown above, after defining the functional flow in each unit process, the square coefficient matrix **A** could be composed of all the functional flows, but not all the economic flows in the product system. Same with the conventional matrix method, columns represent the processes and rows represent the flows. The inputted flows are expressed by negative coefficients and outputted flows by positive ones.

If the coefficient matrix in the example of aluminum can is composed by using the refined matrix model of Heijungs [4], then, a rectangular matrix, which is shown in Eq. (2.6), is composed first. Then, the multifunctional process of 'Can Production' is divided into two processes to allocate the materials and environmental loads to 'can' and 'scrap'. The allocation of the process of 'Can

Production' is shown in Fig. 2.2.

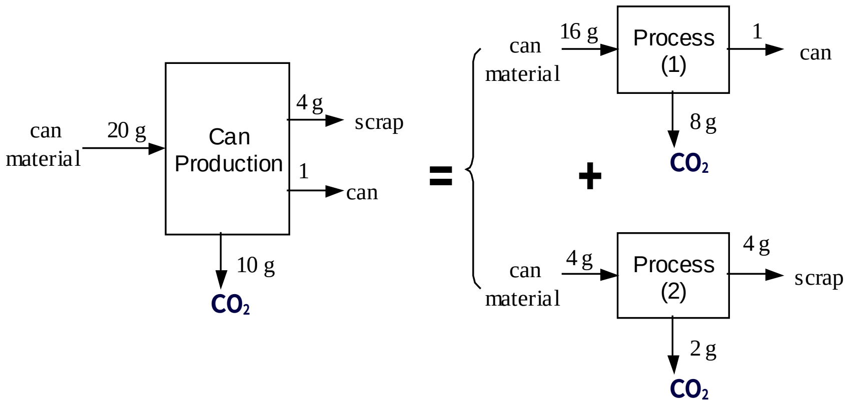

Fig. 2. 2 Allocation of the process of 'Can Production'

After the allocation, the coefficient matrix is recomposed, as shown in Eq. (2.14).

$$\mathbf{A}_1 = \begin{matrix} \text{ground metal} \\ \text{scrap} \\ \text{can material} \\ \text{can} \\ \text{used can} \end{matrix} \begin{pmatrix} -0.85 & 0 & 0 & 0 \\ -0.2 & 0 & 0 & 4 \\ 1 & -16 & 0 & -4 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{2.13}$$

Finally, using the automatic cut-off criterion, which has ever been mentioned in section 2.3 of this chapter, the flow of 'ground metal' in Eq. (2.13) is deleted from the matrix. Consequently, the coefficient is converted to be a square one, which is shown in Eq. (2.14)

$$\mathbf{A}_2 = \begin{matrix} \text{scrap} \\ \text{can material} \\ \text{can} \\ \text{used can} \end{matrix} \begin{pmatrix} -0.2 & 0 & 0 & 4 \\ 1 & -16 & 0 & -1 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{2.14}$$

Comparing Eq. (2.14) with Eq. (2.5), it is known that the coefficient matrix is expanded. Consequently, it will increase the burden of calculation in LCI analysis. For instance, it will cost more time to calculate the inverse matrix of the coefficient matrix. Therefore, compared with the refined matrix model of Heijungs, the method of the coefficient matrix composition proposed herein is simplified. By the refined matrix model of Heijungs, the allocation of the process of 'Can Production' is obliged to carry out. However, it will be shown later, since the scrap is completed recycled in the product system, it is unnecessary to carry out the allocation. Therefore, the refined matrix model of Heijungs sometimes requires unnecessary allocation, which makes the LCI analysis more complicated.

[*Functional flow has been defined above. Different from it, a functional unit is a measure of the performance of the functional outputs of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related [1].*]

§ 2.4.2 Composition of the system boundary vector and environmental load matrix

After composing the coefficient matrix **A**, it is needed to determine the system boundary vector **α**. Since only functional flows are arranged in the coefficient matrix **A**, just the boundary conditions of the functional flows are needed to determine. Moreover, since all the functional flows are used out in the product system or defined as the functional unit of the product system, as the general method for determining the system boundary vector **α**, the system boundary conditions of the functional flows, which are defined as the functional unit of the product system, are given values, and the others are set to be zero. So that, the second problem shown in section 2.3 is resolved.

Then environmental load matrix **B** is composed of the environmental load flows to be studied. After that, the process vector **p** can be derived by using Eq. (2.2) and the final environmental load vector **β** is calculated by using Eq. (2.3) or Eq. (2.4).

In the product system shown in Fig. 2.1, the system boundary vector **α** is composed as:

$$\boldsymbol{\alpha} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \tag{2.15}$$

By Eq. (2.2), the process vector **p** is calculated as:

$$\mathbf{p} = \begin{pmatrix} 20 \\ 1 \\ 1 \end{pmatrix} \tag{2.16}$$

The environmental load matrix **B** is composed of ‘CO_2’ and ‘solid waste’.

$$\mathbf{B} = \begin{matrix} \text{solid waste} \\ \text{CO2} \end{matrix} \begin{pmatrix} 0.05 & 0 & 0 \\ 0.5 & 10 & 25 \end{pmatrix} \tag{2.17}$$

By using Eq. (2.3) or Eq. (2.4), the final environmental load **β** vector is derived as:

$$\boldsymbol{\beta} = \begin{pmatrix} 1 \\ 45 \end{pmatrix} \tag{2.18}$$

From Eq. (2.18), it is known that the final cumulative solid waste in the product system is 1 g and the cumulative CO_2 emission is 45 g.

§ 2.4.3 Composition of the surplus flow matrix

[Definition 2] [Except for the flows in the coefficient matrix **A** and the environmental matrix **B**, all flows are useless in calculating the quantitative occurrence of each unit process, therefore, they are defined as the surplus flows. The matrix, which is composed of them, is defined as the surplus flow matrix, and noted by symbol **C**.]

Then, the final surplus flow vector $\boldsymbol{\gamma}$, whose elements show the finally cumulative values of the surplus flows in the product system, can be calculated as:

$$\boldsymbol{\gamma} = \mathbf{C}\mathbf{p} \tag{2.19}$$

$$\boldsymbol{\gamma} = \mathbf{C}\mathbf{A}^{-1}\boldsymbol{\alpha} \tag{2.20}$$

Same with the matrix **A** and **B**, in the matrix **C**, columns represent the processes and the rows represent the flows. Input flows are expressed by positive coefficients and output flows by negative ones. In such a way, the third problem in the conventional matrix method stated in section 2.3 is resolved. The further treatment about the surplus flows will be introduced in section 2.4.4 and Chapter 4.

In the product system shown in Fig. 2.1, the surplus flow matrix **C** is composed of the residual flows of ‘ground metal’ and ‘scrap’ as:

$$\mathbf{C} = \begin{matrix} \text{ground metal} \\ \text{scrap} \end{matrix} \begin{pmatrix} -0.85 & 0 & 0 \\ -0.2 & 4 & 0 \end{pmatrix} \tag{2.21}$$

By using Eq. (2.19) or Eq. (2.21), the final surplus flow vector $\boldsymbol{\gamma}$ is calculated to be:

$$\boldsymbol{\gamma} = \begin{pmatrix} -17 \\ 0 \end{pmatrix} \tag{2.22}$$

From Eq. (2.22), we know that the required value of ground metal in the product system of aluminum can is 17 g. Moreover, since the value of scrap in vector $\boldsymbol{\gamma}$ is 0, till now, we get to know that the scrap is complete recycled in the product system and it is a closed recycling loop. Towards the closed loop, allocation can be avoided.

§ 2.4.4 Allocation problem in this improved matrix method

In the matrix method, the materials and parts etc., which are imported into the product system from outside, and the byproduct and valuable waste for recycling etc., which are exported from the product system to outside, are all included in the surplus flow vector $\boldsymbol{\gamma}$. In the conventional process analysis based LCI, the environmental loads associated with the surplus flows are neglected by setting them at the site of outside of the LCA scope. However, in order to realize a complete LCA and obtain a more correct LCA result, it is necessary to take the environmental loads into account. Namely, it is needed to add the environmental loads corresponding to the imported materials, and subtract those corresponding to the exported materials from the LCI result; the latter is usually named as allocation operation. Adding the environmental loads corresponding to the imported materials to LCI result is called as addition operation in this thesis. Herein, how the surplus flows should be dealt with is discussed. As a result, the matrix-based LCI is reasonably integrated.

With respect to the allocation problem, there have been many discussions [14, 16-18, 22-24]. In ISO 14041, it is emphasized that allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration. For example, if allocation is made to usable products (e.g. intermediate or discarded products) leaving the system, then the allocation procedure shall be similar to the allocation procedure used for such products entering the system [2]. The conventional allocation methods are mostly based on the individual processes, while not based on the whole product system. In the conventional allocation, in some cases, the imported materials and the exported materials are often dealt with separately with different allocation procedures. As a result, the conventional allocation is not always consistent with ISO standards.

Here, based on the final surplus flow vector $\boldsymbol{\gamma}$, allocation is carried out based on the whole product system. On the vector $\boldsymbol{\gamma}$, if the value of a element is zero, it shows that the materials is completed used out in the product system and it is in a closed-loop, therefore, allocation may be avoided to the material. Since there are a large amount of surplus flows in vector $\boldsymbol{\gamma}$, it is difficult to study the environmental influences of all the surplus flows one by one. Therefore, as the appropriate and practical allocation method, the essential surplus flows, whose coefficients in vector $\boldsymbol{\gamma}$ are large, are selected firstly. After that, the allocation is considered towards the exported essential surplus flows and the addition is considered towards the imported essential surplus flows. Therefore, herein, different from the conventional matrix method, allocation is not carried out recklessly so as to compose a square coefficient matrix; it is carried out to the materials, which really need the allocation operations. Consequently, the efficiency of the matrix method proposed in this chapter is improved.

The concrete and practical allocation (or addition) methods towards the essential surplus flows are summarized to be the external allocation method and the interior allocation method, which are shown as follows.

(1) The simply simplest method for allocation (or addition) is named as direct method or external method herein. In this method firstly, the unit environmental load values of the essential surplus flows are investigated or calculated. After that, the environmental influences of the surplus flows are added to the LCI result, which is calculated in Eq. (2.3) or Eq. (2.4). The environmental loads corresponding to the imported surplus flows are added into the LCI result, and those corresponding to the to the exported surplus flows are subtracted from the LCI result. As the methods for obtaining the environmental load values per unit of the essential surplus flows, we could use the data from literatures, or public LCA database. Otherwise, we can calculate them by using the Input-Output Analysis (IOA) method. The IOA method and how it could be jointed with the matrix method for LCI will be introduced in Chapter 4. By this allocation (or addition) method, the environmental influences are studied outside of the product system and added to the LCI directly, and the composed life cycle of the product will not be changed any more. This direct approach for allocation (or addition) is very easy to apply, and the composed product system will not be changed. However, the result by this method is of low reliability due to the low accuracy of the environmental load values per unit. Moreover, since this allocation (or addition) is done based on the final LCI result, the influence of the unit environmental load values to the final LCI result cannot be studied by using the matrix-based sensitivity analysis.

(2) The other allocation (or addition) method introduced here is the interior method. In a practical LCA case study, surplus flows occur because process data are unknown for certain processes. Therefore, if the process data are collected and the processes are introduced into the product system, the surplus flows will be not surplus flows any longer. In the interior allocation (or addition) method, keeping the original processes in the product system as constant, other processes corresponding to the essential surplus flows are introduced into the product system. In the introduced processes, the original essential surplus flows are defined as the functional flows. By re-composing the necessary matrices for LCI analysis and recalculating the environmental loads, the effect of the essential surplus flows could be added to the LCI result. Since the environmental loads corresponding to the surplus flows could be avoided by introducing new processes into the product system, the introduced processes are generally called avoided processes, and this allocation (or addition) method is called as avoided process method as well.

In this allocation (or addition) method, what is most important is to compile the new processes relevant to the essential surplus flows. If the surplus flow is part or product, it is needed to compile an independent production process of the part or product. If the surplus flow is used product or waste, it is needed to compile the disposal process of the used product or waste. If it is difficult to compose the direct production process of the surplus flow, some other methods could be used to obtain the avoided process.

[**Avoided process 1:**] We could divide the original multifunctional process into two sub processes, then, take one of the sub process as the avoided process, which is corresponding to the surplus flow. After that, the avoided process is introduced into the product system. While the original multifunctional process should be kept as unchanged in the product system. Consequently, the essential surplus flow becomes the functional flow of the sub process. By re-composition of the matrices for LCI analysis, this flow is removed from the surplus flow matrix **C**, and arranged in the coefficient matrix **A**. By recalculation, the environmental influence of the original essential surplus flow can be added to the LCI result automatically. Of course, if there is more than one by products in a multifunctional process, the process should be divided into more than two sub processes. Concerning process division, it can be realized depending on the physical value of the products or the economic value of the products [16, 17]. To obtain the information about the process division might be somewhat delicate or difficult.

[**Avoided process 2:**] If we have known the unit environmental load values of the essential surplus flow, we could compose such a process and treat it as the avoided process. In the process, only the essential surplus flow is inputted or outputted accompanied with the environmental loads. Since it is a mono-functional process, the essential surplus flow is the functional flow.

[**Avoided process 3:**] Otherwise, we could select another product in society, which has the same function of the essential surplus flow, as the substituting product of the essential surplus flow. So that, the product process of the selected product may be introduced into the product system to substitute the avoided process.

The merit of the avoided process method of allocation (or addition) is that by introducing avoided process into the product system, the allocation (or addition) can be carried out automatically in the composition and calculation of matrix. While, the original processes in the product system will not be changed.

How the issue of allocation (or addition) is dealt with in the matrix-based LCI is introduced above. The merits and the shortcomings of the two allocation (or addition) methods (external method and interior method) are discussed as well. Both of the allocations are carried out after confirming that the surplus flows are surely exported out of the product system based on the final surplus flow vector $\boldsymbol{\gamma}$, while not carried out recklessly so as to compose a square coefficient matrix. Therefore, the matrix method proposed in this thesis is more efficient. Furthermore, compared the external method, in which the environmental effect of surplus flows are directly added to the LCI result, the interior method of introducing avoided process into the product system is more appropriate to the matrix based LCI. It is because that the accuracy of external method is higher and the information about allocation is included in the recomposed matrix.

About the case study shown in Fig. 2.1, from Eq. (2.22), it is known that the required amount of ground metal in the product system of aluminum can is 17 g and the exported value of scrap 0. Therefore, addition is necessary to ground metal and allocation is not necessary to scrap.

If the external method is adopted, it is needed to investigate the unit environmental load of the ground metal. From the JLCA database [13], it is learned the unit CO_2 emission of the aluminum ground metal is about 10 g-CO_2/g ground metal. Consequently, the CO_2 emission associated with 17 g ground metal is calculated to be 170 g. Adding this value to the result in Eq. (2.18), the total CO_2 emission is derived to be 215 g.

If we adopt the interior method, it is needed to compile the avoided process. The production process of ground metal is composed to serve as the avoided process, as shown in Fig. 2.3. Of course, the outputted ground metal is defined as the functional flow of the process. In a practical LCA case study, more detailed and complicated avoided processes will be composed for the surplus flows.

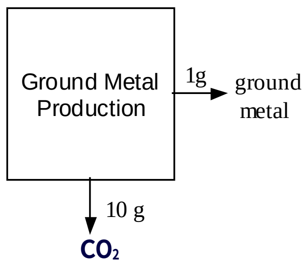

Fig. 2. 3 Production process of ground metal

Then, after adding this process into the product system shown in Fig. 2.1, the coefficient matrix **A** is recomposed of all the functional flows, as shown in Eq. (2.23). In this coefficient matrix **A**, the fourth column represents the added avoided process of the ground metal.

$$\mathbf{A} = \begin{matrix} \text{ground metal} \\ \text{can material} \\ \text{can} \\ \text{used can} \end{matrix} \begin{pmatrix} -0.85 & 0 & 0 & 1 \\ 1 & -20 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{2.23}$$

$$\boldsymbol{\alpha} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \tag{2.24}$$

The system boundary vector **α** is recomposed as Eq. (2.24). Using Eq. (2.2), the process vector **p** is calculated as:

$$\mathbf{p} = \begin{pmatrix} 20 \\ 1 \\ 1 \\ 17 \end{pmatrix} \tag{2.25}$$

The environmental load matrix **B** is recomposed as:

$$\mathbf{B} = \begin{matrix} \text{solid waste} \\ \text{CO2} \end{matrix} \begin{pmatrix} 0.05 & 0 & 0 & 0 \\ 0.5 & 10 & 25 & 10 \end{pmatrix} \tag{2.26}$$

Using Eq. (2.3) or Eq. (2.4), the final environmental load vector **β** is derived as:

$$\boldsymbol{\beta} = \begin{pmatrix} 1 \\ 215 \end{pmatrix} \tag{2.27}$$

From Eq. (2.27), it is known that the final CO_2 emission is 215 g. Therefore, it is confirmed that after adding the avoided process into the product system, the allocation is carried out automatically by recomposing the necessary matrices and recalculating. Moreover, the surplus flow matrix **C** is recomposed as:

$$\mathbf{C} = \text{scrap} \begin{pmatrix} -0.2 & 4 & 0 & 0 \end{pmatrix} \tag{2.28}$$

By using Eq. (2.19) or Eq. (2.20), the final surplus flow vector is calculated to be:

$$\boldsymbol{\gamma} = \begin{pmatrix} 0 \end{pmatrix} \tag{2.29}$$

From Eq. (2.29), it is known that since the value of the cumulative surplus flow in the product system is zero, no more allocation (or addition) is needed. Therefore, these are the final LCI results.

In such a way, in this chapter, the matrix-based LCI analysis is generalized. The proposed practical approach of matrix method for LCI analysis is very effective and easy to use, especially to the practitioners, who have a few experiences and knowledge of LCA.

§ 2.4.5 General procedure of the matrix method for LCI analysis

The algorithm of the matrix method for LCI analysis has been generalized above. Herein, the general procedure of the matrix method is developed and it is shown in Fig. 2.4.

Firstly, the necessary process data are collected.

Secondly, a functional flow is defined in each unit process and the environmental flows of concern are determined and noted.

Thirdly, coefficient matrix is composed of the defined functional flows. The system boundary vector is composed and the process vector is calculated.

Fourthly, the environmental load matrix is composed and the final environmental load vector is calculated. Meanwhile, the surplus flow matrix is composed and the final surplus flow vector is calculated as well.

Then, based on the final surplus flow vector, allocation is carried out, if it is necessary.

Finally, the obtained LCI result is interpreted.

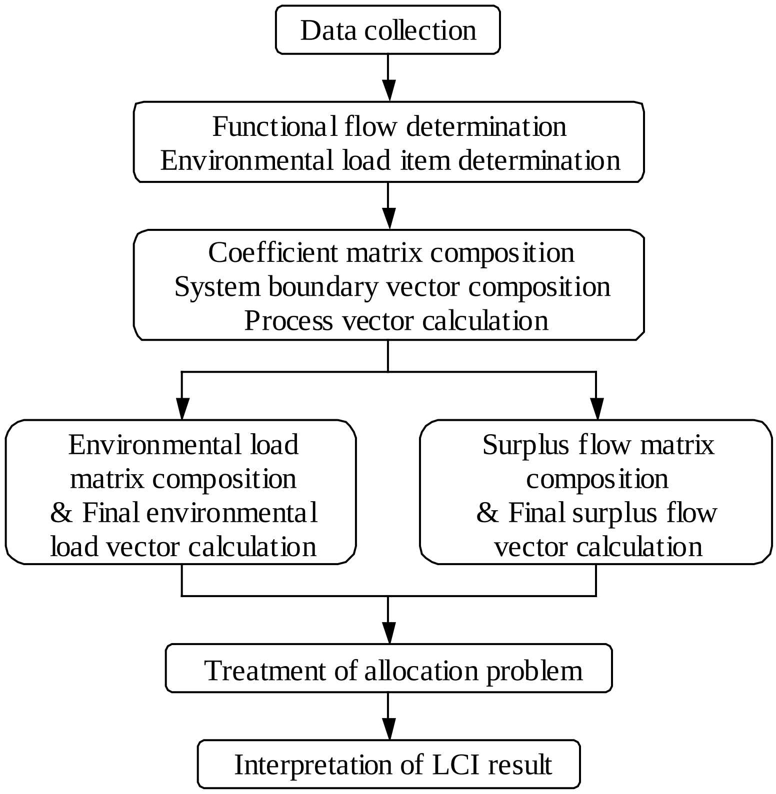

Fig. 2. 4 General procedure of the matrix method for LCI analysis

§ 2.4.6 Comparison of the process flow diagram method and the matrix method

The process flow diagram method and the matrix method are two main methods for LCI analysis. All the product system for LCA, which can be analyzed by the process flow diagram method, could be dealt with by using the matrix method as well. Compared with the process flow diagram method, the merits of the matrix method have been simply stated in section 2.1.

The general approach and the procedure of the matrix method for LCI analysis have been shown above. Herein, using the example of LCA case study shown in Fig. (2.1), the proposed matrix method in this chapter and the process flow diagram method [7] are simply compared. The LCI analysis by using the proposed matrix method has been shown above. While, the LCI analysis by using the process flow diagram method is shown as follows.

The process flow diagram method is a bottom-up technique. After having drawn the process flow diagram of the product system, in which boxes generally represent processes and arrows the commodity flows (as shown in Fig. (2.1)), the quantitative occurrence of each unit process to meet the product system function is calculated in upstream order. Based on the process flow diagram shown in Fig. (2.1), firstly, since the functional unit of the product system is set to be the outputted flow of 1 'used can', the quantitative occurrence of the process of 'Can Use' is calculated to be 1 and 1 'can' is needed to input into the process. Secondly, the process of 'Can Production' needs to produce 1 'can' and the quantitative occurrence of the process can be derived to be 1 as well. Furthermore, it can be known that 20 g 'can material' shall be inputted into the process of 'Can Production' in order to product one can. Thirdly, when 20 g 'can material' is outputted from the process of 'Plate Rolling', the necessary quantitative occurrence of the process is derived to be 20. Consequently, in such a one by one upstream process, the quantitative occurrences of all the unit processes are obtained to be 20, 1 and 1. This result is consistent with the one obtained by using the matrix method, which is shown in Eq. (2.16). Using the calculated quantitative occurrences of all the unit processes, the final cumulative environmental loads can be calculated as:

$$\text{solid waste (g)}:\ 0.05\times 20+0\times 1+0\times 1=1 \tag{2.30}$$

$$CO_2\ \text{(g)}:\ 0.5\times 20+10\times 1+25\times 1=45 \tag{2.31}$$

The other materials, which are inputted into or outputted from the product system, can be calculated as:

$$\text{ground metal (g)}:\ -0.85\times 20+0\times 1+0\times 1=-17 \tag{2.32}$$

$$\text{scrap (g)}:\ -0.2\times 20+4\times 1+0\times 1=0 \tag{2.33}$$

These results are quite consistent with the ones shown in Eq. (2.18) and Eq. (2.22).

Therefore, it shows that the matrix method for LCI analysis proposed in this chapter is effective and it can give us a correct and reliable LCI analysis result. The allocation operations in the process flow diagram method, such as the substitution method and the partitioning method, are basically similar to those in the matrix method; therefore, the comparison of allocation is omitted herein.

§ 2.4.7 Comparison of the conventional matrix method and the present one in this thesis

In this section, the practical approach of matrix method for LCI analysis in this thesis is compared with the conventional one, which is proposed by Heijungs [4], and the merits of former are shown. The details of the comparison are shown in Table 2.1.

In the conventional approach, in order to compose the proper matrices, it is needed to divide all the input/output flows into economic flows and environmental load flows and separate the economic flows into tow categories: goods and waste. Furthermore, before the matrix composition, allocations have to be carried out to all the multifunctional processes, whether the byproducts are in open-loop or in closed-loop. Finally, an automatic cut-off criterion is also required to improve the coefficient matrix **A** to be a square one. In contrast, in the practical approach in this paper, it is only necessary to specify the functional flows and the environmental load flows. Then, the square coefficient matrix **A** could be composed of the functional flows directly. And the allocation is only carried out to the valuable material, which is in open-loop recycling. Therefore, it is obvious that the practical approach in this paper is much easier and more consistent to the ISO serious. The efficiency of the practical approach proposed in this paper will be shown in the following example.

Table 2. 1 Comparison of the conventional matrix method and the present one in this thesis

	Matrix method by Heijungs [4]	Matrix method in this thesis
Input/Output Flow Notation	All the flows are divided into economic flows and environmental flows, and all the economic flows are divided into two categories: goods and waste.	A functional flow is defined in each unit process, and the environmental flows of concern are determined and noted.
Allocation	Allocation operation is carried out to each multifunctional process, before composing the matrices, either the byproduct is in open-loop or closed-loop	Based on the final surplus flow vector, allocation is only carried out on the byproduct, which is in open recycling loop.
Automatic cut-off criterion	Needed	Not needed
Method for the coefficient matrix composition	A common matrix is composed of all the economic flows, then, the square coefficient matrix is separated from the common matrix by an automatic cut-off criterion.	The square coefficient matrix is composed of the functional flows directly.

§ 2.5 An example of LCA case study using the practical approach of matrix method

In this section, using an extended example that Heijungs set out in the book (chapter 3.11) [4], how the new practical approach of matrix method for LCI analysis is applied is shown, and the applicability and effectiveness is examined. The difference between the practical approach proposed in this chapter and the general formulation of the refined matrix model of Heijungs is shown concretely.

The product system in the example case study comprises two alternative product systems with two separate reference flows emanating from two consumption processes. The product system contains two multifunctional processes as well. The relations of the processes in the product system are shown in Fig. 2.5. In this case study, '10 hr of light' are specified as the functional unit, and '10 hr of incandescent lamp light' and '10 hr of fluorescent lamp light' are defined as the two alternative reference flows. The purpose is to study the environmental loads corresponding to '10 hr of light', and compare the two alternatives. This case study is carried out by using the refined model of Heijungs and the practical approach of matrix-based LCI respectively, and the two kind of analysis are compared.

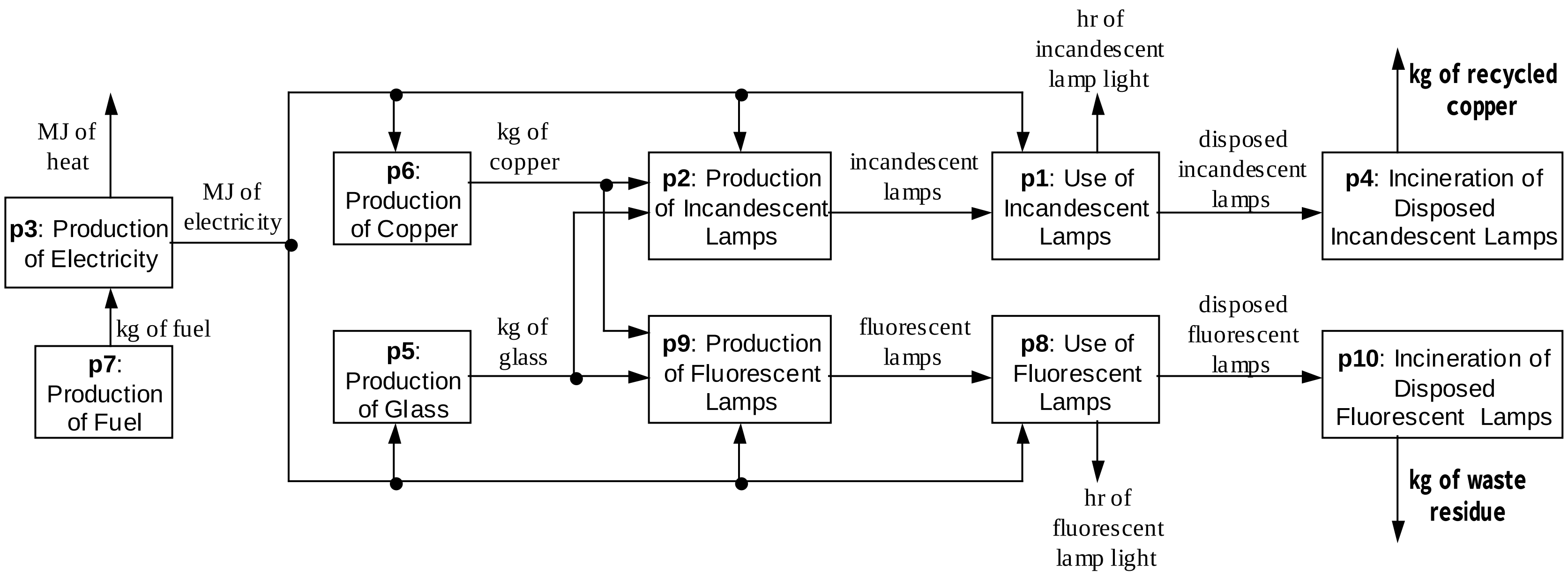

Fig. 2. 5 Process construction in the case study of lamps

§ 2.5.1 LCI analysis by using the refined model Heijungs [4]

Using the general formulation of the refined model for inventory analysis developed by Heijungs, firstly, all the flow are divided into economic flows and environmental flows and all the economic flows are classified into goods and waste, as shown in the following table.

Table 2. 2 Classification of the flows in the case study of lamps

ECONOMIC FLOWS		ENVIRONMENTAL FLOWS
Goods	**Waste**	
m1: incandescent lamps	m3: disposed incandescent lamps	l1: kg of carbon dioxide to air
m2: MJ of electricity	m9: disposed fluorescent lamps	l2: kg of sulphur dioxide to air
m4: hr of incandescent lamp light	m13: kg of waste residue	l3: kg of copper to soil
m5: kg of glass		l4: kg of sand
m6: kg of copper		l5: kg of copper
m7: kg of fuel		l6: kg of crude oil
m8: fluorescent lamps		
m10: hr of fluorescent lamp light		
m11: MJ of heat		
m12: kg of recycled copper		

After the classification of the flows in the product system, a technology matrix **A** is composed of all the economic flows, as:

$$
\mathbf{A} = \begin{array}{c} \\ m1 \\ m2 \\ m3 \\ m4 \\ m5 \\ m6 \\ m7 \\ m8 \\ m9 \\ m10 \\ m11 \\ m12 \\ m13 \end{array}
\begin{array}{c} \begin{array}{cccccccccc} p1 & p2 & p3 & p4 & p5 & p6 & p7 & p8 & p9 & p10 \end{array} \\
\left(\begin{array}{cccccccccc}
-1 & 1000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-10000 & -1000 & 1\times10^{6} & 0 & -100 & -10000 & 0 & -5000 & -3000 & 0 \\
1 & 0 & 0 & -100 & 0 & 0 & 0 & 0 & 0 & 0 \\
5000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -10 & 0 & 0 & 1000 & 0 & 0 & 0 & -20 & 0 \\
0 & -5 & 0 & 0 & 0 & 100 & 0 & 0 & -150 & 0 \\
0 & 0 & -500 & 0 & 0 & 0 & 1000 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1000 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 10 & 0 & -100 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 25000 & 0 & 0 \\
0 & 0 & 2\times10^{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2
\end{array} \right) \end{array}
$$

It is obvious that the technology matrix **A** is not a square matrix, since there are 13 rows and 10 columns in it. Therefore, further treatment on the matrix **A** is needed.

[Multifunctional process is defined by Heijungs [4] as: *A process is said to be multifunctional when it absorbs two or more wastes, produces two or more goods, or absorbs one or more wastes and produces one or more goods. Otherwise, it is said to be monofunctional.*]

It is known that there are two multifunctional processes in the product system, the third column (production of electricity) and the fourth column (incineration of disposed incandescent lamps). The former one will be treated with the partitioning method, allocating 0.8 to electricity and 0.2 to heat. The latter one will be treated with the substitution method, considering recycled copper as equivalent to copper, with a correction factor of 0.9 to account for differences in quality. Although process 1, for instance, has 2 outputs, it is not a multifunctional process, because only one of these outputs is a good. Moreover, by applying a cut-off criterion, waste residue (m13) is removed from the technology matrix.

[**Cut-off criterion:** *An economic flow is said to be cut-off when, in case of a good, all coefficients for that flow in the technology matrix are non-positive, and in case of a waste, all coefficients for that flow in the technology matrix are non-negative*.]

Then, the technology matrix after cut-off and allocation **A′** becomes:

$$\mathbf{A}' = \begin{pmatrix} -1 & 1000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -10000 & -1000 & 1\times10^{6} & 0 & 0 & -100 & -10000 & 0 & -5000 & -3000 & 0 \\ 1 & 0 & 0 & 0 & -100 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -10 & 0 & 0 & 0 & 1000 & 0 & 0 & 0 & -20 & 0 \\ 0 & -5 & 0 & 0 & 0.45 & 0 & 100 & 0 & 0 & -150 & 0 \\ 0 & 0 & -400 & -100 & 0 & 0 & 0 & 1000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -100 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 25000 & 0 & 0 \\ 0 & 0 & 0 & 2\times10^{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

This matrix is square and non-singular, hence it is invertible.

Two alternative final demand vectors are formalized as:

$$\mathbf{f}_1 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 10 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \text{ and } \mathbf{f}_2 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 10 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

These final demand vectors are modified in accordance with the cut-off and allocation operations, and changed into

$$\mathbf{f}'_1 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 10 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \text{ and } \mathbf{f}'_2 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 10 \\ 0 \end{pmatrix}$$

Multiplication of the inverse of the modified technology matrix $\mathbf{A'}$ with the two respective final demand vectors yields the scaling vectors for both alternative systems:

$$\mathbf{s}'_1 = \begin{pmatrix} 0.002 \\ 2\times10^{-6} \\ 2\times10^{-5} \\ 0 \\ 2\times10^{-5} \\ 2\times10^{-8} \\ 1\times10^{-8} \\ 8\times10^{-6} \\ 0 \\ 0 \\ 0 \end{pmatrix} \text{ and } \mathbf{s}'_2 = \begin{pmatrix} 0 \\ 0 \\ 2\times10^{-6} \\ 0 \\ 0 \\ 8\times10^{-9} \\ 6\times10^{-7} \\ 8\times10^{-7} \\ 0.004 \\ 4\times10^{-7} \\ 4\times10^{-6} \end{pmatrix}$$

The intervention matrix **B** is composed of the environmental flows in Table 2.2.

$$\mathbf{B} = \begin{pmatrix} 0 & 0 & 1000 & 100 & 0 & 0 & 200 & 0 & 0 & 200 \\ 0 & 0 & 100 & 0 & 0 & 0 & 5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & 0 & 4 \\ 0 & 0 & 0 & 0 & -1000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1200 & 0 & 0 & 0 \end{pmatrix}$$

After allocation, it is becomes:

$$\mathbf{B}' = \begin{pmatrix} 0 & 0 & 800 & 200 & 100 & 0 & 0 & 200 & 0 & 0 & 200 \\ 0 & 0 & 80 & 20 & 0 & 0 & 0 & 5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & 0 & 4 \\ 0 & 0 & 0 & 0 & 0 & -1000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1200 & 0 & 0 & 0 \end{pmatrix}$$

Observe that cut-off does not affect **B**, but the allocation does.

Multiplication of this matrix with the $\mathbf{s}_1'$ and $\mathbf{s}_2'$ yields the two inventory vectors:

$$\mathbf{g}_1 = \begin{pmatrix} 0.020 \\ 0.0016 \\ 1.5\times10^{-5} \\ -2\times10^{-5} \\ -1\times10^{-5} \\ -0.0096 \end{pmatrix} \text{ and } \mathbf{g}_2 = \begin{pmatrix} 0.0026 \\ 0.00016 \\ 1.6\times10^{-5} \\ -8\times10^{-6} \\ -0.0006 \\ -0.00096 \end{pmatrix}$$

From the result, it is known that the environmental loads associated with using incandescent lamps mostly are much more than those associated with using fluorescent lamps. However, the emitted copper to soil and consumed copper ore corresponding to fluorescent lamps are more than those corresponding to incandescent lamps, since copper is not recycled in the process of ‘Incineration of Disposed Fluorescent Lamps’, but done in the process of ‘Incineration of Disposed Incandescent Lamps’.

§ 2.5.2 LCI analysis by using the practical approach of matrix method in this thesis

Here, for the comparison, the case study of lamp is carried out by using the practical approach of matrix method proposed in this thesis. After that, these two LCI analysis methods are compared, and the merits of the present matrix method are shown.

Firstly, all the processes and the defined functional flows in the product system are shown in Table 2.3. In the definition of each function flow, it is important to clarify the purpose of introducing the process into the product system, especially towards a multifunctional process. For instance, although the valuable material 'recycled copper' is also outputted from the process of 'Incineration of disposed incandescent lamps', the inputted flow of 'disposed incandescent lamps' is defined as the functional flow, since the purpose of introducing the process is to dispose the used incandescent lamps, while not to produce copper.

Table 2. 3 Definition of functional flows for each process

	PROCESS	FUNCTIONAL FLOW
p_1	Use of Incandescent Lamps	hr of incandescent lamp light
p_2	Production of Incandescent Lamps	incandescent lamps
p_3	Production of Electricity	MJ of electricity
p_4	Incineration of Disposed Incandescent Lamps	disposed incandescent lamps
p_5	Production of Glass	kg of glass
p_6	Production of Copper	kg of copper
p_7	Production of Fuel	kg of fuel
p_8	Use of Fluorescent Lamps	hr of fluorescent lamp light
p_9	Production of Fluorescent Lamps	fluorescent lamps
p_{10}	Incineration of Disposed Fluorescent Lamps	disposed fluorescent lamps

After the definition of functional flows, the coefficient matrix A is composed of the flows directly.

$$\mathbf{A} = \begin{array}{c} \\ f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \\ f_8 \\ f_9 \\ f_{10} \end{array} \begin{array}{c} \begin{array}{cccccccccc} \mathbf{p}_1 & \mathbf{p}_2 & \mathbf{p}_3 & \mathbf{p}_4 & \mathbf{p}_5 & \mathbf{p}_6 & \mathbf{p}_7 & \mathbf{p}_8 & \mathbf{p}_9 & \mathbf{p}_{10} \end{array} \\ \begin{pmatrix} 5000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1E4 & -1000 & 1E6 & 0 & -100 & -1E4 & 0 & -5000 & -3000 & 0 \\ 1 & 0 & 0 & -100 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -10 & 0 & 0 & 1000 & 0 & 0 & 0 & -20 & 0 \\ 0 & -5 & 0 & 0 & 0 & 100 & 0 & 0 & -150 & 0 \\ 0 & 0 & -500 & 0 & 0 & 0 & 1000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.5E4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -100 \end{pmatrix} \end{array}$$

The environmental load matrix is composed of the environmental items, which are to be studied. Here, the environmental load flows from l1 to l6 are 'kg of CO_2 to air', 'kg of SO_2 to air', 'kg of copper to soil', 'kg of sand', 'kg of copper ore' and 'kg of crude oil' respectively.

$$\mathbf{B}=\begin{matrix} l_1 \\ l_2 \\ l_3 \\ l_4 \\ l_5 \\ l_6 \end{matrix}\begin{pmatrix} 0 & 0 & 1000 & 100 & 0 & 0 & 200 & 0 & 0 & 200 \\ 0 & 0 & 100 & 0 & 0 & 0 & 5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & 0 & 4 \\ 0 & 0 & 0 & 0 & -1000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1200 & 0 & 0 & 0 \end{pmatrix}$$

Except for the functional flows and the environmental load flows, all the others are arranged in the surplus flow matrix. The surplus flows are ‘MJ of heat’, ‘kg of recycled copper’ and ‘kg of waste residue’ respectively.

$$\mathbf{C}=\begin{matrix} s_1 \\ s_2 \\ s_3 \end{matrix}\begin{pmatrix} 0 & 0 & 2E6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \end{pmatrix}$$

The functional unit of the product system is defined as ’10 hr of light’; therefore, the system boundary vectors for two alternatives can be written as:

$$\boldsymbol{\alpha}_1=\begin{pmatrix} 10 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \text{ and } \boldsymbol{\alpha}_2=\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 10 \\ 0 \\ 0 \end{pmatrix}$$

Using Eq.(2.4), the final environmental load vectors are derived as:

$$\boldsymbol{\beta}_1=\begin{pmatrix} 0.024 \\ 0.00205 \\ 1.5E-5 \\ -2E-5 \\ -0.0001 \\ -0.012 \end{pmatrix} \text{ and } \boldsymbol{\beta}_2=\begin{pmatrix} 0.00301 \\ 0.00021 \\ 1.6E-5 \\ -8E-6 \\ -0.0006 \\ -0.0012 \end{pmatrix}$$

Using Eq.(2.18), the final surplus flow vectors are derived as:

$$\boldsymbol{\gamma}_1 = \begin{pmatrix} 40.006 \\ 1E-5 \\ 0 \end{pmatrix} \quad \text{and} \quad \boldsymbol{\gamma}_2 = \begin{pmatrix} 4.0144 \\ 0 \\ 8E-6 \end{pmatrix}$$

From the final surplus flow vectors **γ**1 and **γ**2, it is known that there are 40.006 MJ of heat and 1E-5 kg of recycled copper outputted from the incandescent lamp system, and 4.0144 MJ of heat and 8E-6 kg of waste residue outputted from the fluorescent lamp system. If all the surplus flows are judged to neglect, or they are set outside of the product system, the environmental effect of them can be ignored. Then, the environmental load vectors **β**1 and **β**2 are the final LCI results. Otherwise, the effect of the surplus flows should be studied.

Based on the final surplus flow vectors **γ**1 and **γ**2, since the outputted waste residue is judged to be useless material, no allocation is necessary to it. Therefore, it is only needed to carry out allocation to the outputted heat and the recycled copper.

If the environmental loads corresponding to the final cumulative heat could be calculated, for instance using Input-Output analysis method, then, as the allocation operation, it is only needed to subtract the amount of environmental from the final result. Besides of it, the allocation can be carried out using the avoided process method. Here, the avoided process method is used. The co-production of the heat is argued to substitute the stand-alone production of heat. The stand-alone production process of heat is compiled by splitting the process of electricity production to certain portion (heat: electricity-1: 4). The compiled avoided process of heat is shown in Fig. 2.6. After that, the compiled process of heat production denoted by 'p11' is added into the product, and the functional flow is defined by 'MJ of heat', while the process of electricity production is not changed.

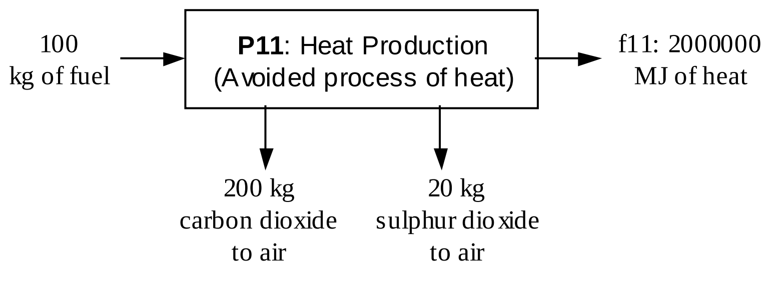

Fig. 2. 6 Avoided process of heat in the case study of lamps

The recycled copper is considered to be equivalent to copper and substitute the copper consumed in lamp production. So, a substitution process is made as the avoided process of the recycled copper, with a correction factor of 0.9 to account for differences in quality, as shown in Fig. 2.7. In this substitution process, recycled copper is defined as the functional flow.

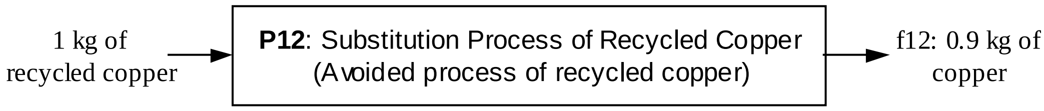

Fig. 2. 7 Substitution process of recycled copper in the case study of lamps

Then, the coefficient matrix and the environmental load matrix are re-composed as:

$$\mathbf{A}' = \begin{pmatrix} 5000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1E4 & -1000 & 1E6 & 0 & -100 & -1E4 & 0 & -5000 & -3000 & 0 & 0 & 0 \\ 1 & 0 & 0 & -100 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -10 & 0 & 0 & 1000 & 0 & 0 & 0 & -20 & 0 & 0 & 0 \\ 0 & -5 & 0 & 0 & 0 & 100 & 0 & 0 & -150 & 0 & 0 & 0.9 \\ 0 & 0 & -500 & 0 & 0 & 0 & 1000 & 0 & 0 & 0 & -100 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.5E4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -100 & 0 & 0 \\ 0 & 0 & 2E6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2E6 & 0 \\ 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{pmatrix}$$

$$\mathbf{B}' = \begin{pmatrix} 0 & 0 & 1000 & 100 & 0 & 0 & 200 & 0 & 0 & 200 & 200 & 0 \\ 0 & 0 & 100 & 0 & 0 & 0 & 5 & 0 & 0 & 0 & 20 & 0 \\ 0 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1200 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Since the flows of 'MJ of heat' and 'kg of recycled copper' are included in the coefficient matrix, therefore, the surplus flow matrix is only composed of 'kg of waste residue'. The recomposed surplus flow matrix and the new system boundary vectors for two alternatives are shown as:

$$\mathbf{C}' = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 \end{pmatrix}$$

$$\boldsymbol{\alpha}_1' = \begin{pmatrix} 10 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad \text{and} \quad \boldsymbol{\alpha}_2' = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 10 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

The process vectors are recalculated as:

$$\mathbf{p}_1' = \begin{pmatrix} 0.002 \\ 2E-6 \\ 2E-5 \\ 2E-5 \\ 2E-8 \\ 1E-8 \\ 8E-6 \\ 0 \\ 0 \\ 0 \\ -2E-5 \\ 1E-5 \end{pmatrix} \quad \text{and} \quad \mathbf{p}_2' = \begin{pmatrix} 0 \\ 0 \\ 2E-6 \\ 0 \\ 8E-9 \\ 6E-7 \\ 8E-7 \\ 0.0004 \\ 4E-7 \\ 4E-6 \\ 2E-6 \\ 0 \end{pmatrix}$$

The final environmental load vectors and the final surplus flow vectors are recalculated as:

$$\boldsymbol{\beta}_1' = \begin{pmatrix} 0.0196 \\ 0.00164 \\ 1.5E-5 \\ -2E-5 \\ -1E-5 \\ -0.0096 \end{pmatrix} \quad \text{and} \quad \boldsymbol{\beta}_2' = \begin{pmatrix} 0.002566 \\ 0.0001646 \\ 1.6E-5 \\ -8E-6 \\ -0.0006 \\ -0.000963 \end{pmatrix}$$

$$\boldsymbol{\gamma}_1' = (0) \quad \text{and} \quad \boldsymbol{\gamma}_2' = (8E-6)$$

These result $\boldsymbol{\beta}_1'$ and $\boldsymbol{\beta}_2'$ coincide with those calculated by Heijungs. Similarly, each element in $\boldsymbol{\beta}_1'$ is larger than that in $\boldsymbol{\beta}_2'$, except for the third and the fifth ones. On the whole, the environmental burden associated with the incandescent lamps is larger than that associated with the fluorescent lamps.

Therefore, we can give the conclusion that the fluorescent lamps are relatively more environmentally benefit.

Heijungs composed a non-square technology matrix at first. After that, allocations are carried out on both the co-produced heat and the recycled copper, and material of waste residue is cut-off in order to make the technology matrix to be a square one. While, by the practical approach of matrix method in this thesis, the square coefficient matrix is composed of the defined functional surplus flows directly. The allocations are carried out after confirming that they are really necessary and un-avoidable based on the final surplus flow vector $\boldsymbol{\gamma}$. Therefore, no unnecessary allocation will be obliged in the matrix method proposed in this thesis.

Moreover, the scaling vector $\mathbf{s}_1'$ and the process vector $\mathbf{p}_1'$ are compared here. In the scaling vector $\mathbf{s}_1'$, we can see that the scaling factor of electricity production process (the third element) is $2*10^{-5}$, while that (the fourth element) of heat production process is 0. However, in practical, one electricity production must company with one heat production. Therefore, the division of the multifunctional process cannot reflect the real situation, and how much heat will be co-produced cannot be known based on the scaling vector $\mathbf{s}_1'$. However, based on the process vector $\mathbf{p}_1'$, the scaling factor of the avoided process of heat (the eleventh element) shows that how much heat will be co-produced in the product system. Since the scaling factor is negative, the environmental loads corresponding to the heat will be subtracted from the LCI result automatically. Furthermore, since the substitution process of recycled copper is set in the product system, how the recycled copper is treated can be known based on the coefficient matrix and the process vector. By studying the sensitivity of the correction factor of 0.9, the influence of the recycling rate can also be known. However, these cannot be known based on the technology matrix and the scaling vector by Heijungs.

All the calculations by the practical approach are carried out using computer programs. Therefore, the recalculations of the final environmental loads and the final surplus flows are also very easy.

§ 2.6 Conclusions of Chapter 2

In this chapter, firstly, the basic algorithm of the matrix method for LCI analysis is reviewed and the problems in the conventional matrix method are discussed. After that, a new practical approach for matrix-based LCI analysis is proposed. In the practical approach, the necessary matrices can be composed easily by specifying some process data. All the process data are managed in three matrix: the coefficient matrix **A**, the environmental load matrix **B** and the surplus flow matrix **C**. Especially, the coefficient matrix **A**, which is the most important one, is composed of the functional flows, each of which is defined in each unit processes. As a result, the coefficient matrix is guaranteed to be a square one. In the matrix method, the allocation is not recklessly carried out on all the multifunctional processes to guarantee the coefficient matrix as a square one. It is carried out in the end after confirming that the allocation is really necessary based on the final surplus flow vector. Consequently, the efficiency of the matrix method for LCI analysis is improved further. The general approach for allocation is discussed as well. Furthermore, the general procedure of the matrix method is also summarized.

In the end, an extend example of LCA case study is carried out by using the refined model of Heijungs and the practical approach of matrix-based LCI respectively, and the two kind of analysis are compared. From the comparison, it is known that the practical approach proposed in this thesis reflects the practical situation more properly, and it assists the sensitivity analysis better, therefore, it is more reasonable and practicable.

As a result, adopting this practical approach, it is quite convenient to calculate the final environmental loads associated with the functional unit of the product system. This approach is appropriate to the practitioners with few LCA technologies and experience, as it is not necessary to analyze the structure of the product system deeply and few judgments of LCA experts are needed. Furthermore, this practical approach can be easily carried out by computer program.

Although there are many merits in the matrix method for LCI analysis and it has been improved suitable to practical LCA case studies in this chapter, there are still some limits to resolve in future. It is time consuming to derive the inverse matrix when the coefficient matrix becomes large. The matrix method is based on linear assumption; therefore it is not so suitable to the non-linear systems.

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Chapter 3

Generalization of Sensitivity and Uncertainty Analysis in The Matrix-based LCI Analysis

In this chapter, based on the matrix method for LCI analysis developed in Chapter 2, how the sensitivity analysis and uncertainty analysis are dealt with in the matrix-based LCI is introduced. The sensitivity analysis adopts the rate sensitivity and quantitatively studies the influence of each process datum on the final cumulative environmental loads. Herein, by formulating the sensitivity analysis of the environmental load matrix **B**, the sensitivity analysis based on matrix method is improved and completed to be a whole.

The uncertainty analysis studies the uncertainties of the final cumulative environmental loads, which are propagated from the uncertainties of process data. Firstly, a simplified method of the uncertainty analysis in LCI is proposed. The approximate calculation of uncertainty in the simplified method is based on the central limit theorem and uses the rate sensitivity analysis result. Secondly, a detailed method of the uncertainty analysis, which is based on the Monte Carlo simulation, is introduced as well. It is shown that the matrix method greatly supports the Monte Carlo simulation in LCI. Thirdly, a general procedure for uncertainty analysis from the simplified method to the detailed method is proposed. Finally, using some examples of LCA case studies, the sensitivity analysis method and the two uncertainty analysis methods are demonstrated and the effectiveness of them are examined. The practicability and effectiveness of the general procedure for uncertainty analysis are examined and confirmed as well.

As a result, based on the matrix method, the operations from LCI analysis to sensitivity and uncertainty analysis are connected to facilitate the LCA analysis.

Key words: Central Limit Theorem, General Procedure, Monte Carlo Simulation, Sensitivity Analysis, Uncertainty Analysis.

§ 3.1 Introduction

The importance and necessity of sensitivity and uncertainty analysis in Life Cycle Assessment (LCA) have been strongly emphasized in many literatures. The International Standardization Organization (ISO) has recognized the relevance of these works by including several cautionary statements in the standards [1-3].

In LCA, it is also very important to study the improvements of a product system in the environmental aspect. In other words, LCA is utilized in order to determine the priority of improvements for the reduction of resource/energy consumed in a product system and pollution emitted from it. For an analysis centered on decision-making, the sensitivity analysis is extremely important in addition to the evaluation of the total amount of environmental load. The importance of the sensitivity in LCA has been widely recognized and it has been widely used to investigate the relation between input data quality and model output value [4, 5]. Heijungs pointed out that the identification of key issues in an iterative procedure is also important to achieve a certain level of reliability in LCA [6]. Sensitivity analysis is also expected to play an important role at the interpretation stage, which is the last phase of LCA in the ISO standard [7].

In some of LCA software, the sensitivity analysis is carried out by changing each of the process data by a very small definite amount and studying the LCI results' changes for many times. However, this method of sensitivity analysis is quite time consuming. Heijungs [8] has ever discussed the use of matrix theory for sensitivity and uncertainty issues in LCA. The analytical way based on the algebraic manipulation is easier and more time saving than the numerical way. Sakai [9] proposed a new method for the efficient sensitivity analysis in LCA by introducing the perturbation method. This will enable one to evaluate the degree of influence of each element on the total sum of environmental loads. By this sensitivity analysis method based on matrix algebra, all sensitivities can be calculated easily, even if the number of processes becomes larger.

In Life Cycle Assessment (LCA), uncertainty is a crucial limitation for a clear and proper interpretation of LCA results. Due to this problem, it is very important to determine and quantify the uncertainty of Life Cycle Inventory (LCI) results or/and LCA results. According to the ISO guidelines [1, 2], an uncertainty analysis is obliged for an environmental comparison of products. Uncertainty assessment in LCA is also an important aspect for decision-makers to judge the significance of differences in product or process options. There have been some discussions about the uncertainty in LCA [12-15]. Sugiyama [11] has proposed a new inventory data model for uncertainty evaluation in LCA, which incorporates the differences of input/output between comparable factories into LCA data as probability distributions and correlation coefficients. Stochastic models (e.g. Monte Carlo simulation) [10] are often used in LCI to compute the uncertainty of cumulative emissions and resource requirements. However, uncertainty analysis is rarely carried out in the conventional LCA practices. Moreover, there are still some problems, such as: it is difficult, time and cost consuming to determine the probability distributions of the input parameters and it is even unnecessary in some cases.

In this chapter, based on the matrix-based LCI analysis, how to carry out sensitivity analysis and uncertainty analysis is introduced. The flow chart of the chapter is shown in Fig. 3.1.

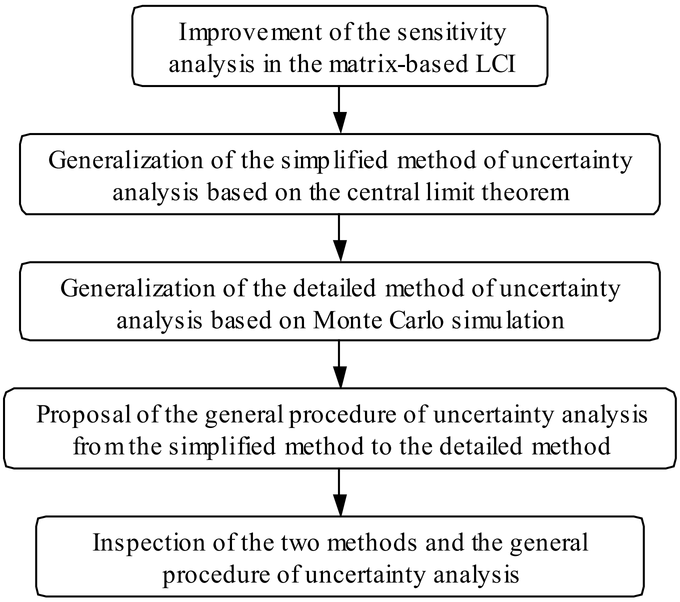

Fig. 3. 1 Flow chart of Chapter 3

Firstly, following the formulation of sensitivity analysis by Sakai [9], the sensitivity analysis of the environmental load matrix **B** is formulated in this chapter. As a result, the sensitivity analysis based on matrix method is improved and completed to be a whole.

After that, a simplified method and a detailed method for uncertainty analysis, which are based on the central limit theorem and the Monte Carlo simulation respectively, are generalized based on the matrix method for LCI analysis.

Continuatively, a general procedure for uncertainty analysis from the simplified method to the detailed method is proposed as well.

Finally, using some examples of LCA case studies, the sensitivity analysis method and the two uncertainty analysis methods are demonstrated and the effectiveness of them are examined. The practicability and effectiveness of the general procedure for uncertainty analysis are examined and confirmed as well.

§ 3.2 Sensitivity analysis in matrix-based LCI

It is generally understood that the sensitivity means the degree of the effect of each element in the system on the evaluation quantity. As a simple procedure, the sensitivity can be evaluated by estimating the influence of the minute fluctuation of the element of interest on the summed up value of the environmental load. Such a method is also available for the sensitivity analysis in LCA. However, a one by one treatment is required for the sensitivity analysis of all elements since it is rather difficult to generalize the procedure. In such a method, it may be time consuming and a laborious work to prioritize the elements if there are many elements in the system. Therefore, it is extremely important to formulate the procedure of the sensitivity analysis for general purposes.

From this viewpoint Heijungs proposed the sensitivity analysis for the LCA using process analysis and formulated the procedure thus it could be used for general purposes [6, 16]. In his method, the sensitivity analysis is formulated on the basis of the matrix-based LCA. Since the method is expressed in mathematical form, it is easy to integrate the method to LCA. However, the derived equation is slightly complicated and somewhat difficult for practical use. Using perturbation method Sakai and Yokoyama [9] formulated the sensitivity analysis in LCA, which is advantageous in many aspects for practical use. In the method, the derived equation is expressed explicitly in matrix form and so its application is extremely simple. Therefore, not only is its application simple, but also the method does not require much calculation time.

In this section, the formulation of rate sensitivity analysis in LCA is reviewed. After that, following the formulation of sensitivity analysis by Sakai [9], the sensitivity analysis of the environmental load matrix **B** is formulated in this chapter. As a result, the sensitivity analysis based on matrix method is improved and completed to be a whole.

§ 3.2.1 Review of the formulation of rate sensitivity analysis in LCI

In the matrix method for LCI analysis in this thesis, all the process data are arranged in three matrices: the coefficient matrix **A**, the environmental matrix **B** and the surplus flow matrix **C**. In the process analysis of the product system, since the elements in matrix **C** have no influence in calculating the process vector **p**, they will not affect the final cumulative environmental loads. Therefore, herein, sensitivity analysis is to study the effects of the flows in matrix **A** and **B** on the final LCI result.

Concerning the influence of the matrix **A** on the final environmental loads, based on the Eq. (2.1) – (2.3), Sakai and Yokoyama [9] studied the rate sensitivity in LCI and developed the matrix-based formula for the sensitivity analysis. The rate sensitivity is defined as:

$$s_{ij}^{k} = \frac{\Delta\beta_k \big/ \overline{\beta}_k}{\Delta a_{ij} \big/ \overline{a}_{ij}} \tag{3.1}$$

where s_{ij}^{k} is the rate sensitivity of the ith element a_{ij} in the jth column in the matrix **A** to the kth environmental load β_k in the environmental load vector **β**. $\overline{\beta}_k$ and $\overline{a}_{ij}$ are the means in the matrix calculation (Eq. (2.1) – (2.3)). $\Delta\beta_k$ is the variation due to the minute variation Δa_{ij}. Using the perturbation method and according to the first order approximation, the sensitivity analysis formula is developed as:

$$\mathbf{S}^{k} = \mathbf{E}^{t}\mathbf{e}_{k}\mathbf{p}^{t} \otimes \mathbf{A} \tag{3.2}$$

where $\mathbf{S}^{k}$ is the rate sensitivity matrix of matrix **A** to the kth environmental load β_k, $\mathbf{p}^{t}$ is the transpose vector of **p**. Furthermore, the **E** is defined as follows.

$$\mathbf{E} = -\boldsymbol{\beta}_{diag}\mathbf{B}\mathbf{A}^{-1} \tag{3.3}$$

$$\boldsymbol{\beta}_{diag} = \begin{bmatrix} 1/\beta_1 & & & \\ & \ddots & & \\ & & \ddots & \\ & & & 1/\beta_s \end{bmatrix} \tag{3.4}$$

$$\mathbf{e}_{k} = \begin{pmatrix} e_1 \\ \vdots \\ e_i \\ \vdots \\ e_n \end{pmatrix}, \quad e_i = \begin{cases} 1 & if \quad i = k \\ 0 & otherwise \end{cases} \tag{3.5}$$

$\otimes$ is an operation between matrices of same size, which is defined as:

$$\mathbf{X} = \mathbf{Y} \otimes \mathbf{Z}, \qquad x_{ij} = y_{ij} \times z_{ij} \tag{3.6}$$

This sensitivity matrix is expressed by an explicit operation of matrices and vectors. The advantage of this method is that it is not required to solve the system for many times for different values of the entity of matrix **A**. Thus, it is time saving and easy to calculate all sensitivities for all environmental load terms even if the number of processes becomes larger. Moreover, this sensitivity analysis in LCA is extremely easy to incorporate the algorithm into computer programs.

§ 3.2.2 Improvement of the rate sensitivity analysis in matrix-based LCI

In the study of sensitivity analysis in LCA by Sakai and Yokoyama, only the influence of the matrix **A** is concerned and that of the matrix **B** is omitted. As the continuative study on sensitivity analysis in LCA, the sensitivity of the matrix **B** to the final cumulative environmental loads is formulated in this section.

Same with Eq. (3.1), the rate sensitivity is defined as:

$$s'^{k}_{ij} = \frac{\Delta\beta_k / \overline{\beta}_k}{\Delta b_{ij} / \overline{b}_{ij}} \tag{3.7}$$

where s'^{k}_{ij} is the rate sensitivity of the *i*th element b_{ij} in the *j*th column in the matrix **B** to the *k*th environmental load β_k in the environmental load vector **β**. $\overline{\beta}_k$ and $\overline{b}_{ij}$ are the means in the matrix calculations (Eq. (2.1) – (2.3)). $\Delta\beta_k$ is the variation due to the minute variation Δb_{ij}.

Since the coefficient matrix **A** and the system boundary vector **α** are set to be constant, the calculated process vector **p** will not be varied. Then, the variation $\Delta\boldsymbol{\beta}$ due to the minute variation Δb_{ij} is expressed as

$$\Delta\boldsymbol{\beta} = \Delta\mathbf{B}\mathbf{p} \tag{3.8}$$

In the environmental load matrix **B**, the rows represent the environmental load items. Therefore, when studying the *k*th environmental load variation $\Delta\beta_k$, it is only needed to study the *k*th row in the matrix **B**. Therefore, $\Delta\beta_k$ can be expressed as

$$\Delta\beta_k = \begin{pmatrix} \Delta b_{k1} & \cdots & \Delta b_{kj} & \cdots & \Delta b_{kn} \end{pmatrix} \begin{pmatrix} p_1 \\ \vdots \\ p_j \\ \vdots \\ p_n \end{pmatrix} \tag{3.9}$$

If only b_{kj} has variation Δb_{kj}, $\Delta\beta_k$ can be derived as

$$\Delta\beta_k = \Delta b_{kj} p_j \tag{3.10}$$

Then, the rate sensitivity $s_{ij}'^{k}$ is obtained as

$$s_{ij}'^{k} = \begin{cases} \dfrac{\bar{b}_{ij} p_j}{\bar{\beta}_k}, & \text{if i = k} \\ 0, & \text{if i} \neq \text{k} \end{cases} \tag{3.11}$$

$\bar{b}_{ij} p_j$ shows the contribution of the *j*th process on the total *k*th environmental load.

On the whole, another sensitivity matrix can be defined as:

$$\mathbf{S}' = \boldsymbol{\beta}_{diag} \mathbf{B} \mathbf{p}_{diag} \tag{3.12}$$

where $\boldsymbol{\beta}_{diag}$ has been defined in Eq. (3.4). **B** is the environmental load matrix. $\mathbf{p}_{diag}$ is defined as:

$$\mathbf{p}_{diag} = \begin{pmatrix} p_1 & & & \\ & p_2 & & \\ & & \ddots & \\ & & & p_n \end{pmatrix} \tag{3.13}$$

where p_i (i = 1, 2, ⋯, n) is the element in the process vector **p**.

Each element $(\mathbf{S}')_{ij}$ in the matrix **S′** shows the sensitivity of the flow b_{ij} in the matrix **B** to the *i*th environmental load β_i in the final environmental load vector **β**. The formula developed here is consistent with that developed by Sakai [9]. Therefore, the sensitivity analysis based on matrix method is completed to be a whole.

In the process analysis using Eq. (2.1) – (2.3), the flows arranged in the surplus flow matrix **C** are cut off from the product system, therefore, they have no influence on the final cumulative environmental loads. However, by using Input-Output Analysis (IOA) method etc., the environmental effect of the surplus flow matrix **C** can also be added to the LCI result. Then, in the hybrid analysis for LCI, to study the sensitivity of the matrix **C** to the final LCI result will become one of the important tasks in future.

§ 3.3 Uncertainty analysis in matrix-based LCI

In LCA, in order to obtain a more correct and reliable result, it is very important to determine and quantify the uncertainty of LCI results or/and LCA results. There are many sources of uncertainty in each stage of LCA, for example, the input parameter uncertainties, model uncertainty, spatial and temporal variability etc [10, 17]. Huijbregs carried out an investigation about the uncertainty and variability in LCA. He did a detailed classification about the uncertainty and variability related to the phase of LCA [15], as shown in Table 3.1. Although there have been much discussion about the uncertainty analysis in LCA, so far, it is quite difficult to assess all the uncertainties as a whole.

In this section, focusing on the uncertainty of LCI result propagated from the input parameter uncertainties, an approximate calculation of uncertainty based on the central limit theorem is developed. After that, the uncertainty analysis based on Monte Carlo simulation is introduced as well, from which it is shown that the matrix method greatly supports the Monte Carlo simulation in LCI. Furthermore, a general procedure for uncertainty analysis from the simplified method to the detailed method is proposed. Finally, using some examples of LCA case studies, the sensitivity analysis method and the two uncertainty analysis methods are demonstrated and the effectiveness of them are examined. The practicability and effectiveness of the general procedure for uncertainty analysis are examined and confirmed as well. All the operations and calculations of the uncertainty analysis in LCI are fully based on the matrix algebra.

Table 3. 1 Examples of types of uncertainty and variability related to the phase of LCA (Huijbregts, PHD Thesis, 2001 [15])

Phase	Goal and scope	Inventory	Choice of impact categories	Classification	Characterisation	Weighting
Source						
Parameter uncertainty		Inaccurate emission measurements	Impact categories are not known		Uncertainty in life times of substances	Inaccurate normalisation data
Model unertainty		Linear instead of non-linear modelling	Leaving out known impact categories	Contribution to impact category is not known	Characterision factors are not known	Weighting criteria are not operational
Uncertainty due to choices	Functional unit	Use of several allocation methods			Using several characterisation methods within one category	Using several weighting methods
Temporal variability		Differences in yearly emission inventories			Change of temperature over time	Change of social preferences
Spatial variability		Regional differences in emission inventories			Regional differences in environmental sensitivity	Regional differences in distance to (political)
Variability between objects/ sources		Differences in emissions between factories which produce same			Differences in human characteristics	Differences in individual preferences, when using panel method

§ 3.3.1 Simplified uncertainty analysis based on the central limit theorem

[The central limit theorem]

The theorem most often called the central limit theorem is the following. Let $X_1, X_2, X_3, \cdots$ be a sequence of random variables, which are defined on the same probability space, share the same probability distribution D and are independent. Assume that both the expected value μ and the standard deviation σ of D exist and are finite. Consider the sum: $S_n= X_1+ X_2+\cdots+ X_n$. Then the expected value of S_n is $n\mu$ and its standard deviation is $\sigma n^{1/2}$. Furthermore, informally speaking, the distribution of S_n approaches the normal distribution $N(n\mu, \sigma^2 n)$ as n approaches ∞ [21].

§ 3.3.1.1 Formulation of the first order approximation of the variation of final cumulative environmental load in LCI

The uncertainty analysis in this thesis focuses on the uncertainty of LCI result, which are propagated from the input parameter uncertainties. Assuming that all the input parameters in LCI (including all the data in the coefficient matrix **A** and the data in the environmental load matrix **B**) are fluctuated, the variation of the final cumulative environmental load in LCI analysis is investigated in this section. Since the data in the surplus flow matrix **C** will not affect the final cumulative environmental load, it is unnecessary to take the matrix **C** into account.

When the data in the matrix **A** and **B** are varied, then, the final cumulative environmental load can be derived as:

$$\boldsymbol{\beta}^0 + \Delta\boldsymbol{\beta} = \left(\mathbf{B}^0 + \Delta\mathbf{B}\right)\left(\mathbf{p}^0 + \Delta\mathbf{p}\right) \tag{3.14}$$

where $\mathbf{B}^0$, $\mathbf{p}^0$ and $\boldsymbol{\beta}^0$ are the original environmental load matrix, the original process vector and the original final cumulative environmental load vector respectively. $\Delta\mathbf{B}$ is the minute variation of the matrix **B**. $\Delta\mathbf{p}$ is the variation of process vector **p** due to the minute variation ($\Delta\mathbf{A}$) of the coefficient matrix **A**. $\Delta\boldsymbol{\beta}$ is the variation of the final cumulative environmental load vector due to minute variation of $\Delta\mathbf{A}$ and $\Delta\mathbf{B}$.

By using the perturbation method, $\Delta\mathbf{p}$ can be formulated as follows.

$$\mathbf{p} = \mathbf{p}^0 + \sum_{ij}\mathbf{p}^I_{ij}\varepsilon_{ij} + \sum_{ij}\sum_{kl}\mathbf{p}^{II}_{ij,kl}\varepsilon_{ij}\varepsilon_{kl} + \ldots + \sum_{ij}\sum_{kl}\cdots\sum_{mn}\mathbf{p}^N_n\varepsilon_{ij}\varepsilon_{kl}\cdots\varepsilon_{st} + \cdots \tag{3.15}$$

where ε_{ij} ($=\Delta a_{ij}$) is the minute variation of the element a_{ij} of the coefficient matrix **A**.

$$\mathbf{p}^I_{ij} = \frac{\partial\mathbf{p}}{\partial\varepsilon_{ij}},\ \mathbf{p}^{II}_{ij,kl} = \frac{\partial^2\mathbf{p}}{\partial\varepsilon_{ij}\partial\varepsilon_{kl}},\ \mathbf{p}^N_n = \frac{\partial^n\mathbf{p}}{\partial\varepsilon_{ij}\partial\varepsilon_{kl}\cdots\partial\varepsilon_{st}} \tag{3.16}$$

When the data in the matrix **A** are varied, the balance equation of the materials can be written as:

$$\mathbf{A}^0\mathbf{p} + \sum_{ij} \mathbf{A}_{ij}^I \varepsilon_{ij} \mathbf{p} = \boldsymbol{\alpha} \tag{3.17}$$

Substitute the vector **p** in Eq. (3.17) by Eq. (3.15), we can derive

$$\begin{aligned} \mathbf{A}^0\mathbf{p}^0 + \sum_{ij}(\mathbf{A}^0\mathbf{p}_{ij}^I + \mathbf{A}_{ij}^I\mathbf{p}^0)\varepsilon_{ij} + \sum_{ij}\sum_{kl}(\mathbf{A}^0\mathbf{p}_{ij,kl}^{II} + \mathbf{A}_{ij}^I\mathbf{p}_{kl}^I)\varepsilon_{ij}\varepsilon_{kl} + \ldots \\ + \sum_{ij}\sum_{kl}\cdots\sum_{st}(\mathbf{A}^0\mathbf{p}_n^N + \mathbf{A}_{ij}^I\mathbf{p}_{n-1}^{N-1})\varepsilon_{ij}\varepsilon_{kl}\cdots\varepsilon_{st} + \cdots = \boldsymbol{\alpha} \end{aligned} \tag{3.18}$$

From Eq. (3.18), we can derive

Constant item: $$\mathbf{A}^0\mathbf{p}^0 = \boldsymbol{\alpha} \tag{3.19}$$

1st degree item: $$\mathbf{A}^0\mathbf{p}_{ij}^I + \mathbf{A}_{ij}^I\mathbf{p}^0 = \boldsymbol{\alpha} \tag{3.20}$$

2nd degree item: $$\mathbf{A}^0\mathbf{p}_{ij,kl}^{II} + \mathbf{A}_{ij}^I\mathbf{p}_{kl}^I + \mathbf{A}^0\mathbf{p}_{kl,ij}^{II} + \mathbf{A}_{kl}^I\mathbf{p}_{ij}^I = \boldsymbol{\alpha} \tag{3.21}$$

$$\vdots$$

Therefore, in the first order approximation, we can derive

$$\begin{aligned} \Delta\mathbf{p} \approx \sum_{ij}\mathbf{p}_{ij}^I\varepsilon_{ij} &= -\left(\mathbf{A}^0\right)^{-1}\left(\sum_{ij}\mathbf{A}_{ij}^I\varepsilon_{ij}\right)\mathbf{p}^0 \\ &= -\left(\mathbf{A}^0\right)^{-1}\Delta\mathbf{A}\mathbf{p}^0 \end{aligned} \tag{3.22}$$

Substitute $\Delta\mathbf{p}$ in Eq. (3.14) by Eq. (3.22), we can derive

$$\boldsymbol{\beta}^0 + \Delta\boldsymbol{\beta} = \mathbf{B}^0\mathbf{p}^0 + \Delta\mathbf{B}\mathbf{p}^0 + \left(\mathbf{B}^0 + \Delta\mathbf{B}\right)\left(-\left(\mathbf{A}^0\right)^{-1}\Delta\mathbf{A}\mathbf{p}^0\right) \tag{3.23}$$

$$\begin{aligned} \Delta\boldsymbol{\beta} &= \Delta\mathbf{B}\mathbf{p}^0 - \mathbf{B}^0\left(\mathbf{A}^0\right)^{-1}\Delta\mathbf{A}\mathbf{p}^0 - \Delta\mathbf{B}\left(\mathbf{A}^0\right)^{-1}\Delta\mathbf{A}\mathbf{p}^0 \\ &\approx \Delta\mathbf{B}\mathbf{p}^0 - \mathbf{B}^0\left(\mathbf{A}^0\right)^{-1}\Delta\mathbf{A}\mathbf{p}^0 \end{aligned} \tag{3.24}$$

Therefore, from Eq. (3.24), the *k*th item $\Delta\boldsymbol{\beta}_k$ in the variation vector $\Delta\boldsymbol{\beta}$ can be expressed as

$$\begin{aligned} \Delta\boldsymbol{\beta}_k = C_{11}^k\Delta a_{11} + C_{12}^k\Delta a_{12} + \cdots + C_{ij}^k\Delta a_{ij} + \cdots + C_{n,n}^k\Delta a_{n,n} \\ + D_1^k\Delta b_{k1} + D_2^k\Delta b_{k2} + \cdots + D_n^k\Delta b_{kn} \end{aligned} \tag{3.25}$$

where C_{ij}^{k} and D_{i}^{k} are the coefficients. Δa_{ij} and Δb_{ki} are the minute variations of the elements in the coefficient matrix **A** and the environmental load matrix **B**.

Therefore, it is known that the variation of the final cumulative environmental load can be approximately expressed as the linear addition of the variations of the input parameters in LCI analysis. If the mean values and the standard deviations of the variations are μ_{ij}, μ_{ij}' and σ_{ij}, σ_{ij}' respectively, then, the mean value and the standard deviation of the variation of the final cumulative environmental load can be derived as:

$$E[\Delta\boldsymbol{\beta}_k] = \sum_{ij} C_{ij}^{k}\mu_{ij} + \sum_{i} D_{i}^{k}\mu_{ki}' \tag{3.26}$$

$$\sigma[\Delta\boldsymbol{\beta}_k] = \sqrt{\sum_{ij}\left(C_{ij}^{k}\right)^2\sigma_{ij}^2 + \sum_{i}\left(D_{i}^{k}\right)^2\left(\sigma_{ki}'\right)^2} \tag{3.27}$$

Assuming that all Δa_{ij} and Δb_{ki} share the same probability distribution and are independent, according to the central limit theorem, the variation of the final cumulative environmental load estimated to be normal distribution.

§ 3.3.1.2 Formulation of the simplified uncertainty analysis based on the central limit theorem

Generally, in LCI analysis, a lot of unit processes and a great number of process data are needed to construct the product system, and those process data are independent of each other in most cases. Moreover, in general, the LCI analysis is based on the linear assumption of the established product system.

On the other hand, it has been shown in section 3.3.1.1 that the variation of the final cumulative environmental load can be estimated to normal distribution approximately. Consequently, the final environmental load will be normal distribution as well, although it cannot expressed as the linear addition of the input parameters exactly. Then, the mean value of kth environmental load β_k is calculated by using Eq. (2.4),

$$\boldsymbol{\beta} = \mathbf{B}\mathbf{A}^{-1}\boldsymbol{\alpha} \tag{2.4}$$

the standard deviation $\sigma[\beta_k]$ of β_k is can be calculated by

$$\sigma[\beta_k] = \sqrt{\left(\frac{\partial\beta_k}{\partial a_{11}}\right)^2(\sigma[a_{11}])^2 + \left(\frac{\partial\beta_k}{\partial a_{12}}\right)^2(\sigma[a_{12}])^2 + \cdots + \left(\frac{\partial\beta_k}{\partial a_{ij}}\right)^2(\sigma[a_{ij}])^2 + \cdots} \tag{3.28}$$

where a_{ij} is the input parameters in LCI analysis, $\sigma[a_{ij}]$ is the standard deviation of a_{ij}. Using the result of rate sensitivity analysis s_{ij}^k, $\frac{\partial \beta_k}{\partial a_{ij}}$ can be obtained as:

$$\frac{\partial \beta_k}{\partial a_{ij}} \approx \frac{\Delta \beta_k}{\Delta a_{ij}} = s_{ij}^k \frac{\beta_k}{a_{ij}} \tag{3.29}$$

Then, substituting the calculated $\frac{\partial \beta_k}{\partial a_{ij}}$ into Eq. (3.28), the standard deviation $\sigma[\beta_k]$ can be derived as:

$$\sigma[\beta_k] = \sqrt{\sum_j \sum_i \left(\frac{\overline{\beta}_k}{\overline{a}_{ij}} S_{ij}^k \right)^2 \left(\sigma[a_{ij}] \right)^2} \tag{3.30}$$

Approximate calculation of uncertainty based on the central limit theorem, herein, is calculated by using the sensitivity analysis results and gives a rough result about the final cumulative uncertainty of LCI result. In this uncertainty analysis method, only the standard deviations of the process data are needed. It is not necessary to find out the distribution types of the process data, which are very time and cost consuming. Since the approximate calculation of uncertainty is based on the matrix-based LCI and uses the rate sensitivity analysis result, the calculation of the uncertainty will not cost much time. Therefore, the approximate calculation of uncertainty based on the central limit theorem is quite easy to use.

The development of the simplified method for uncertainty analysis in LCI is based on the approximate reasoning. It is also based on the assumption that the process data share the same probability distribution and are independent. Therefore, it is still needed to prove in practical LCA case studies that whether the simplified uncertainty analysis based on the central limit theorem can give us a correct and reliable result. The proof and the inspection will be stated in section 3.4.

§ 3.3.2 Detailed uncertainty analysis based on the Monte Carlo simulation

Besides the approximate calculation method of uncertainty based on the central limit theorem, in a few LCA case studies, some stochastic models (e.g. Monte Carlo) are used in LCI to compute the uncertainty of cumulative emissions and resource requirements. However, there are still some problems to solve in those models for LCI.

(1). Though uncertainty analysis has ever been carried out in some case studies, the established LCA models are not suitable to many other LCA case studies. It means that they are not general-purpose LCA models. Moreover, many LCA software, which have the uncertainty analysis function, are somewhat complex, so, they are not appropriate to the practitioners who have few LCA experience.

(2). Another problem is that there are a great number of input parameters in a practical LCA case study. It is unreasonable and even impossible to determine all the parameter distributions for the Monte Carlo simulation. Therefore, it is difficult to carry out Monte Carlo simulation for uncertainty analysis in LCA.

In this section, matrix based Monte Carlo simulation method for uncertainty analysis in LCA is proposed. The procedure and the algorithm of Monte Carlo simulation for uncertainty analysis in LCA are introduced in detail. Different from the conventional methods, the introduced Monte Carlo simulation method in this thesis is based on the matrix method and suitable to all the general LCA case studies.

The general algorithm of Monte Carlo simulation is stated as follows.

(1). Determine the relationship of the inputted parameters and the outputted expectations;

(2). Determine the probability distributions of the inputted parameters;

(3). Set the number of iterations and carry out Monte Carlo simulation. In each run of the Monte Carlo simulation, a new value of each inputted parameter is produced randomly according to the defined probability distribution. Consequently, new values of the outputted expectations are produced automatically. Repeated calculations produce a distribution of the predicted output values, reflecting the combined input parameter uncertainties. Each simulation consists of enough (e.g. 10000) iteration, which is considered sufficient to obtain a representative frequency chart of the outputted expectations.

In a practical LCI analysis, many environmental loads (e.g., CO2, SO2) are needed to calculate, so, there are many relationships to determine. For example, if there are m expected outputs and n input parameters, in conventional Monte Carlo simulations, it is needed to define m relationships one by one as follows:

$$\begin{aligned} y_1 &= f_1(x_1, x_2, \cdots, x_n) \\ &\vdots \\ y_m &= f_m(x_1, x_2, \cdots, x_n) \end{aligned} \tag{3.31}$$

However, it is very delicate when the m becomes large. If the relationships can be defined in matrix form, as shown in Eq. (3.32), it will become easier to determine the relationships.

$$Y = F(X) \tag{3.32}$$

Herein, in the Monte Carlo simulation for uncertainty analysis in LCA, the expected environmental loads are calculated by matrix algebraic operation, using Eq. (2.4).

$$\boldsymbol{\beta} = \mathbf{B}\mathbf{A}^{-1}\boldsymbol{\alpha}$$

Therefore, in the matrix-based LCI, it is quite easy to determine the relationships of the inputted parameters and the outputted expectations for the Monte Carlo simulation. Since the matrix method for LCI analysis developed in chapter 2 is a general-purpose method, if an LCA model is established once by using Eq. (2.4), this model is appropriate to all practical LCA case studies. Therefore, by the LCA model, the Monte Carlo simulation can also be carried out to different LCA case studies by different practitioner, without determining the relationships again.

§ 3.3.3 Development of the general procedure for uncertainty analysis

In a practical LCA case study, since there are a great number of input parameters, it is unreasonable to determine all the probability distributions of them. Therefore, it is considered to select some essential input parameters in advance, which have significant influences on the final LCA result. After that, the uncertainty of LCA result propagating from the uncertainties of the essential input parameters is to be studied.

Concerning the selection of essential input parameters, it has been suggested that the key input data, which determine the value and uncertainty of the cumulative results, should be identified according to their uncertainty and their contributions to the cumulative results [6, 12], as shown in Fig. 3.2.

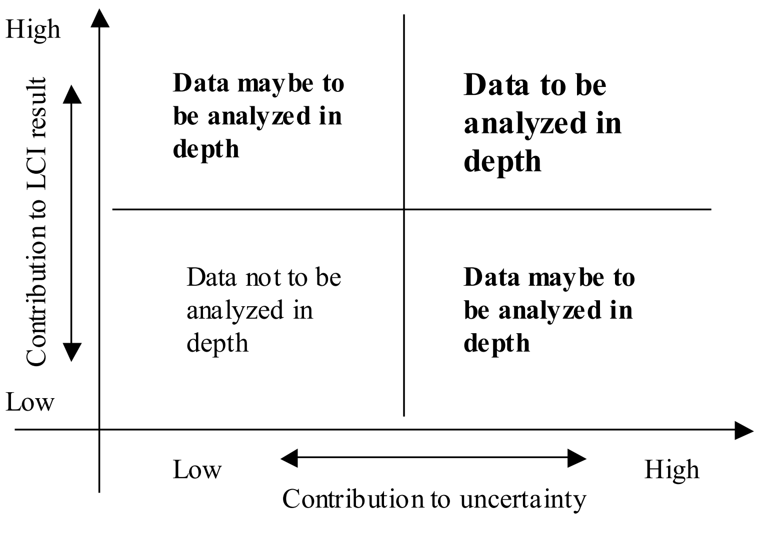

Fig. 3. 2 Data classification according to their contributions

In Fig. 3.2, the data that make a large contribution to the final LCI result are in the upmost row. The data, whose contributions to the uncertainty of LCI result are large, are in the rightmost column. Consequently, the data in the right top region are the most essential data, and their uncertainties or reliabilities are needed to study in deep.

Herein, we may use the rate sensitivity analysis results to express the process data's contributions to the final LCI result. Eq. (3.30) represents the approximate calculation method of uncertainty. Based on Eq. (3.30), the ratio shown in Eq. (3.33) may be used to express the contribution of datum a_{ij} to the uncertainty of LCI result.

$$r_{ij} = \frac{\left(\frac{\overline{\beta}_k}{\overline{a}_{ij}} S_{ij}^k\right)^2 (\sigma[a_{ij}])^2}{(\sigma[\beta_k])^2} = \frac{\left(\frac{\overline{\beta}_k}{\overline{a}_{ij}} S_{ij}^k\right)^2 (\sigma[a_{ij}])^2}{\sum_j \sum_i \left(\frac{\overline{\beta}_k}{\overline{a}_{ij}} S_{ij}^k\right)^2 (\sigma[a_{ij}])^2} \tag{3.33}$$

Then, the general procedure of uncertainty analysis in LCA, in which the sensitivity analysis and uncertainty analysis are combined, is shown in Fig. 3.3.

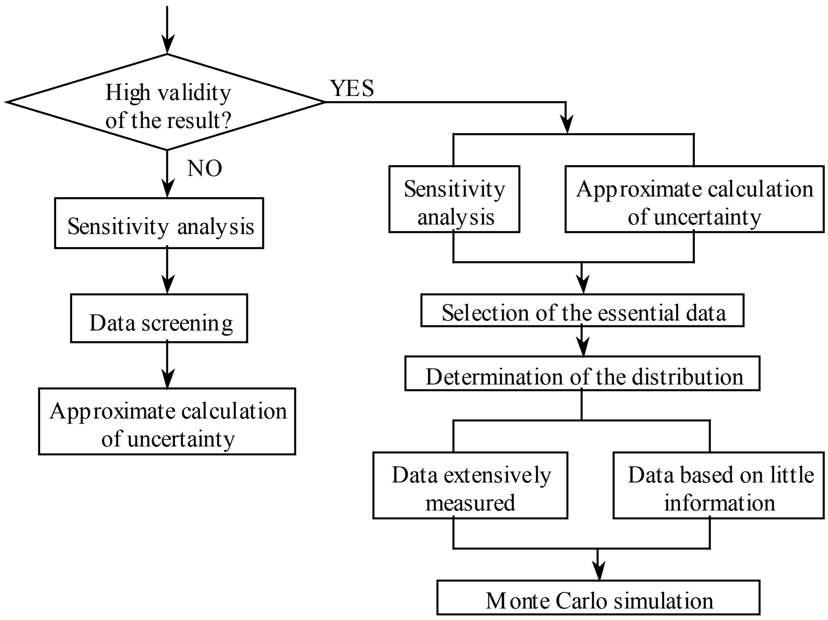

Fig. 3. 3 General procedure for uncertainty analysis in LCA

In the first place, it is needed to judge by the LCA practitioner whether a high validity of the uncertainty analysis result is needed. If the required validity of the uncertainty analysis result is not so high, it is just needed to carry out the rate sensitivity analysis to do data screening. After that, the uncertainties of the selected essential data are studied. Finally, the uncertainty of the final LCI result propagated from the uncertainties of the essential data is estimated by using the simplified method of uncertainty analysis.

While, when the required validity of the uncertainty analysis result is high, the uncertainty analysis should be carried out by the following steps.

Firstly, in order to screen out the essential data in an LCA case study, the sensitivity analysis or the approximate calculation of uncertainty is needed to carry out.

Secondly, according to the sensitivity analysis results or the results of approximate calculation of uncertainty or both of them, the essential data are selected.

Thirdly, the uncertainties of the selected essential data are studied and their probability distributions are determined. As the methods for determining the probability distribution, statistic method based on extensively measured data may be used. Or, based on little information of the data, some estimation methods can be used, such as using the Bayesian theorem [18, 19].

Fourthly, the probability distributions of the data and the expected items are set. Trial number of Monte Carlo simulation is set as well. Then, Monte Carlo simulation for uncertainty analysis is carried out.

Finally, the frequency charts of the outputted expectations and some statistic values of the result are exported.

§ 3.4 Inspection and comparison of the two uncertainty analysis methods

It has been shown in section 3.3.1.1 that the variation of the final cumulative environmental load can be estimated to normal distribution approximately. Consequently, it is estimated that the final environmental load will be normal distribution as well, although it cannot expressed as the linear addition of the input parameters exactly. However, it is necessary to study further whether the final cumulative environmental loads are really normal distribution when the input parameters are uncertain in practical LCA case studies.

Therefore, in this section, by using two examples of LCA case studies, the practicability and effectiveness of the approximate calculation of uncertainty based on the central limit theorem are examined. One of the case studies is the LCA case study of sandwich package [6], which is composed of 4 processes, and the other one is that of PVC, which is composed of 10 processes. The product system of sandwich package for LCA is shown in Fig. 3.4 and that of PVC is shown in Fig. 3.5. In these case studies, the uncertainty analysis results by Monte Carlo simulation are regarded to be the true results. By comparing the uncertainty analysis results by the approximate calculation with those by Monte Carlo simulation, the effectiveness of the former one is examined. It has known that if the processes in a LCA case study are fairly few, the final LCI result or LCA result will not be normal distribution. The approximate calculation method of uncertainty is based on the first order approximation, therefore, when the variations of the input parameters become large, it will result in big error on the final LCI/LCA result. In this section, the influences of the coefficient of variation of the inputted data and the process number of the result of uncertainty analysis are particularly investigated.

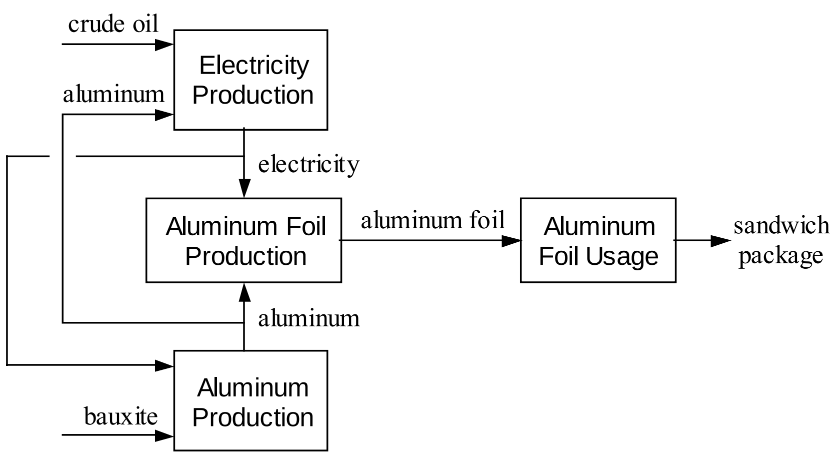

Fig. 3. 4 The product system of sandwich package for LCA

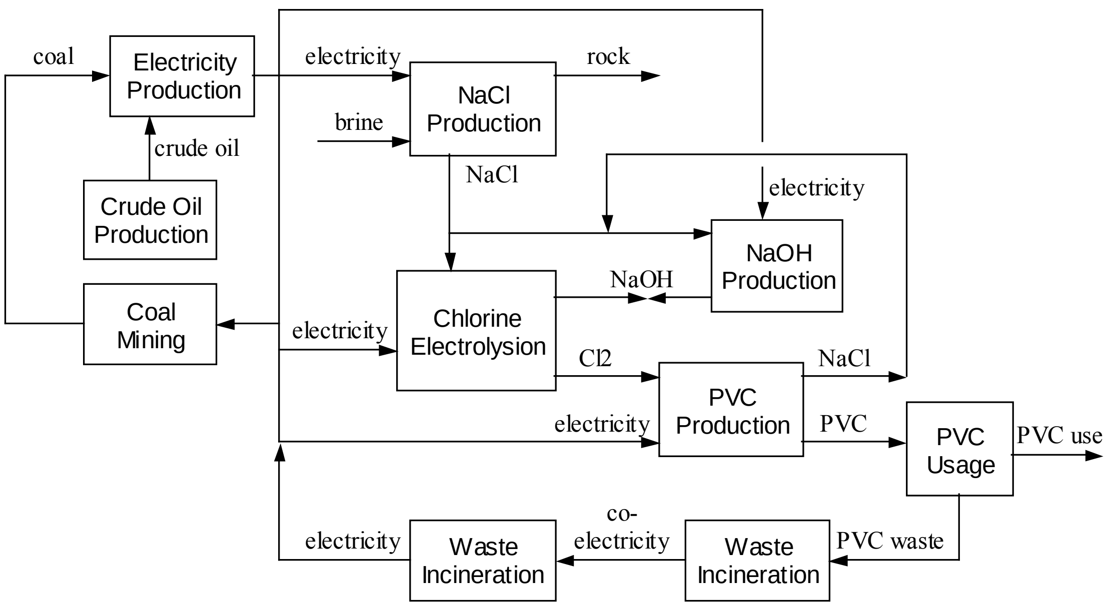

Fig. 3. 5 The product system of PVC for LCA

In the case studies of sandwich package and PVC, the uncertainties of the final cumulative CO_2 emission are analyzed by the approximate calculation method and Monte Carlo simulative respectively. It is assumed that all the process data are uncertain and they are given different coefficient of variation, for instance 5%, 10% and 30%. In the Monte Carlo simulation, the probability distribution of each uncertain datum is randomly assumed to be normal distribution, triangle distribution, logarithmic normal distribution or Weibull distribution.

Then, the calculated mean and standard of the final CO_2 emission by the two uncertainty analysis methods are shown in Table 3.2 and Table 3.3. The cumulative distributions of the CO_2 emissions in the normal distribution paper are shown in Fig. 3.6 and Fig. 3.7.

Table 3. 2 Uncertainty analysis results in the case study of sandwich package

	Approximate Calculation of Uncertainty		Monte Carlo simulation	
CO2 emission (Unit: g)	Mean	Standard Deviation	Mean	Standard Deviation
Coefficient of Variation				
～5%	30.60	5.51	31.39	5.88
～10%	30.60	11.37	34.45	23.43
～30%	30.60	34.19	41.30	10710.30

Table 3. 3 Uncertainty analysis results in the case study of PVC

	Approximate Calculation of Uncertainty		Monte Carlo simulation	
CO2 emission (Unit: kg)	Mean	Standard Deviation	Mean	Standard Deviation
Coefficient of Variation				
～5%	337.65	27.48	338.84	27.31
～15%	337.65	123.60	342.06	59.21
～30%	337.65	169.32	371.58	6402.51

In the LCA case study of sandwich package, which is composed of 4 processes, when the coefficient variation is about 5%, the uncertainty analysis result by the approximate calculation method is quite consistent with that by Monte Carlo simulation. Therefore, when the dispersion of the input parameters are very small, although the number of processes is as little as 4, the approximate calculation method can still give out a correct enough result of the uncertainty analysis. When the coefficient variation becomes as large as about 30%, the result of the approximate calculation is completely different from that of Monte Carlo simulation.

In the case study of PVC, which is composed of 10 processes, when the coefficient variation is about 5%, the uncertainty analysis result by the approximate calculation method is almost completely consistent with that by Monte Carlo simulation. When the coefficient variation becomes to be about 15%, an error will be produced in the result by the approximate calculation of uncertainty.

When the coefficient variation becomes as large as about 30%, the result of the approximate calculation is different from that of Monte Carlo simulation.

It is known that a normal distribution in a normal distribution paper is shown as a straight line. From Fig. 3.6, we can see that when the coefficient of variation is about 5%, the cumulative distribution of CO_2 emission is approximately shown as a straight line. While, when the coefficient of variation becomes to be about 10% or 30%, curliness happens to the lines, which shows that they are not normal distribution. From Fig. 3.7, we can see that all the lines are so straight. Especially, the line with the coefficient of variation of about 5% is almost a completely straight one.

From the discussions above, it is confirmed that when the dispersion of the input data gets smaller, the approximate calculation of uncertainty can give a more accurate result of the uncertainty analysis. Moreover, if the processes of a LCA case study become more, the uncertainty analysis result by the approximate calculation is more accurate. In a practical LCA case study, the product system is generally composed of hundreds of processes, therefore, it may be inferred that the approximate calculation based on the central limit theorem is an effective method for the uncertainty analysis.

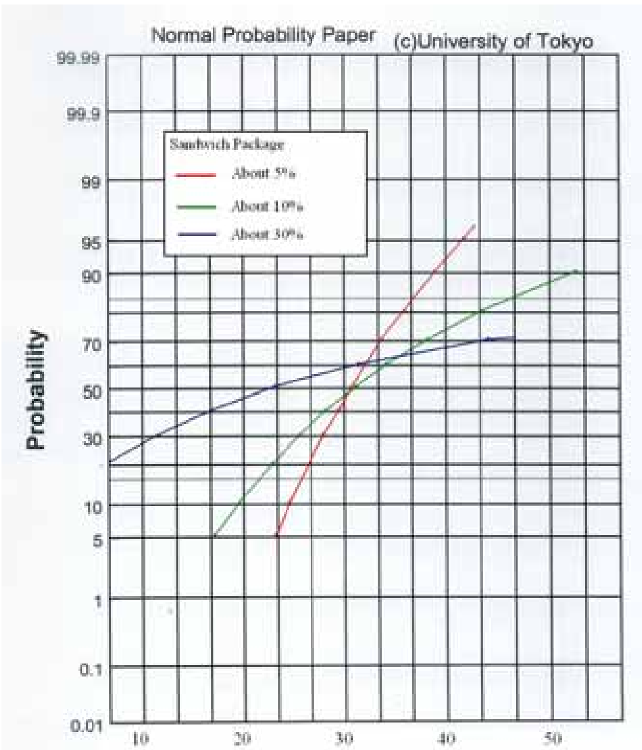

Fig. 3. 6 Cumulative distribution of CO2 emission (sandwich package)

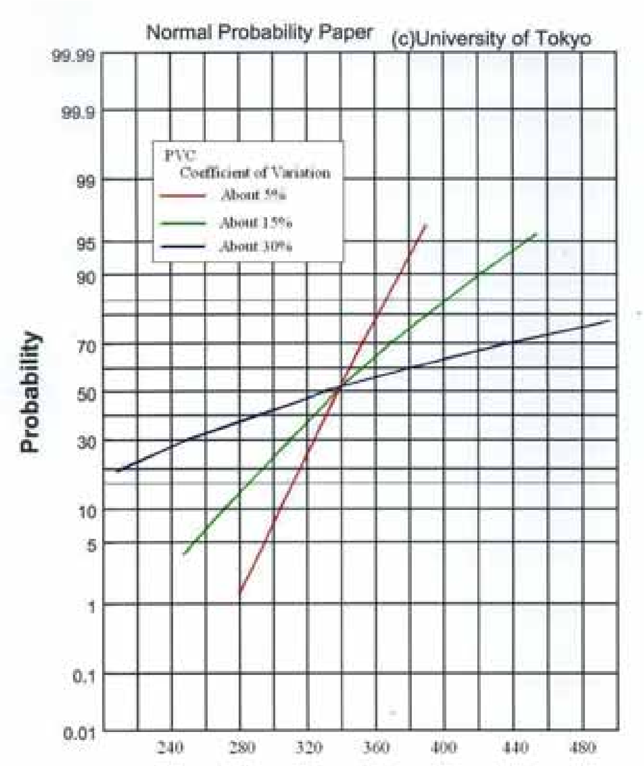

Fig. 3. 7 Cumulative distribution of CO_2 emission (PVC)

In the approximate calculation of uncertainty in LCA, which is based on the central limit theorem, only the mean and standard deviation of the inputted data are needed. This method is relatively easy and gives out an approximate result of the uncertainty. On the other hand, when more detailed information of the probability distribution of the inputted data are known, it is possible to carry out a more accurate assessment of the uncertainty in LCA. In this case, Monte Carlo simulation is the most often used. However, in the Monte Carlo simulation for the uncertainty analysis in LCA, much more information about the uncertainties of the input data are needed, which results in consuming much more time, cost and labor. Moreover, in the Monte Carlo simulation, much more time is consumed in a huge number of iterative calculations. Therefore, when the required accuracy of uncertainty analysis is not so high, the approximate calculation of uncertainty is recommended here, since it is more practical and easier. When the required accuracy of uncertainty is high, Monte Carlo simulation may be carried out, by using the general procedure shown in Fig. 3.3.

§ 3.5 An example of LCA case study for sensitivity and uncertainty analysis

Herein, an LCA case study of roof gutter [15] is used to demonstrate the sensitivity analysis and the uncertainty analysis based on the central limit theorem and the Monte Carlo simulation. By using this case study, the practicability and effectiveness of the general procedure for uncertainty analysis are examined and confirmed as well.

The goal of the study is to assess the Global Warming Potential (GWP) of the roof gutter in its life cycle. The constructed product system of the roof gutter is shown in Fig. 3.8. The defined functional flows in the processes are shown in the figure as well.

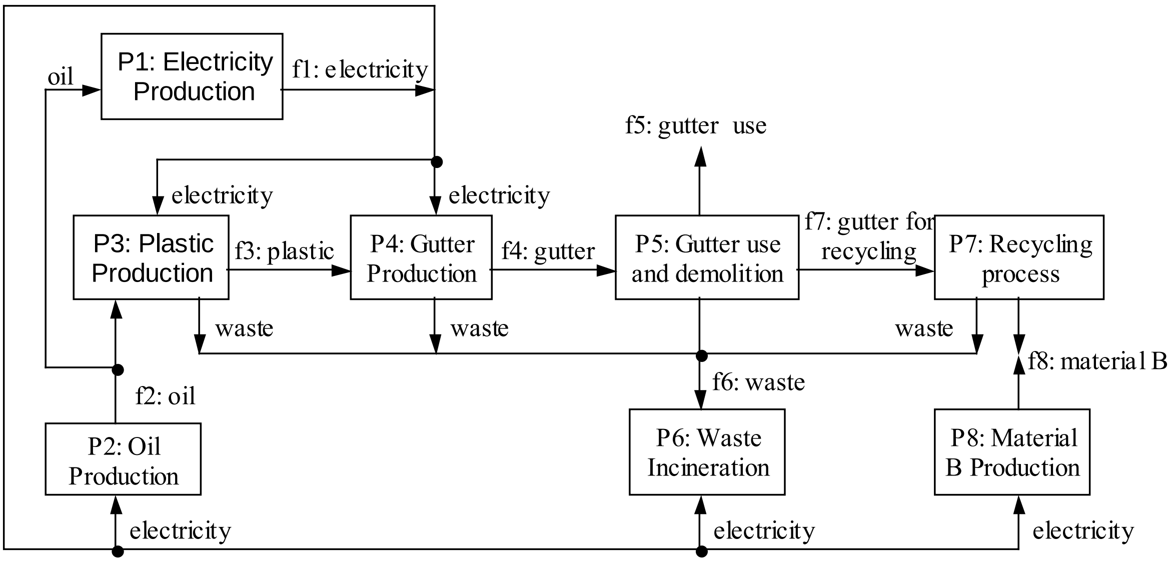

Fig. 3. 8 The product system of roof gutter for LCA

After defining the functional flows, the coefficient matrix **A** is composed as:

$$
\mathbf{A} = \begin{array}{c} \\ \mathbf{f}_1 \\ \mathbf{f}_2 \\ \mathbf{f}_3 \\ \mathbf{f}_6 \\ \mathbf{f}_4 \\ \mathbf{f}_7 \\ \mathbf{f}_8 \\ \mathbf{f}_5 \end{array}
\begin{array}{c} \begin{array}{cccccccc} \mathbf{p}_1 & \mathbf{p}_2 & \mathbf{p}_3 & \mathbf{p}_4 & \mathbf{p}_5 & \mathbf{p}_6 & \mathbf{p}_7 & \mathbf{p}_8 \end{array} \\
\begin{pmatrix}
1 & -0.011 & -50 & -1 & 0 & -1 & -25 & -40 \\
-0.0061 & 1 & -0.8 & 0 & 0 & -0.5 & -0.1 & -0.3 \\
0 & 0 & 1 & -325 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.01 & 0.05 & 65 & -1 & 0.1 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 260 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1.8 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0
\end{pmatrix} \end{array} \tag{3.34}
$$

The environmental load matrix **B** is composed as:

$$\mathbf{B} = \begin{matrix} CO_2 \\ CH_4 \\ N_2O \end{matrix} \begin{pmatrix} 1.1E-2 & 0.5 & 2 & 0 & 0 & 3 & 2 & 1.5 \\ 3.1E-4 & 4.1E-3 & 0 & 0 & 0 & 5.1E-5 & 4.1E-3 & 0 \\ 1.1E-6 & 1.1E-4 & 1.1E-5 & 0 & 0 & 5.1E-5 & 3.1E-4 & 2.1E-4 \end{pmatrix} \tag{3.35}$$

The system boundary condition vector **α** is defined as:

$$\boldsymbol{\alpha} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 \end{pmatrix}^T \tag{3.36}$$

Then, the final environmental load vector **β** is calculated to be:

$$\boldsymbol{\beta} = \begin{pmatrix} 181.05383 & 0.64878 & 0.00383 \end{pmatrix}^T \tag{3.37}$$

The units of the environmental loads are all kg. According to IPCC1995 [20], the characterization factors of GWP(100years) are 1, 21 and 310 kg-CO_2/kg respectively. Then, the expected GWP(100years) associated with roof gutter is calculated to be 195.87 kg-CO_2, among which the contribution of CO_2 emission takes the most proportion.

In order to decrease the global warming potential, it will be efficient to reduce the CO_2 emission. So, the sensitivity analysis is carried out to CO_2 emission and the result is shown as:

$$\mathbf{S}_{CO2} = \begin{pmatrix} -0.064 & 3.72E-5 & 0.252 & 1.55E-5 & 0 & 1.46E-3 & 0.101 & -0.291 \\ 0.014 & -0.120 & 0.144 & 0 & 0 & 0.026 & 0.014 & -0.078 \\ 0 & 0 & -1.126 & 1.126 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.012 & 1.80E-4 & 0.234 & -0.340 & 0.094 & 0 \\ 0 & 0 & 0 & -1.126 & 1.126 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.360 & 0 & 0.360 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1.144 & 1.144 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0.050 & 0.120 & 0.718 & 0 & 0 & 0.313 & 0.574 & -0.775 \end{pmatrix} \tag{3.38}$$

By using the data of uncertainty provided by Huijbregs [15] and assuming that the process data are triangle distributions and the GWP factors are normal distributions, the uncertainty of the final expected GWP is studied. In the Monte Carlo simulation for uncertainty analysis, the simulation consists of 10000 iterations, the probability distribution chart of GWP and some statistic values are shown in Fig. 3.9 and Table 3.4.

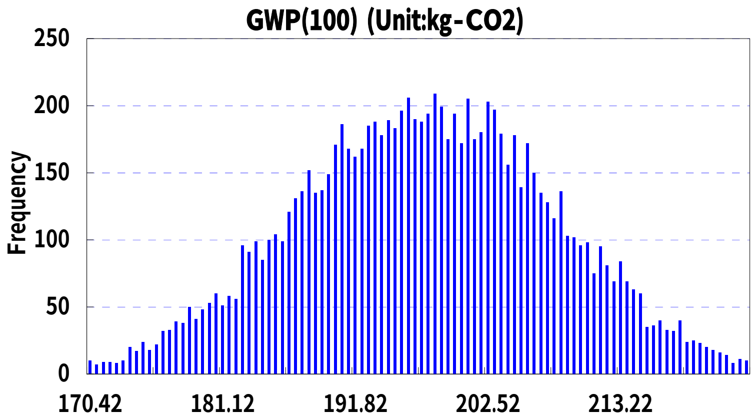

Fig. 3. 9 Probability distribution of GWP in the LCA case study of roof gutter

Table 3. 4 Statistic of the GWP(100years) (kg-CO_2)

Statistic	Value
Trial number	10,000
Mean	197.59
Median	197.63
Standard deviation	10.62
Variance	112.82
Skewness	0.04
Kurtosis	2.94
Coefficient of variance	0.05
Lower range bound	159.97
Upperrange bound	234.6
Range	74.63
Average standard error	0.11

Checking the statistics, it can be known that the mean of GWP(100years) is 197.59 kg-CO_2 and the standard deviation is 10.62 kg-CO_2.

In the meanwhile, the approximate calculation of uncertainty is also carried out and the result is shown in Table 3.5.

Table 3. 5 Comparison of the two uncertainty analysis results

GWP(100years)(kg-CO_2)	Monte Carlo simulation	Approximate calculation	Error
Mean	197.59	195.87	-0.87%
Standard deviation	10.62	9.37	-11.77%

The probability distributions of GWP(100years) by the approximate calculation and Monte Carlo simulation are shown in Fig. 3.10 and Fig. 3.11. Comparing the two uncertainty analysis results, in both of the figures, it can be seen that the two uncertainty analysis graphs are approximately overlapped. Therefore, the conclusion can be obtained that the approximate calculation method can give a correct uncertainty interpretation in LCA. Especially, in Fig. 3.11, the line of Monte Carlo simulation is such a straight line, which shows that the GWP is exactly normal distribution. Therefore, it is recommended to use the approximate calculation method instead of Monte Carlo simulation when the required uncertainty analysis precision is not so high, since it is much easier.

In the uncertainty analysis in the LCA case study of roof gutter, the uncertainty of GWP is propagated from the uncertainties of 50 process data and the GWP factors. Herein, furthermore, the influence of the number of studied uncertain data on the final uncertainty analysis result is studied as well. The effectiveness of the general procedure of Monte Carlo simulation based uncertainty analysis is examined.

According to the sensitivity analysis result shown in Eq. (3.38), the most essential data, which determine the value the final cumulative CO_2 emission, are selected. After that, the uncertainties of final CO_2 emission and GWP propagated from the selected data's uncertainties are studied. In each analysis, the number of selected most essential data are different. So, the influence of the number of uncertain data on the final uncertainty analysis result is studied and the results are shown in Fig. 3.12, Fig. 3.13 and Table 3.6.

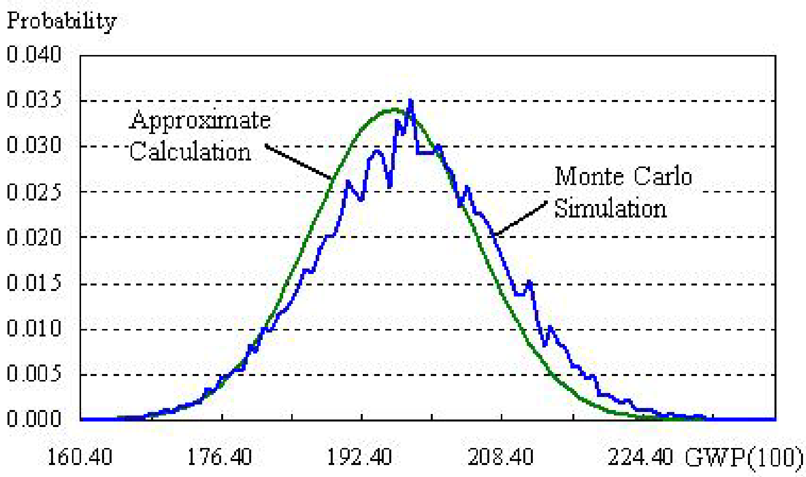

Fig. 3. 10 Comparison of the probability distributions of GWP(100)

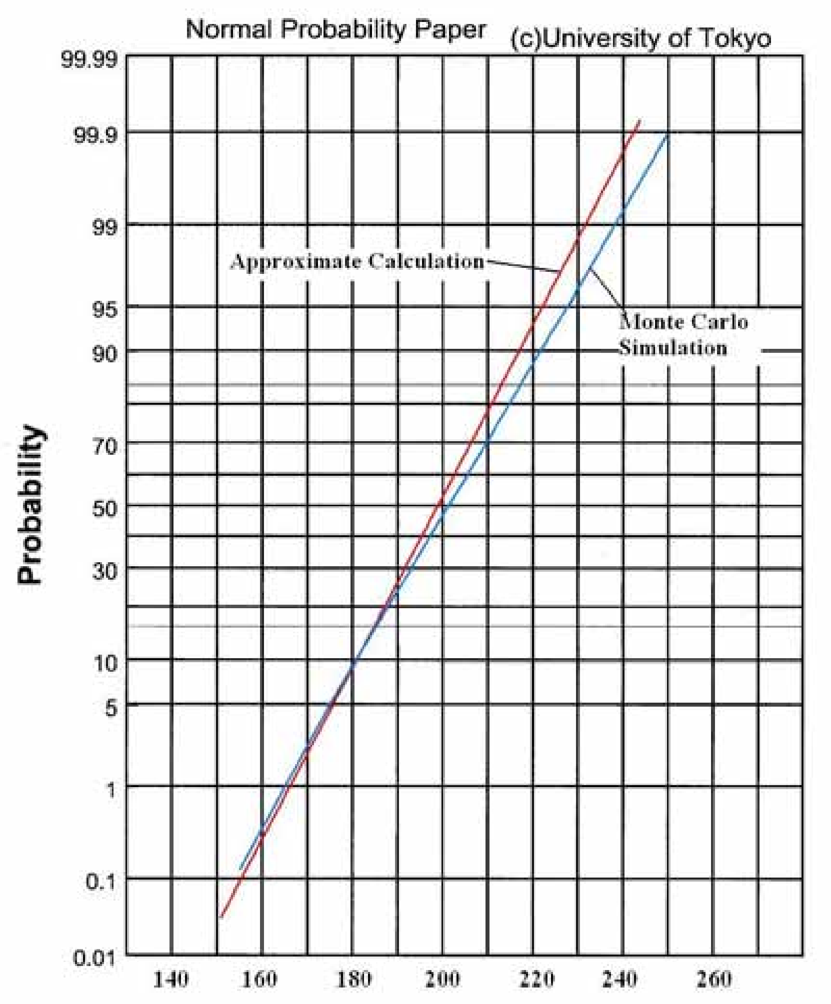

Fig. 3. 11 Cumulative distribution of GWP(100) in normal distribution paper

From Fig. 3.12, Fig. 3.13 and Table 3.6, we can see that when the number of selected most essential data is 10, 20, and 30 respectively, the uncertainty analysis results of CO_2 emission and GWP are almost not changed. Compared with the uncertainty analysis result propagated from the total 50 uncertain data, both the mean and standard deviation of the final CO_2 emission are almost not changed. In the same way, compared with the result of the total 50 uncertain data, when 10, 20, 30 most essential uncertain data are selected, the means of GWP are almost the same, while the standard deviation is changed with a very small value. Therefore, it is known that when analyzing the uncertainty of LCI/LCA result propagated from the uncertainties of input data, not all the uncertain data but only the essential uncertain data are needed to investigate. In this LCA case study of roof gutter, it is enough to investigate the uncertainties of the only 10 most essential data for the uncertainty analysis of GWP. Rather than to investigate the uncertainties of total 50 data, 4/5 of the labor may be saved. Therefore, it can be confirmed that it is quite necessary to screen the essential data when carrying out uncertainty analysis in LCA. The general procedure of uncertainty analysis is extremely effective in a practical LCA case study, especially when the process number becomes large.

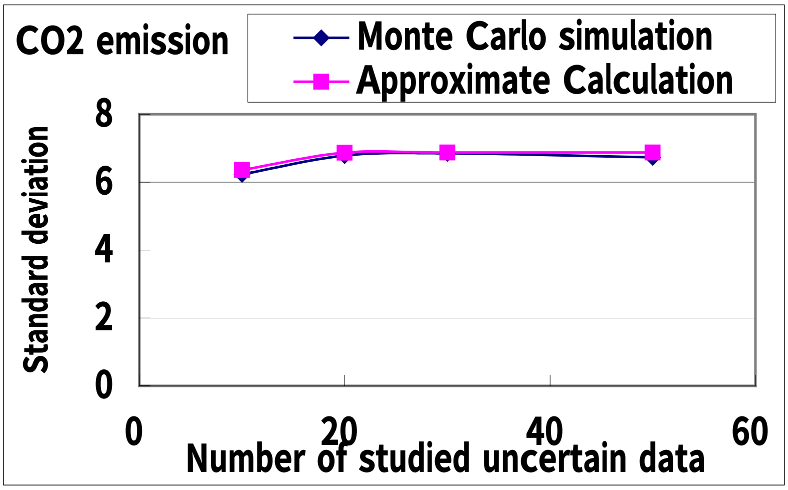

Fig. 3. 12 The influence of the number of uncertain data in uncertainty analysis (a)

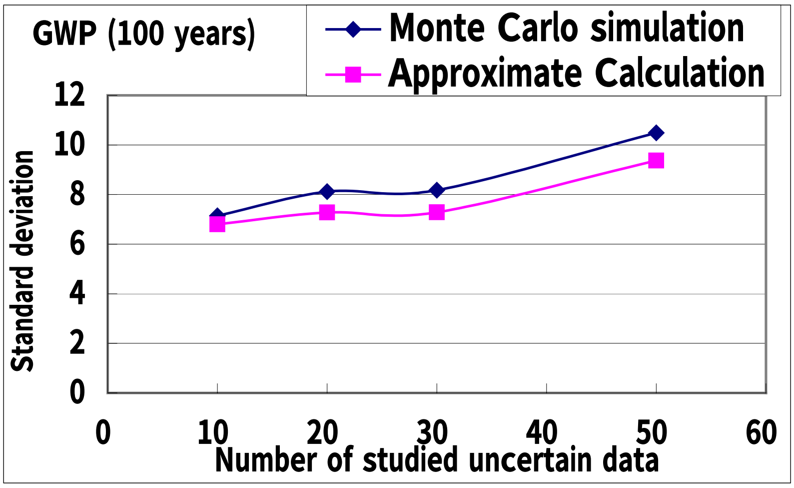

Fig. 3. 13 The influence of the number of uncertain data in uncertainty analysis (b)

Table 3. 6 The uncertainty analysis results with different number of uncertain data

	Monte Carlo simulation				Approximate Calculation			
	CO2 (kg)		GWP(100years) (kg-CO2)		CO2 (kg)		GWP(100years) (kg-CO2)	
Number of uncertain data	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
10	181.479	6.229	196.363	7.140	181.054	6.358	195.870	6.799
20	181.441	6.781	196.252	8.119	181.054	6.869	195.870	7.279
30	181.361	6.850	196.172	8.179	181.054	6.874	195.870	7.284
50	181.294	6.731	197.613	10.491	181.054	6.874	195.870	9.370

§ 3.6 Conclusions of Chapter 3

In this chapter, based on the matrix method introduced in chapter 2, how the sensitivity analysis and uncertainty analysis are dealt with in the matrix-based LCI is introduced.

The sensitivity analysis adopts the rate sensitivity and quantitatively studies the influence of each process datum on the final cumulative environmental loads. Following the formulation of sensitivity analysis by Sakai [9], the sensitivity analysis of the environmental load matrix **B** is formulated in this chapter. As a result, the sensitivity analysis based on matrix method is improved and completed to be a whole.

The uncertainty analysis studies the uncertainty of the LCI/LCA result, which is propagated from the uncertainties of the process data. A simplified method and a detailed method for uncertainty analysis, which are based on the central limit theorem and the Monte Carlo simulation respectively, are generalized based on the matrix method for LCI analysis. And, it is shown that the matrix method greatly supports the Monte Carlo simulation in LCI. After that, a general procedure for uncertainty analysis from the simplified method to the detailed method is proposed as well.

Finally, using some examples of LCA case studies, the sensitivity analysis method and the two uncertainty analysis methods are demonstrated and the effectiveness of them is examined. It is recommended to use the approximate calculation method instead of Monte Carlo simulation when the required uncertainty analysis precision is not so high. Moreover, the effectiveness of the general procedure of uncertainty analysis is examined and confirmed as well.

All the operations and calculations of sensitivity analysis and uncertainty analysis are based on matrix algebra. As a result, based on matrix method, the operations from LCI analysis to sensitivity and uncertainty analysis are connected to facilitate the LCA analysis.

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Chapter 4

Development of A General and Consistent Method for System Boundary Definition in LCA

It is known that the introduction of the concept of "life cycle" is the most essential feature of LCA. Therefore, it is extremely important to objectively compose an appropriate product system for LCA. Although there have been some discussion about the product system boundary definition, there is yet no general and consistent method to compose the appropriate product system, which is composed of all the essential unit processes.

In this chapter, considering the cost performance and the result's accuracy in a practical LCA case study, a general and consistent method about how to compose the appropriate product system is proposed. The matrix method proposed in Chapter 2 is combined with the conventional Input-Output Analysis (IOA) method. Using the combined method, the product system boundary is defined by an iterative process. A general procedure for system boundary definition is introduced as well, and it is compared with a conventional method. By using the method proposed in this chapter, as a result, the product system is composed of all the essential relevant unit processes, which provides the result of LCA with high accuracy. Furthermore, the product system is composed of only the essential relevant unit processes, which makes the LCA case study to be simplified and of low cost. Finally, as examples, case studies of desktop computer and refrigerator are performed to demonstrate the proposed method for system boundary definition, and the practicability and effectiveness of the method are examined.

Key words: Cost Performance, Input-Output Analysis, Iterative Process, Matrix Method, Result's Accuracy, System Boundary Definition

§ 4.1 Introduction

It is known that the introduction of the concept of "life cycle" is the most essential feature of Life Cycle Assessment (LCA). Therefore, in a practical LCA case study, to compose an appropriate product system objectively is one of the most important issues. Although there has been much discussion about the system boundary definition in LCA [4-9, 23-25], there is yet no general and consistent method for determining the system boundary and composing the appropriate product system. System boundary of LCA includes many aspects, such as temporal boundary and spatial boundary etc., particularly, the system boundary definition in this chapter focuses on the product system composition of a product, namely, which processes should be included in the product system is considered in this chapter.

In ISO 14040 [1], it is defined that the goal and scope of an LCA study should be clearly defined and consistent with the intended application at the first step of LCA. However, without any analysis about the object of LCA, it is rather difficult to compose the appropriate life cycle objectively. Moreover, it is recommended that the system boundary should be determined by an iterative process, in which an initial system boundary is chosen, and then further refinements are made by including new unit processes that are shown to be significant [1-3]. However, no concrete and practical method is given out in ISO standard.

Tillman et al [6] roughly discussed different principles for choosing system boundaries. However, most of those principles only concern the boundaries between the life cycle of the product and the related life cycle of other products. Also Suh et al [11] had a critical review about the system boundary selection in LCI using hybrid approaches, however, no general and concrete procedure for product system composition is stated.

Hondo and Sakai [5] developed a consistent method for system boundary definition using an economic input-output table with sensitivity analysis. However, since the usage of a product and the disposal of a used-product etc. cannot be assessed by Input-Output Analysis (IOA) method, these processes and their relative flows might be lost from the life cycle. If the lost processes or flows are important, it will result in a large effect on the final LCA result.

In a practical LCA case study, since a full scale LCA study is usually excessively detailed, expensive and time-consuming, simplification should be considered together with the completeness of the life cycle. There have been some discussion about the simplification of LCA [10, 26, 27]; however, the completeness of LCA is not stated sufficiently together with the simplification.

In this chapter, considering the cost performance and the result's accuracy in practical LCA case studies, a general and consistent method about how to compose the appropriate product system is proposed. Herein, the concept of 'appropriate product system' means that all of the essential processes, but not all the relevant ones are included in the product system. The method for system boundary definition uses the hybrid analysis method, which combines the improved matrix method and the conventional IOA method. The product system is composed by an iterative process. After the statement of the general procedure for product system composition, case studies of desktop computer and refrigerator are used to demonstrate the proposed method for system boundary definition.

§ 4.2 Review of the methods for LCI analysis

In this section, as the mathematical methods used for system boundary definition, the matrix method and the IOA method for LCI are reviewed.

§ 4.2.1 Review of the matrix method proposed in Chapter 2

The matrix method for LCI analysis has been discussed in detail in Chapter 2, and the practical approach for composing the necessary matrices was proposed in the chapter as well. Here, as one of the methods used for defining the appropriate system boundary, the matrix method is reviewed very simply.

In the matrix method, the quantitative occurrence of each unit process, which is needed in accomplishing the product system function, is derived by solving a set of linear balance equations as:

$$\mathbf{Ap} = \boldsymbol{\alpha} \tag{4.1}$$

where, **A** is the coefficient matrix, which is composed of the functional flows defined in unit processes. **α** is the boundary condition vector, whose items represent the absolute values of the materials in the coefficient matrix **A**, which pass through the system boundary. **p** is the process vector, items in which show the quantitative occurrences of unit processes. Then, process vector **p** can be obtained by calculating the inverse matrix $\mathbf{A}^{-1}$ of the matrix **A** as:

$$\mathbf{p} = \mathbf{A}^{-1}\boldsymbol{\alpha} \tag{4.2}$$

Then, the final environmental load vector **β** can be derived by using the environmental load matrix **B**, which is composed of the environmental load flows.

$$\boldsymbol{\beta} = \mathbf{Bp} = \mathbf{BA}^{-1}\boldsymbol{\alpha} \tag{4.3}$$

Moreover, except for the flows the in matrix **A** and **B**, all flows are arranged in the surplus flow matrix **C**. Then, the final surplus flow vector **γ** is calculated as:

$$\boldsymbol{\gamma} = \mathbf{CA}^{-1}\boldsymbol{\alpha} \tag{4.4}$$

In matrix **A**, **B** and **C**, columns represent processes and rows represent functional flows. Output flows are expressed by positive coefficients and input flows by negative ones.

§ 4.2.2 Review of the Input-Output Analysis (IOA) method

The IOA method for LCI is based on the input-output table, which describes how industries are inter-related through producing and consuming intermediate industry products represented by monetary transaction flows in a country or a region [12, 18, 19]. In IOA method, a square matrix $\mathbf{A'}$ is defined to represent the inter-relationship, and its element $(\mathbf{A'})_{ij}$ shows the amount of industry output i required by industry j to produce a unit of its output. Then, the total industry output $\mathbf{x}$ required to supply the final demanded output $\mathbf{f}$, which are consumed by final consumers, can be derived as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A'})^{-1}\mathbf{f} \tag{4.5}$$

where $\mathbf{I}$ denotes the identity matrix and $\mathbf{A'}$ is generally named as input-output coefficient matrix or direct requirements matrix. Then, the total environmental load vector $\boldsymbol{\beta'}$ associated with the final demanded output $\mathbf{f}$ can be obtained by:

$$\boldsymbol{\beta'} = \mathbf{B'x} = \mathbf{B'}(\mathbf{I} - \mathbf{A'})^{-1}\mathbf{f} \tag{4.6}$$

where $\mathbf{B'}$ is the environmental load density matrix, in which each element $(\mathbf{B'})_{ij}$ denotes the amount of environmental load i , which is generated in producing a unit of output by industry j.

IOA method has many merits, such as low time and cost consuming. However it has its own problems as well, for instance, the classification of industries is too rough in terms of accuracy. In order to resolve this problem, methods such as expanding the number of industry groups etc. have been mentioned [12, 18].

§ 4.3 Combination of the matrix method and the IOA method

In the matrix method, the materials and parts etc., which are imported into the product system from outside, and the byproduct and valuable waste for recycling etc., which are exported from the product system to outside, are all included in the surplus flow vector $\boldsymbol{\gamma}$. In the conventional process analysis based LCI, the environmental loads associated with the surplus flows are neglected by setting them outside of the LCA scope. However, in order to obtain a more correct LCA result, it is necessary to take the environmental loads into account. Namely, it is needed to add the environmental loads corresponding to the imported materials to and subtract those corresponding to the exported materials from the LCI result. In this section, how the surplus flows should be dealt with and how the matrix method joins with IOA method are discussed here. As a result, the matrix-based LCI is reasonably integrated.

Due to the large amount of surplus flows in vector $\boldsymbol{\gamma}$, it is rather difficult to take account of the environmental loads of all the surplus flows one by one. Therefore, as the appropriate and practical method, the essential surplus flows, whose absolute coefficients in vector $\boldsymbol{\gamma}$ are large, are selected firstly. After that, the production processes or the treatment processes of essential surplus flows are compiled and added into the product system. As a result, a new product system is constructed, and the environmental influence of the original essential surplus flows can be taken into account automatically through the next round of calculation by the matrix method. This method has been introduced as the method of allocation in Chapter 2. In this chapter, such a method of adding new unit processes into product system is adopted for the system boundary definition.

On the other hand, the matrix method and the IOA method for LCI can be jointed together by the final surplus flow vector $\boldsymbol{\gamma}$, and it is called hybrid method generally. Here, what to do first is to distribute the materials in vector $\boldsymbol{\gamma}$ to the corresponding industry sectors, which is shown in the matrix $\mathbf{A'}$ in Eq. (4.5). Secondly, the units of the materials are needed to change into monetary values. After that, a new surplus flow vector $\boldsymbol{\gamma}'$ is obtained. By substituting the final demanded output $\mathbf{f}$ in Eq. (4.6) with vector $\boldsymbol{\gamma}'$, the environmental loads associated with $\boldsymbol{\gamma}'$ can be calculated as:

$$\boldsymbol{\beta}' = \mathbf{B}'(\mathbf{I} - \mathbf{A}')^{-1}\boldsymbol{\gamma}' \qquad (4.7)$$

In both the vector $\boldsymbol{\gamma}$ and the vector $\boldsymbol{\gamma}'$, the imported materials are expressed by negative coefficients and the exported materials by positive coefficients. Therefore, in vector $\boldsymbol{\beta}'$, the environmental loads associated with the imported materials are expressed by negative coefficients and those associated with the exported materials are expressed by positive coefficients. Since it is needed to add the former environmental loads to the LCI result and subtract the latter ones from the LCI result, the total environmental loads associated with a product is derived by subtraction as:

$$\boldsymbol{\beta}_{total} = \boldsymbol{\beta} - \boldsymbol{\beta}' \qquad (4.8)$$

where $\boldsymbol{\beta}$ is the result obtained in Eq.(4.3).

In the end, the result of LCI is composed of the part of matrix-based LCI and that of IOA-based LCI. Since the IOA method is of low accuracy [18], it is necessary to minimize the part analyzed by IOA method so as to improve the result's accuracy of LCA. To show the accuracy of result in the hybrid method, herein, an index is defined as:

$$\mathrm{RMA} = \frac{\beta}{\beta - \beta'} \qquad (4.9)$$

where β is one environmental load obtained from matrix method, and β' is that from IOA method. This ratio can be called as the Ratio of Matrix Analysis (RMA). The RMA index means that if the rate of analysis result by the matrix method goes larger, the accuracy of final LCI result will go higher. If there are more than one environmental load in LCA, a environmental impact category index, such as global warming potential (GWP), may be used instead of β and β'.

§ 4.4 Development of the general method for composing the appropriate product system

A new general and consistent method for product system composition is proposed in this section, by which the system boundary is defined by an iterative process. The repeating calculations in the method use the hybrid method, which combines the improved matrix method and the conventional IOA method as shown above. The further refinements of product system are made by including new unit processes that are shown to be significant by IOA method, while not the sensitivity analysis which is conventionally used [11].

Definition of the appropriate product system:

LCA is generally a compromise between practicality and completeness. Herein, the appropriate product system is defined as a life cycle, in which all the essential processes and only the essential processes are included. Since all the essential processes are included in the life cycle, the completeness and result accuracy of LCA is guaranteed. Moreover, since there is no unnecessary and trivial process in the product system, the life cycle is extremely simplified.

§ 4.4.1 Proposal of the general procedure for product system composition

The general procedure for system boundary definition and product system composition is shown in Fig. 4.1.

(1). Firstly, the goal of LCA is defined.

(2). Secondly, a preliminary product system is composed. In order to avoid introducing unnecessary and trivial processes, it is recommended to compose the most preliminary product system. Since the usage and disposal of a product cannot be assessed by IOA method, in general, the preliminary product system is composed of the processes of manufacture, usage, disposal and others, which have been judged to be important. When compiling each of these processes, it should not be judged subjectively that which flow inputted into or outputted from the process is unimportant and can be neglected, since the neglected flow might link a process, whose environmental contribution is very large.

(3). The constructed product system is analyzed by the matrix method; the final cumulative environmental loads and the final surplus flows are calculated. After that, the environmental loads corresponding to the surplus flows are calculated by IOA method.

(4). Based on the IOA result of the final surplus flows, if there are some essential surplus flows, whose environmental contributions are large, their linking processes (production process or disposal process) are considered important. Therefore, the process data of them are collected (on site, or from general LCA database, or from literature, etc.), and the processes are compiled and added into the product system. Thus, a new product system is composed. Continuously, by recomposing the necessary matrices, the environmental loads are calculated again by matrix method. Since new unit processes are added into the product system, the surplus flows might be changed and the originally unimportant surplus flows might become to be essential. Therefore, it is necessary to recalculate the final cumulative surplus flows and the environmental loads associated with them.

(5). If there is no essential surplus flow, the appropriate product system is composed and the analysis can be continued to the next step in LCA. It could be judged by the defined Ratio of Matrix Analysis (RMA) index in sector 4.3 whether there are essential surplus flows or not. A required RMA index may be determined at first, and if the RMA index reaches the required level, the iterative process for product system composition may be stopped.

(6). If it is necessary, by carrying out sensitivity analysis based on the process-based LCI [20], the influence of the process data on the LCI result can be studied quantitatively, and the priority of the process data can be determined. By improving the reliabilities of the essential process data, the accuracy of the LCI result can be further improved.

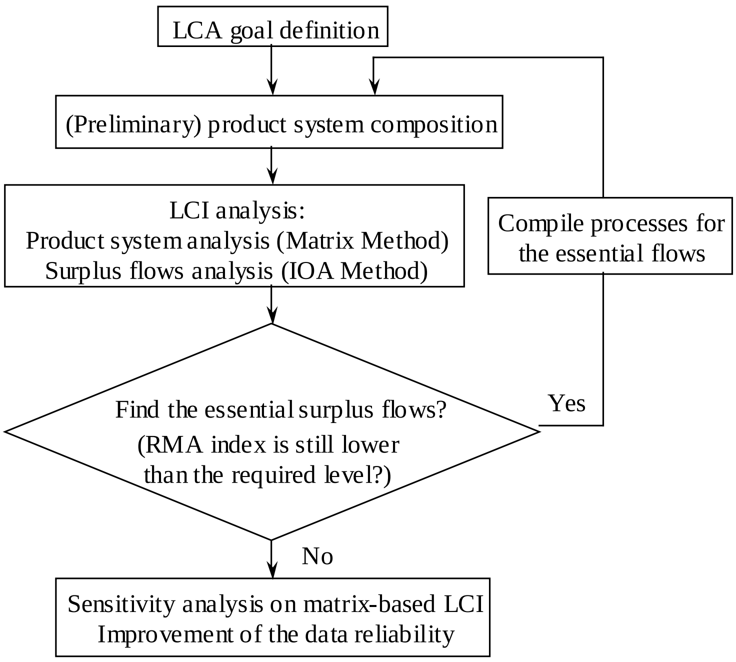

Fig. 4. 1 General procedure for product system composition in LCA

Moreover, when compiling a unit process in step (2) and (4), by carrying out the sensitivity analysis based on IOA-based LCI [19], the essential industry sections connecting with the unit process may be determined. So that, the input/output flows from/to the essential industry sections should be determined clearly at first. And the flows can even be neglected, if they are from or to the very unessential industry sections.

As shown above, since the process selection for product system composition is carried out by an iterative process, it is possible to obtain a correct enough result with minimum cost, time and labor. This method for system boundary definition is quite consistent with ISO series due to the iterative process [1-3], while there has no concrete method or discussion about the iterative process in the conventional method.

§ 4.4.2 Comparison of the present method for system boundary definition and a conventional one

The method for system boundary definition in this paper is compared with the one proposed by Hondo [5], as shown in Table 4.1. The method in this paper mainly uses the matrix method and the IOA method. The former is used to calculate the environmental loads based on the processes, and the latter is used to calculate the environmental loads corresponding to the surplus flows to select new unit processes. Moreover, the sensitivity analysis method based on IOA-based LCI is assistantly used to facilitate the composition of unit process. The sensitivity analysis based on process-based LCI is used to assist the improvement of process data at the end. While, the method by Hondo [5] only uses the sensitivity analysis method based on IOA-based LCI. The applicable objects of the method in this paper may be all kinds of products and processes, however, in the one by Hondo, the product usage etc. cannot be analyzed. Therefore, taking the method by Hondo as an assistant part, the method in this paper is more general and consistent. Although the iterative process aggravates the computation burden, it can be accomplished easily by using computer program or LCA software.

Table 4. 1 Comparison of the present method for system boundary definition and the conventional one by Hondo [5]

	Method by Hondo [5]	Method in this thesis
The used methods in system boundary definition	Sensitivity analysis based on IOA-based LCI	Iterative calculation by matrix method and IOA method (main) Sensitivity analysis based on process-based LCI and IOA-based LCI (assistant)
Applicable scope	The products shown in IOA table and the processes except for product usage, used product disposal	All products and processes
Consistence with ISO	—	Good
Frequency of analysis	One time	More than one time

§ 4.5 Examples of defining the appropriate system boundary in LCA

Herein, two examples of composing the appropriate product system in LCA are shown. One is an LCA case study of desktop computer, the other one is an LCA case study of refrigerator. Using these two examples, the proposed method for composing the appropriate product system is demonstrated. The practicability and effectiveness of the method are examined as well.

§ 4.5.1 LCA case study of desktop computer

In this LCA case study, the object is a space saver desktop computer with a 15-inch TFT monitor. The goal is to calculate the CO_2 emission associated a desktop computer in its life cycle. The process data used in this case study are taken from the LCA database of Life Cycle Assessment Society of Japan (JLCA) [21], and it is assumed that the data are collected on site. The environmental load assessment by IOA is realized using the Japanese input-output table of 1995. The use of one computer is defined as the functional unit of the product system. The required Ratio of Matrix Analysis (RMA) is set to be 95% in advance.

In the conventional LCA studies, the product system of a desktop computer would be composed of the processes of ‘PC Production’, ‘PC Usage’ and ‘Electricity Production’, etc. The productions of

HDD, FDD and CD-ROM would be naturally included in the product system, since it is generally regarded that they are the main components of a desktop computer. While, whether the production processes of HDD, FDD and CD-ROM are really the essential processes in the LCA case study of desktop computer will be checked by using the method of product system composition proposed in this chapter.

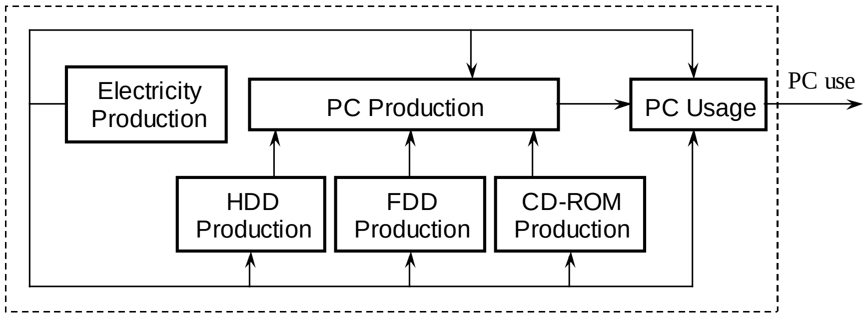

Fig. 4. 2 The conventional product system for LCA of desktop computer

In the first place, the preliminary product system of a desktop computer is just composed of three unit processes: 'PC Production', 'PC Usage' and 'Electricity Production', as shown in Fig. 4.3. The disposal process of used PC is not included in the product system, since the data cannot be obtained. Using the matrix method, the CO_2 emission from the product system in Fig. 4.3 is calculated to be 173.40 kg, furthermore, the final cumulative surplus flows are calculated as shown in Table 4.2. For instance, in order to produce a liquid crystal display (LCD), a piece of liquid crystal (LC) panel is needed to input into the product system. Using the IOA method, the CO_2 emission associated with a piece of LC panel is calculated to be 21.08 kg. On the same way, the CO_2 emission associated with all the other surplus flows are calculated, and the results are also shown in Table 4.2. The sum of the CO_2 emission associated with the surplus flows is 72.88 kg. The total CO_2 emission is 246.28 kg. Using Eq. (4.9), the Ratio of Matrix Analysis (RMA) is calculated to be 70.41%. Since it is less than the required rate, further refinement of the product system is needed.

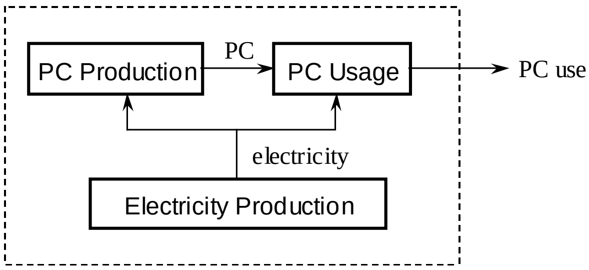

Fig. 4. 3 The 1st product system for LCA of desktop computer

Table 4. 2 Final surplus flows and the CO_2 emission

Surplus Flow	Unit	Value	CO_2 (kg)
LC panel	piece	-1	21.08
coated copy wire	kg	-2	11.83
passive components	piece	-2246	7.70
LNG	kg	-23.94	4.63
cold-rolled plate	kg	-4.95	4.61
resistor	piece	-1321	4.30
...	...	...	...
Sum of the CO_2 emission:			72.88

In order to avoid introducing unnecessary processes into the product system and carry out the LCA case study with minimum cost, just a few new processes are allowed to be added into the product system in one time's refinement. Therefore, from Table 4.2, 'LC panel' and 'coated copy wire', whose contributions are larger than 4%, are selected as significant flows. Then, the necessary process data are collected; the production processes of the essential surplus flows are compiled and added into the product system. Thus, a new product system is composed, as shown in Fig. 4.4. Using the matrix method, the CO_2 emission is recalculated to be 195.99 kg. Since new unit processes are included in the product system, the final cumulative surplus flows might be changed. Therefore, the final surplus flows and the CO_2 emission corresponding to them are recalculated as well. The Ratio of Matrix Analysis (RMA) is recalculated to be 81.89%. Since it is still less than the required rate, refinement of the product system is needed to continue.

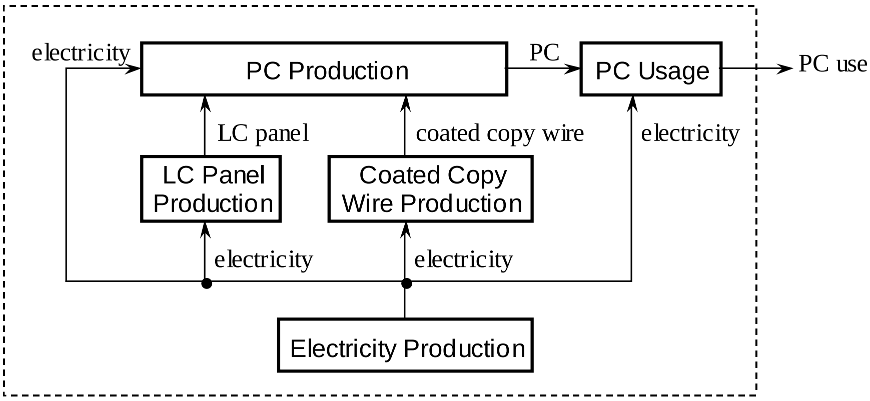

Fig. 4. 4 The 2nd product system for LCA of desktop computer

The proceeding operation shown above is repeated until the Ratio of Matrix Analysis (RMA) reaches the required value 95%. The results are shown in Table 4.3. At the 4th process selection, the RMA is over 95% and the wanted appropriate product system is composed. Consequently, the final life cycle is composed of all the 13 processes shown in Table 4.3. The established product system is shown in Fig. 4.5. The connections of the processes shown in broken line are not shown, since it will make the figure very complex.

Table 4. 3 Iterative processes for product system composition in LCA of desktop computer

	Added processes	CO_2 emission (kg)		Ratio of Matrix Analysis (RMA)
		Matrix method	IOA method	
1st	PC Production, PC Usage, Electricity Production	173.40	72.88	70.41%
2nd	LC Panel Production, Coated Copy-Wire Production	195.99	43.35	81.89%
3rd	Passive Components Production, LNG Production, Cold-rolled plate production, speaker production	227.06	27.30	89.27%
4th	HDD Production, Wiring Board Production, Coal Mining, Electrolytic Copper Production	242.73	10.19	95.97%

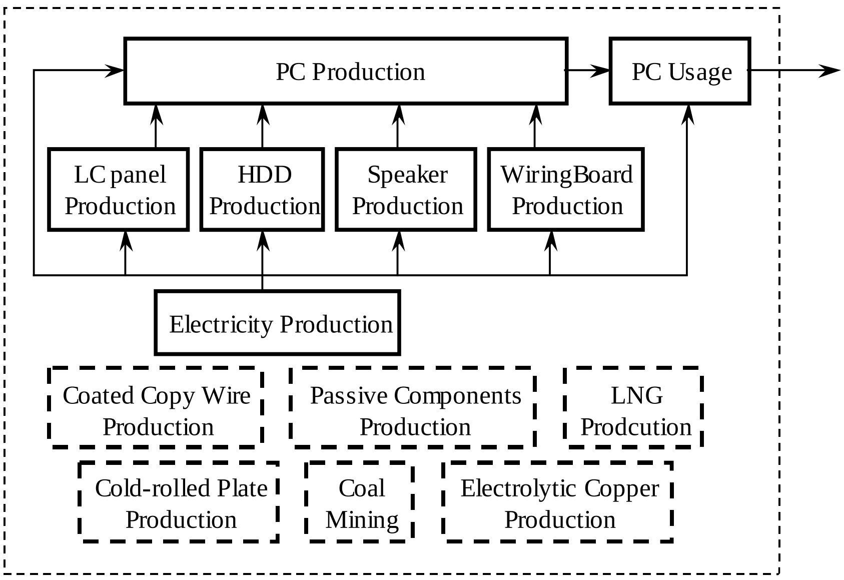

Fig. 4. 5 The final product system for LCA of desktop computer

Comparing the composed product system of a desktop computer shown in Fig. 4.5 and the conventional one shown in Fig. 4.2, it is known that the productions of FDD and CD-ROM are not included since they are not so important in this case study. Therefore, the method for system boundary definition proposed in this chapter is extremely objective and it helps to compose a very appropriate product system in a practical LCA case study.

In each refinement of the product system, some new unit processes are added to the product system. The amount of new unit processes that shall be added to the product system in each refinement relies on the practitioner's judgment. If only a few new unit processes are introduced into the product system, a refined product system may be composed. However, the efficiency of product system composition will be decreased. Herein, in the case study of desktop computer, the influence of introduced new processes' number in each refinement on the whole product system composition is studied as well. The result is shown in Fig. 4.6.

In Fig. 4.6, the red line is drawn by using the results shown in Table 4.3. After three refinements, the Ratio of Matrix Analysis (RMA) reaches the required level of 95%. In the meanwhile, if only one new process is added to the product system, more times of refinements are needed, which is shown by blue line in Fig. 4.6. Furthermore, from the blue line, it is known that after the second last refinement, the RMA has reached the required level of 95%. It shows that it's not necessary to add the last process of 'Electrolytic Copper Production' to the product system. Therefore, if less new unit processes are added to the product system in each refinement, a more refined product system could be composed, although the efficiency will be decreased.

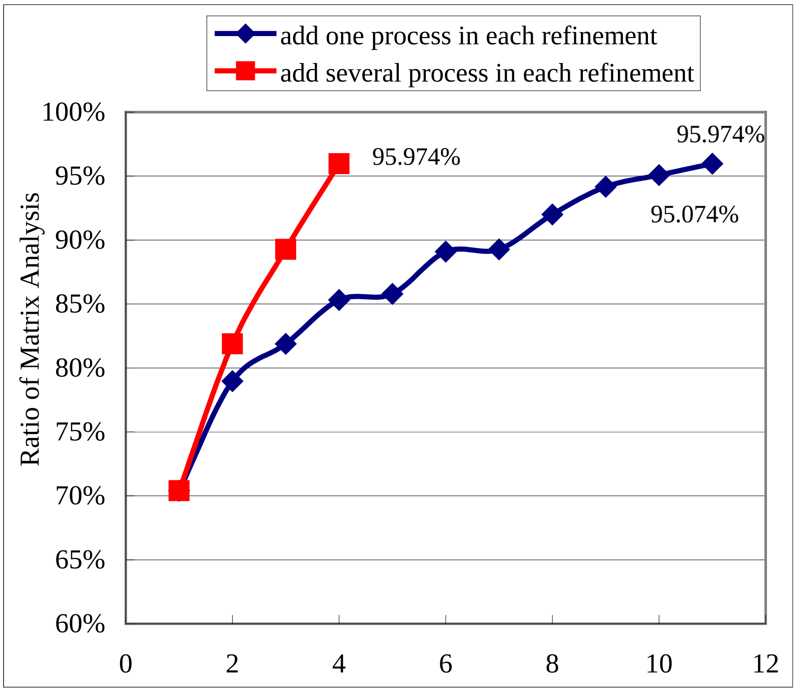

Fig. 4. 6 Refinements of the product system in the case study of desktop computer (Last point in blue: Electrolytic Copper Production)

§ 4.5.2 LCA case study of refrigerator

In this LCA case study, the object is the 400L electric refrigerator, which is sold in Japan from 1998 to 1999. The goal is to assess the environmental burden of a refrigerator in terms of CO_2 emission. The process data are taken from the JLCA Database [21]. The use of one refrigerator for one year is defined as the functional unit of the product system.

Firstly, the preliminary product system of a refrigerator is just composed of three unit processes: 'Refrigerator Production', 'Refrigerator Usage' and 'Disposal Of Used Refrigerator', as shown in Fig. 4.7. Using the matrix method, the CO_2 emission from the product system in Fig. 4.7 is calculated to be 0.5265 kg. After the calculations of the final surplus flows and the CO_2 emissions associated with them, the Ratio of Matrix Analysis (RMA) is recalculated to be 0.186%.

Secondly, electricity, whose associated CO_2 emission is large, is selected from the final surplus flow list. Then, process of electricity production is introduced into the product system and a new product system is composed, as shown in Fig. 4.8. By using matrix method, the CO_2 emission from the product system in Fig. 4.8 is calculated to be 190.4699 kg. The Ratio of Matrix Analysis (RMA) is recalculated to be 92.69%.

Thirdly, the processes of 'LNG Production' and 'Coal Mining' are added into the product system, as shown in Fig. 4.9. CO_2 emission by matrix method is 206.9212 kg and the RMA is recalculated to be 93.73%. If this RMA is considered high enough, the refinement of the product system for refrigerator can be stopped. Then, the product system of a refrigerator shown in Fig. 4.9 is the final wanted product system. If the RMA is not high enough, further refinement of the product system composition is needed.

From Fig. 4.9, we can see that the processes of ‘LNG Production’ and ‘Coal Mining’ only connect with electricity production. It means that these two processes cannot be added into the product system before introducing electricity production. It also shows that a new process in the product system might produce new essential surplus flows. Therefore, it is confirmed that an appropriate product system of a product in LCA should be composed by iterative refining processes.

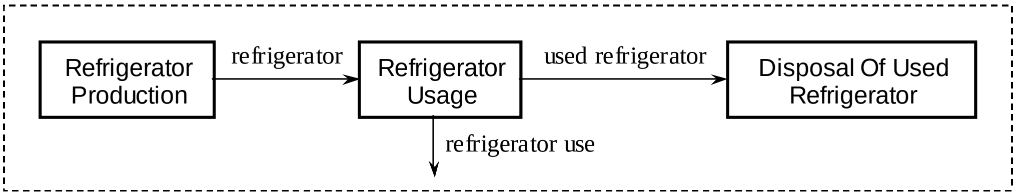

Fig. 4. 7 The 1st product system for LCA of refrigerator

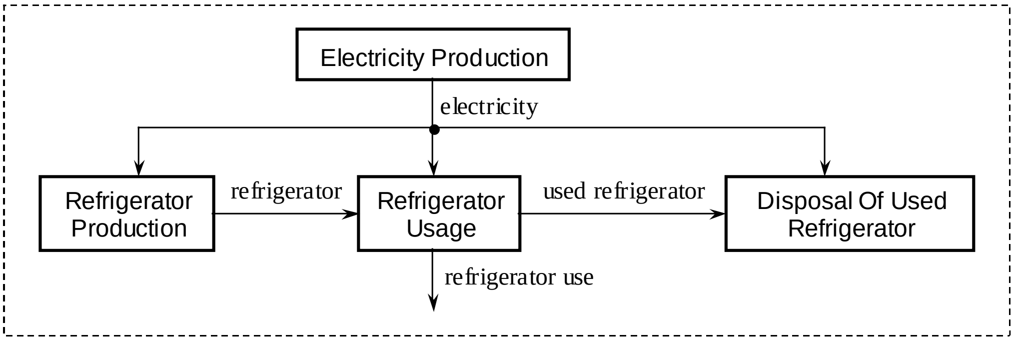

Fig. 4. 8 The 2nd product system for LCA of refrigerator

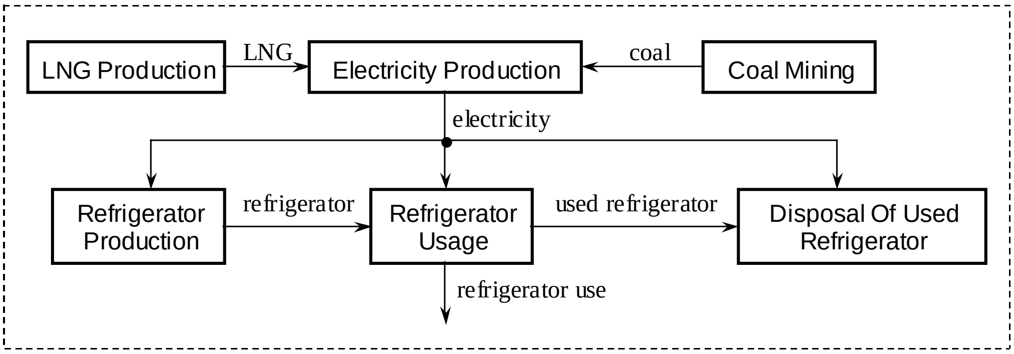

Fig. 4. 9 The 3rd product system for LCA of refrigerator

Table 4. 4 Iterative processes for product system composition in the LCA of refrigerator

	Added processes	CO_2 emission (kg)		Ratio of Matrix Analysis (RMA)
		Matrix method	IOA method	
1st	Refrigerator Production, Refrigerator Usage, Disposal Of Used Refrigerator	0.5265	282.7181	0.186%
2nd	Electricity Production	190.4699	15.0290	92.69%
3rd	LNG Production, Coal Mining	206.9212	13.8417	93.73%
…	…	…	…	…

§ 4.6 Conclusions of Chapter 4

In this paper, a general and consistent method for composing the appropriate product system is proposed, by focusing on the definition of the product system boundary, that is, which processes should be contained in the product system. It mainly uses the improved matrix method and the IOA method. The former was introduced in Chapter 2, and as the continuative research, the combination of these two methods is introduced in this chapter. As the result, the matrix-based LCI is reasonably integrated. Simultaneously, a Ratio of Matrix Analysis (RMA) of the LCI result is defined as well. By the iterative calculations in the method for product system composition, the appropriate product system of a product is composed of all the essential relevant processes, which provides the result of LCA with high accuracy. And the product system is composed of only the essential relevant unit processes, which makes the LCA case study to be simplified and of low cost. Since the definition and refinements of the product system in LCA are made by an iterative process, the method is quite consistent with ISO standards. Moreover, sensitivity analysis methods can also be adopted to facilitate the product system composition. Finally, LCA case studies of desktop computer and refrigerator are used to demonstrate the proposed method, and the practicability and effectiveness of the method are examined. In the case study of desktop computer, when the required RMA index is set to be 95%, the appropriate product system is composed through 4 times of iterative calculations.

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Chapter 5

Practical Application of The Matrix Method for LCI Analysis

In this chapter, we are to practically use the matrix-based LCA methodologies to develop LCA software and carry out LCA case studies. By using the practical LCA case studies, the applicability of the matrix-based LCA methodologies is examined.

In the first place, using the methodologies, a general purpose LCA system is established on the spreadsheet of Excel and it is named as Excel Management LCA (EMLCA). The features of EMLCA are that all the operations and calculations of LCA analysis are based the matrix algebra and all the matrices are shown on sheet, which makes it easy to manage and check the data. Moreover, the Monte Carlo simulation for uncertainty analysis is greatly easy to carry out on EMLCA.

Continuatively, an LCA case study of copier is carried out. In the case study of copier, how the matrix-based LCA methodologies are made good use of are demonstrated. The practicability and effectiveness of the methodologies and software in a practical case study of a product is examined and confirmed. The coefficient matrix composed by defining functional flow in each unit process is made sure to be a square one.

The developed matrix-based LCA methodologies can also be applied to the LCA study of services, if the operations of service are expresses to be a series of processes. As an LCA case study of service, the environmental assessment of the maintenance system of railway track is carried out. By establishing the matrix model of railway track maintenance system, the environmental loads associated with one year's railroad maintenance are calculated. By carrying out sensitivity analysis, the opportunities to obtain environmental improvements are identified and evaluated.

Key words: Case Study, Copier, LCA Software, EMLCA, Maintenance of Railway Track.

§ 5.1 Development of LCA Software

Recent years, Life Cycle Assessment (LCA) has been accepted as an effective tool to evaluate the environmental burdens associated with a product and to assess the impacts of the burdens to environment. At the same time, the methodologies of LCA have been developed to some extent. Accompanying with them, many LCA software are developed as well. Some of the software are based on the process analysis method [2, 16], and some of them adopt the Input-Output analysis method [5] or hybrid analysis method [10]. There are some software as well, which are based on the fuzzy theorem [13]. Many LCA software are developed for a particular category of products, such as constructions, ships, etc [14, 15].

In most of the software, functions of sensitivity analysis and uncertainty analysis are not realized, although the idea of developing an LCA software with sensitivity analysis has been ever stated [11]. Among the process analysis based LCA software, most of them adopt the process flow diagram method [1], but not the matrix method.

Chain Management of LCA (CMLCA) is an LCA software [2], which adopts the matrix method developed by Heijungs [7]. However, in the LCI analysis by CMLCA, all the economic flows have to be divided into two categories: goods and waste. It is obliged to carry out allocation to every multifunctional process, whether the byproduct is exported out of the product system boundary or not. As a result, the LCI analysis becomes somewhat complicated and delicate.

In order to support the practical LCA case studies in society, in our research, some LCA software are developed as well. All of them are based on the matrix method developed in chapter 2 and chapter 3. One is established on the worksheet of Microsoft table software – Excel and named as Excel Management LCA (EMLCA) [3, 4]. Another one is a dialog interface LCA software, which adopts the hybrid analysis method and is named as Matrix-based Hybrid LCA – MHLCA. In MHLCA, the using data are based on the LCA database of Life Cycle Assessment Society of Japan (JLCA) [6] and the 1995-year’s Input-Output Table of Japan.

In this section, the structures and the features of these LCA software are introduced.

§ 5.1.1 Excel Management LCA - EMLCA

Since LCA is a data intensive work, the LCA system established on worksheet is considered to be convenient to use. There have some programs developed for some concrete and individual LCA case studies. However, a general purpose LCA system, which is established on worksheet, has not been reported. In our research, using the matrix method introduced in chapter 2 and chapter 3, a general purpose LCA software, which is established on the spreadsheet of Microsoft Excel, is developed. And, it is named as Excel Management LCA – EMLCA. By using EMLCA, it is very convenient to calculate the environmental loads associated with a product system and carry out the sensitivity analysis and uncertainty analysis based on the matrix method.

§ 5.1.1.1 Structure and principle of EMLCA

The general purpose LCA software EMLCA is intended to support the LCA procedure on the spreadsheets of Excel. The sketchy structure of EMLCA is shown in Fig. 5.1, from which it is known that EMLCA is composed of six parts. The stage of interpretation, which is shown by broken line, is not included in EMLCA.

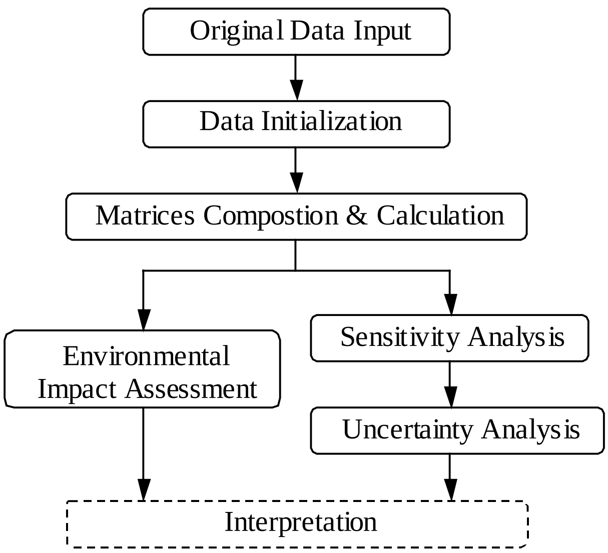


Fig. 5. 1 The sketchy structure of EMLCA

The principle and methodology in each part will be stated as follows.

(1). After the goal and scope definition, the necessary process data are collected and inputted into

EMLCA. Only one functional flow is defined and noted in each unit process, and the environmental load items to be studied are noted as well. The functional unit of the product system is also defined at this step. These works depend on practitioner's operation.

(2). As the preparation of the matrix composition, the inputted process data are automatically initialized at first.

(3). Then, the coefficient matrix **A**, the environmental load matrix **B**, the surplus flow matrix **C** and the boundary condition vector $\boldsymbol{\alpha}$ are composed. The process vector **p**, the final surplus flow vector $\boldsymbol{\gamma}$ and the final environmental load vector $\boldsymbol{\beta}$ are calculated after deriving the inverse matrix $\mathbf{A}^{-1}$. All the matrices and vectors are shown on sheet, which makes it convenient to check the data and result and grasp them as whole.

(4). The environmental impact assessment stage includes four steps: "classification", "characterization", "normalization" and "weighting". The methodology and some of the factors (e.g. characterization factors for global warming) are consulted from the JLCA Database [6].

(5). Herein, sensitivity analysis adopts the rate sensitivity and uses the formulas introduced in chapter 3. In the sensitivity analysis, the influence of each process datum to each environmental load item is studied quantitatively. All the calculated sensitivity matrices are shown in matrix forms on sheet. Moreover, the data of sensitivity analysis result can also be arranged from large to small on the worksheet, which make it easy to determine the priority of the process data.

(6). Uncertainty analysis in EMLCA can be carried out by using the approximate calculation method based on the central limit theorem or using the Monte Carlo simulation. When the process data are inputted into EMLCA, if the standard deviations of them are inputted together, the uncertainty of the final cumulative environmental loads can be automatically assessed by the approximate calculation method based on the central limit theorem.

If the required accuracy of the uncertainty analysis is high, detailed analysis by using the Monte Carlo simulation can be carried out. EMLCA is developed using matrix method and considering the connection of Microsoft Excel and Crystal Ball [9], which is a risk analysis software tool for decision-making. Therefore, Monte Carlo simulation can be carried out using Crystal Ball.

This software is developed on the spreadsheets of Microsoft Excel using VBA programming language and the addin function. The menu of the functions of EMLCA is shown in Fig. 5.2. In LCA software, it is extremely important to unify the names of input and output flows and the units. Therefore, some other functions, such as unit check, are realized in EMLCA as well. Moreover, the process data from a general LCA database, such as LCA database JLCA [6], can be automatically inputted into EMLCA by using the function of 'Import Process Data'. Rather than inputting the process data manually, it is much more convenient and time and laborsaving.

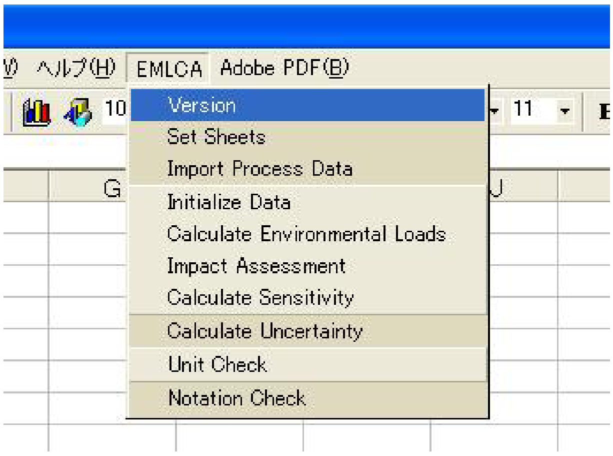
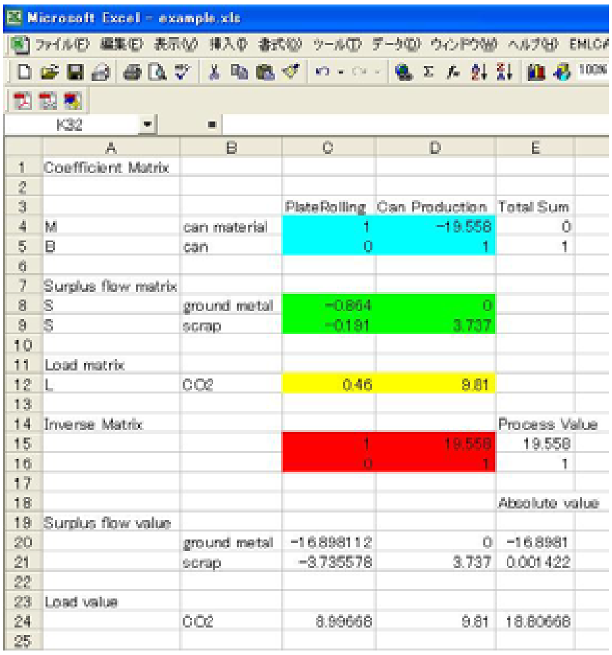


Fig. 5. 2 The menu of the functions of EMLCA

The worksheet for life cycle inventory analysis is shown in Fig. 5.3. The part in blue color is the composed coefficient matrix, consequently, it can be confirmed on this sheet that the composed coefficient matrix is definitely a square one. The parts in green, yellow and red color are the surplus flow matrix, environmental load matrix and the calculated inverse matrix of the coefficient matrix respectively. Since all the composed and calculated matrices and vectors are definitely shown on worksheet, it is quite convenient to manage and check the data and grasp the data as a whole.

With the help of EMLCA, to carry out an LCA case study becomes quite easy; so, it is very appropriate for the practitioners with a few LCA experiences and knowledge.



	A	B	C	D	E
1	Coefficient Matrix				
2					
3			PlateRolling	Can Production	Total Sum
4	M	can material	1	-19.558	0
5	B	can	0	1	1
6					
7	Surplus flow matrix				
8	S	ground metal	-0.864	0	
9	S	scrap	-0.191	3.737	
10					
11	Load matrix				
12	L	CO2	0.46	9.81	
13					
14	Inverse Matrix				Process Value
15			1	19.558	19.558
16			0	1	1
17					
18					Absolute value
19	Surplus flow value				
20		ground metal	-16.898112	0	-16.8981
21		scrap	-3.735578	3.737	0.001422
22					
23	Load value				
24		CO2	8.99668	9.81	18.80668
25					

Fig. 5. 3 Worksheet for LCI analysis by EMLCA

§ 5.1.2 Matrix-based Hybrid LCA - MHLCA

Besides the general LCA software-EMLCA, in order to support the LCI analysis by using Input-Output Analysis (IOA) method, an LCA software, which adopts the matrix-based hybrid analysis method, is developed as well. It is named as Matrix-based Hybrid LCA (MHLCA).

In the example of LCA case study of section 2.5, it has been shown that the two alternatives can be arranged in the same matrix by using the matrix method. In the same way, several product systems for LCA can also be combines in one coefficient matrix, whether they are relevant or not. Simultaneously, the surplus flow matrices and environmental load matrices of the product system can be combined to one new surplus flow matrix and one new environmental load matrix. Although there might be two or more than two same unit processes in the product systems, only one of the unit process is arranged in the newly composed matrices to serve all the product systems. Then, the environmental loads associated with one of the product system could still be calculated by using the matrix method proposed in chapter 2, just by changing the system boundary vector. In such a way, all the process data of a general LCA database could be managed in a coefficient matrix, a surplus flow matrix and an environmental load matrix. Therefore, the proposed matrix method for LCI analysis in chapter 2 provides a method or format for managing the data of an LCA database as well.

In MHLCA, all the processes in the LCA database of JLCA [6] are arranged in one huge coefficient matrix, after defining one functional flow in each of the processes. Simultaneously, a huge surplus flow matrix and a huge environmental load matrix are composed as well. As a result, just by selecting the object and defining the functional unit in MHLCA, the environmental loads associated with a product can be assessed easily based on the LCA database of JLCA.

The input-output coefficient matrix of the input-output table of 1995 and the associated environmental load density matrix can be inputted into MHLCA. So that, the environmental loads associated with a product can be assessed by using IOA method.

The combining method of the matrix method and IOA method has been stated in section 4.3. Using the combining method, herein, the LCA database of JLCA and the input-output table of 1995 can be joined together. Consequently, the environmental loads associated with a product can be assessed by using both of them. Firstly, the environmental loads associated with a product are calculated by using data of LCA database of JLCA in matrix method. Then, the environmental loads associated with the surplus flows are calculated by IOA method. Finally, these tow results are combined together.

The dialog interface of MHLCA is shown in Fig. 5.4.

With the help MHLCA, the environmental loads associated with a product could be easily calculated by using the data of LCA database of JLCA, or the input-output table of 1995, or both of them. However, the result is limited in the processes of the LCA database of JLCA and the scope of input-output table of 1995. Since many processes are lacked in the LCA database and the usage of a product etc. cannot be assessed by IOA method, it should be acknowledged that the result by MHLCA is not so correct on the meaning of life cycle assessment.

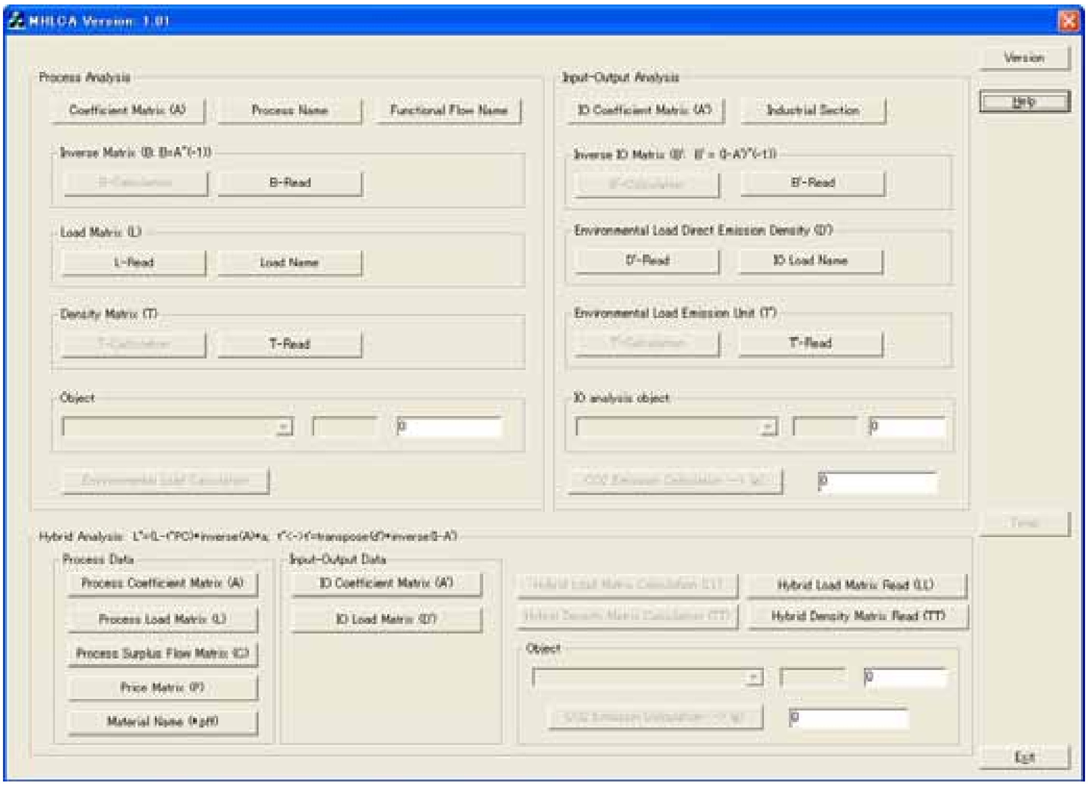


Fig. 5. 4 Dialog interface of MHLCA (Matrix-based Hybrid LCA)

§ 5.1.3 Summary of the developed LCA software

In section 5.1, two LCA software (EMLCA and MHLCA), both of which are based on the matrix method, are introduced. EMLCA is a general purpose LCA software, which is established on the worksheet of Excel. In EMLCA, there are many functions for LCI analysis, such as environmental load calculation, sensitivity analysis and uncertainty analysis. MHLCA is based on the LCA database of JLCA and the input-output table of 1995 and combines both of them together. EMLCA and MHLCA can be used to compose the appropriate life cycle of a product for LCA, as introduced in chapter 4. EMLCA is opened to the public and it can be downloaded from:

http://www.fml.t.u-tokyo.ac.jp/research/

§ 5.2 LCA Case Study of Copier

In this chapter, as a practical case study, the LCA case study of copier is carried out. In most of the conventional LCA case studies of copier [17-19], the data and results obtained from the Input-Output Analysis (IOA) is used. Consequently, the interior analysis about the product system of a copier for the environmental improvements is not sufficiently done and the LCA result might be of low accuracy. In this chapter, a more detailed LCA case study of copier is carried out. Most parts of the data are obtained from the LCA database of Life Cycle Assessment Society of Japan (JLCA) [6], while a few supplementary data are consulted from the report of Japan Business Machine Industries Association [20].

In the LCA case study of copier, the environmental loads associated with one copier in its life cycle are calculated and the consequent global warming potential (GWP) is assessed. Furthermore, environmental contributions of the processes of the product system are stuided. By carrying out sensitivity analysis, the essential items, which have significant influence on the final cumulative environmental loads, are specified and discussed as well.

By using this case study of copier, simutaneously, the practicabilities of the proposed matrix method in chapter 2 and the sensitivity and uncertainty analysis methods in chapter 3 are examined. This case study is carred out by using the general purpose LCA software-EMLCA, so that, the practicability of the LCA software is examined herein.

§ 5.2.1 Construction of the product system of copier for LCA

Object and Goal definition:

The object of the LCA case study is set to be the digital monochrome standard copier sold in Japanese domestic markets in 1999 and 2000.

The goal of this study is to have an environmental assessment to the digital monochrome standard copier taking the whole life cycle into account, in which the final cumulative environmental loads associated with a copier in its whole life cycle are to be calculated. And, if possible, it is expected to have an assessment of the consequent global warming potential as well. Therefore, the use of one copier is defined as the functional unit of the product system of a copier.

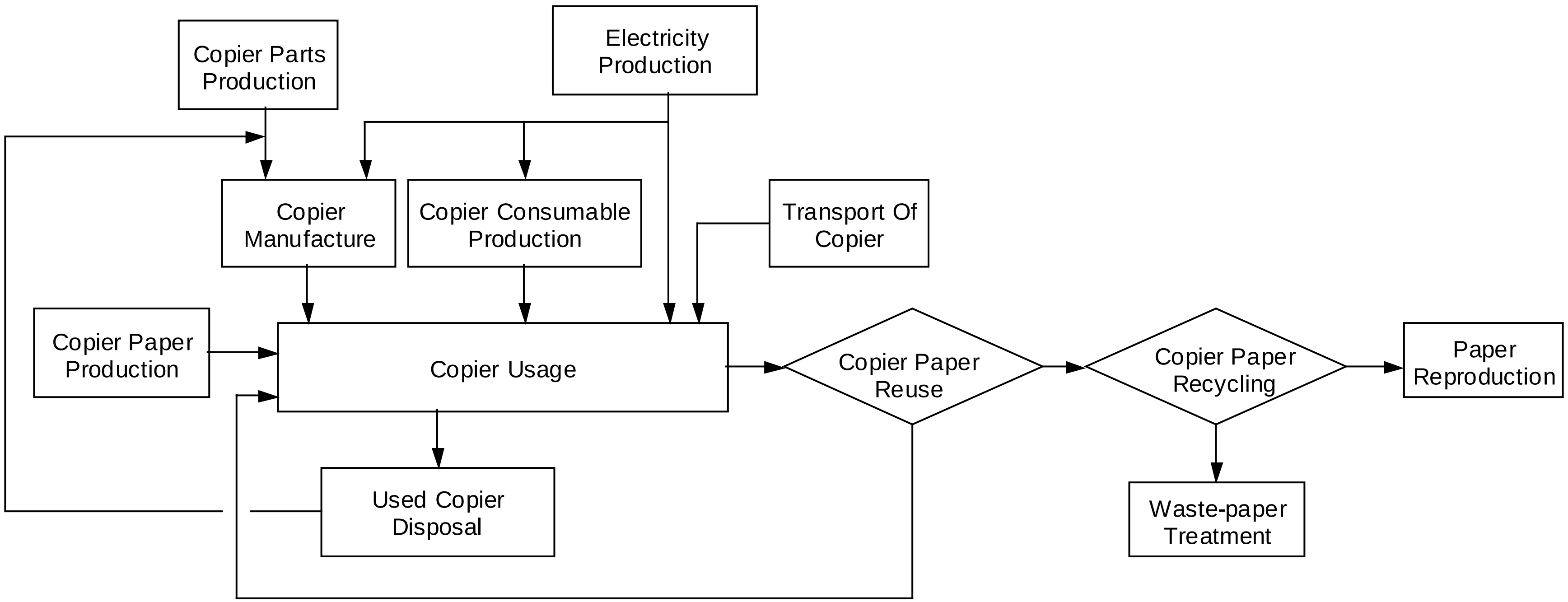


Fig. 5. 5 Life cycle structure of the digital monochrome standard copier for LCA

Product system construction:

After the object and goal definition, the product system of a copier for LCA is constructed. The structure of the product system is shown in Fig. 5.5. In the figure, the stream of copier (manufacture, usage and disposal of a copier) is shown vertically and the stream of copier paper is shown horizontally.

The copier is produced through the processes of 'Copier Parts Production' and 'Copier Manufacture'. And, the used copier is transported to dispose. The disposal of used copier is composed of many detailed processes, such as collection of used copier, parts renewing, material recycling and waste disposal. In the product system shown in Fig. 5.5, they are all summarized in one process of 'Used Copier Disposal'. From the process of 'Used Copier Disposal', a few copier parts are transported into the process of 'Copier Manufacture' to reuse.

The environmental loads associated with the maintenance of copier are assumed to be included in the process of 'Copier Consumable Production'.

About the transport of copier from factory to store and used copier from work place to disposal center etc., the relevant consumed energies and emitted environmental loads are all summarized in the process of 'Transport Of Copier'. Then, the service outputted from the transport process is inputted into the process of 'Copier Usage'.

Copier paper usage in the product system of copier

In the using stage of a copier, it is assumed that 30 sheets of papers are used in an hour and the copier works 20 days in a month. Thus, in the total 5 years of the lifetime of a copier, 288000 sheets of copier papers will be used. All the copier paper being used is assumed to be the A4 size paper of PPC (Plain Paper Copier).

Concerning the used copier papers, as shown in Fig. 5.5, some of them are reused as copier papers and the others go to the process of 'Copier Paper Recycling'. In the recycling process, some of the papers are selected to serve for the raw material for producing another paper product, such as newspaper or toilet paper. The left papers are disposed as waste papers and they are generally incinerated. The reuse rate is set to be 20% and the recycling rate is set to be 27%.

Data collection:

The compiled unit processes for the product system of copier are shown in Table 5.1. The defined functional flows in the processes and the data sources are shown in the table as well.

Table 5. 1 Data collection and functional flow definition in the LCA case study of copier

	Process	Functional Flow	Unit	Data Source
1	Copier Usage	copier use	year･copy	--
2	Copier Manufacture	copier		JLCA Database
3	Copier Parts Production	copier parts	set	JBMA Report
4	Copier Consumable Production	copier consumable	set	JLCA Database
5	Transport Of Copier	transport	one copier	JBMA Report
6	Used Copier Disposal	used copier		JBMA Report
7	Electricity Production	electricity	kWh	JLCA Database
8	Copy Paper Production	copier paper	piece	JBMA Report
9	Copy Paper Reuse	used copier paper	piece	JBMA Report
10	Copy Paper Recycling	recycling paper	piece	JBMA Report
11	Paper Reproduction	reproduced paper	piece	JBMA Report
12	Waste-paper Treatment	waste paper	g	JBMA Report
13	LNG Production	LNG	MJ	JLCA Database
14	Coal Mining	coal	kg	JLCA Database
15	LPG Production	LPG	kg	JLCA Database
16	Paper Production	paper	kg	JLCA Database
17	Aluminum Production	aluminum	kg	JLCA Database (aluminum new ground metal)
18	ABS Resin Pellet Production	ABS resin pellet	kg	JLCA Database
19	Polyethylene Production	polyethylene	kg	JLCA Database (low density polyethylene)
20	Naphtha Production	naphtha	l	JLCA Database
21	Polyester Resin Production	polyester resin	kg	JLCA Database
22	Phthalic Acid Production	phthalic acid	kg	JLCA Database
23	Glycerin Production	glycerin	kg	JLCA Database
24	City Gas Production	city gas	m3	JLCA Database
25	Kerosene Production	kerosene	l	JLCA Database
26	Light Oil Production	light oil	l	JLCA Database
27	Heavy Oil Production	heavy oil	l	JLCA Database (A heavy oil)
28	Crude Oil Production	crude oil	l	JLCA Database

§ 5.2.2 Calculation of the environmental loads associated with a copier

The collected process data are inputted into the LCA software-EMLCA. The functional flows shown in Table 5.1 and the environmental loads to be studied are noted and attached marks. Then, the coefficient matrix **A**, the boundary condition vector **α**, the surplus flow matrix **C** and the environmental load matrix **B** are all composed automatically. The matrix **A**, **B** and the vector **α** are shown in the tables of Appendix 5.1 and Appendix 5.2, while the surplus matrix **C** is not shown, since there are too many trivial material items in it. From Appendix 5.1, it is confirmed that the composed coefficient matrix **A** by defining functional flow in each unit process is definitely a square one. Consequently, it is possible to obtain the inverse matrix **A′**, which is as shown in Appendix 5.3. By using the function of EMLCA, the process vector **p** and the final environmental load vector **β** are calculated and they are shown in Appendix 5.4 and Appendix 5.5. For instance, in this LCA case study of copier, the CO_2 emission associated with one copier is 1477500.5 g.

These LCI analysis result is compared with the conventional ones and the comparison is shown in Fig. 5.6.

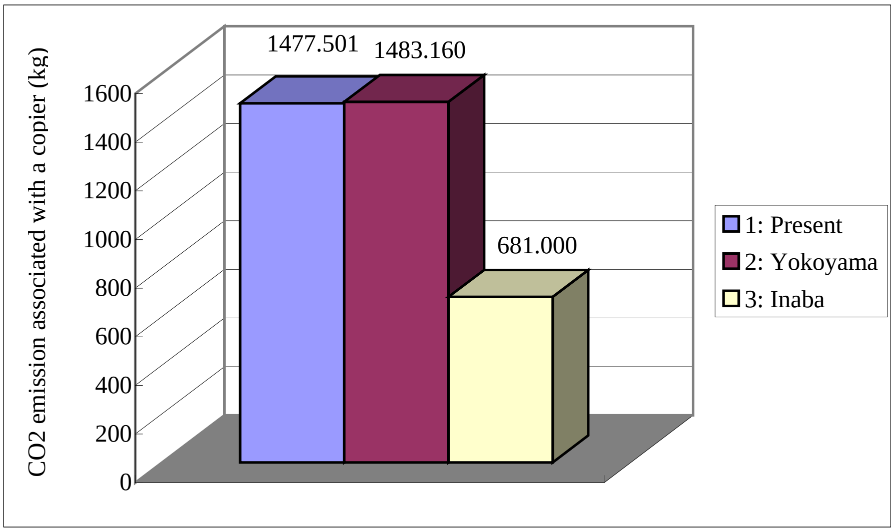


Fig. 5. 6 Comparison of the LCA results of a copier (Results by Yokoyama [21] and Inaba [17])

From Fig. 5.6, we can see that the CO_2 emission in the present study is quite consistent with the result by Yokoyama, which shows the LCI analysis result of this case study of copier is correct. However, the third result is much less than the former two, since the consumed copier paper is not included in the product system and the associated CO_2 emission is not taken into account. Therefore, it is known that the consumed copier paper will contribute a lot of CO_2 emission to the LCA of a copier.

§ 5.2.3 Environmental impact assessment in terms of Global Warming Potential

After the calculation of the environmental loads in the product system of copier, continuatively, environmental impact assessment in terms of global warming potential (GWP) is carried out as well. What should be paid attention here is that not all the environmental load data are collected in the processes of JLCA database at present, while the CO_2 emission data are compiled in all the processes. Therefore, the results of GWP are only for consultation.

Then, as the first step of the assessment of GWP, from the calculated final environmental load vector **β**, the necessary load items are selected for GWP assessment, which is generally called as classification in LCA methodology. After that, the characteristic factors of GWP for the load items are investigated. Herein, the characteristic factors of GWP corresponding to 20 years and 100 years are consulted from the JLCA database [6]. The selected environmental load items for GWP and the characteristic factors of GWP are all shown in Table 5.2.

Table 5. 2 Classification of the environmental loads for GWP

	Emission (kg)	GWP Factor (20 years	GWP Factor (100 years
CO2	1.478E+03	1	1
CH4	3.148E-01	62	23
N2O	2.421E-03	275	296
CO	1.886E-04	2.8	1
SF6	5.059E-05	15100	22200
HFC	1.495E-05	3291	2244

By adding up the multiplied values of the environmental load and the characteristic factor, the global warming potential of a copier in its life cycle is calculated. The result is shown in Fig. 5.7.

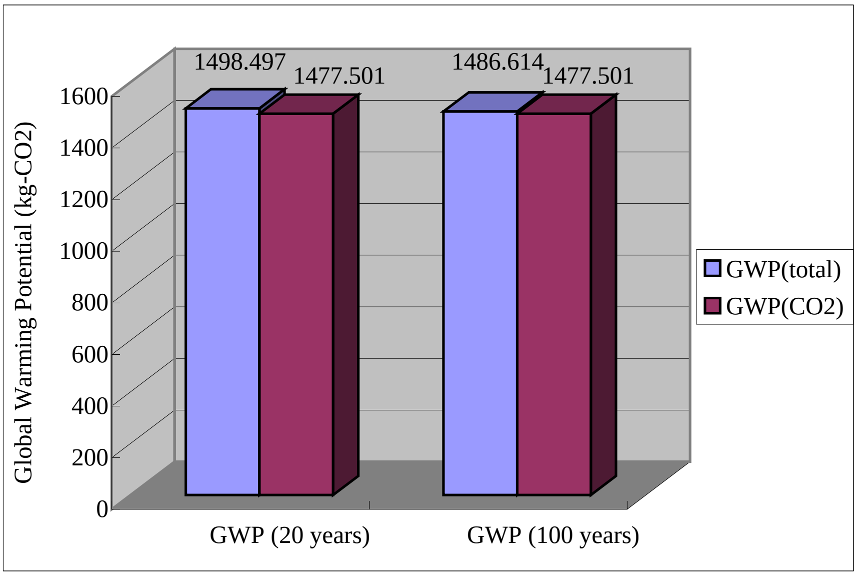


Fig. 5. 7 Global Warming Potential associated with one copier

From Fig. 5.7, it can be seen that the GWP(20 years) associated with a copier is 1498.479 kg-CO_2, and the GWP(100 years) is 1486.614 kg-CO_2. The two GWP values are almost equal to each other. From the figure it is also known that the GWPs due to CO_2 emission are both 1477.501 kg-CO_2. So that, it can be known that almost all the global warming impact comes from the CO_2 emission. If the CO_2 emission associated with a copier is efficiently decreased, the GWP will be reduced as well.

§ 5.2.4 Discussion about the environmental improvements of a copier

In section 5.2.3, it has been stated that if the CO_2 emission associated with a copier is efficiently decreased, the GWP will be reduced as well. Therefore, the study of this section is focused on the CO_2 emission and how the CO_2 emission could be effectively reduced is discussed.

§ 5.2.4.1 Contribution of each unit process to CO_2 emission

The contributions of the processes to CO_2 emission are studied and the result is shown in Fig. 5.8, from which the key processes can be identified.

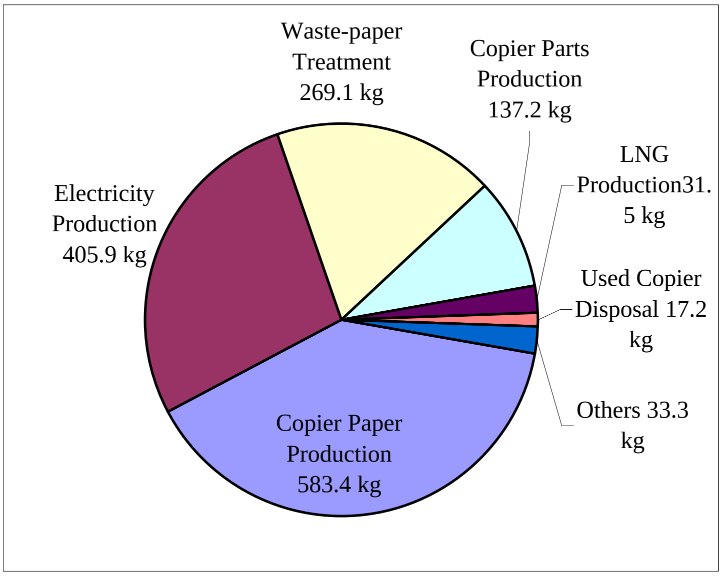


Fig. 5. 8 The ratio of CO2 emission in life cycle of a copier

From Fig. 5.8, we can see that the CO_2 emission in the process of 'Copier Paper Production' accounts for about 40% of the whole and it is the most important process in the product system of a copier. The CO_2 emission in the process of 'Waste-paper Treatment' accounts for a big ratio as well. These two paper concerned processes result in almost 60% of the total CO_2 emission. Therefore, when we endeavor to decrease the CO_2 emission, it will be very effective to do some improvement about the used copier paper, such as improving the reuse rate or the recycling rate of copier paper.

Furthermore, from Fig. 5.8, it is known that the CO_2 emission in the process of 'Electricity Production' is the second most. Therefore, Designing electricity saving copiers or saving the used electricity in the usage of copier will be quite beneficial in reducing CO_2 emission.

§ 5.2.4.2 Sensitivity analysis of the product system of copier

By using the function of sensitivity analysis in EMLCA, the sensitivity matrices to all the environmental load items can be easily calculated. As an example, the calculated sensitivity matrix to the CO_2 emission is shown in Appendix 5.6, from which it is confirmed that the sensitivity analysis is definitely carried out in matrix form. In Appendix 5.6, the last row shows the sensitivity of CO_2 emission in each unit process to the final cumulative CO_2 emission. Therefore, it is made sure that the sensitivity analysis of the environmental load matrix in LCI analysis is realized. By using the sensitivity analysis result, it is easy to specify the essential process data, which have large influences on the final LCI result. The sensitivity values in the sensitivity matrix to CO_2 emission are prioritized from large to small in Table 5.3, from which it is easier to determine the priority of the process data.

Among the result of sensitivity analysis, not all the data of sensitivity can support the environmental improvement. It means that not each datum of sensitivity analysis result has a practical meaning. Therefore, judgments of the LCA practitioner are needed in the interpretation of sensitivity analysis result.

Table 5. 3 Sensitivity analysis result in the LCA of a copier

	PROCESS	FLOW	SENSITIVITY
1	Copier Usage	copier use	-1.0000
2	Copier Usage	copier paper	0.4935
3	Copy Paper Production	copier paper	-0.3948
4	Copy Paper Production	CO2	0.3948
5	Electricity Production	electricity	-0.3033
6	Copier Usage	electricity	0.2754
7	Electricity Production	CO2	0.2747
8	Copy Paper Reuse	recycling paper	0.1827
9	Copy Paper Recycling	recycling paper	-0.1827
10	Waste-paper Treatment	waste paper	-0.1821
11	Waste-paper Treatment	CO2	0.1821
12	Copy Paper Recycling	waste paper	0.1821
13	Copier Manufacture	copier	-0.1048
14	Copier Usage	copier	0.1048
15	Copy Paper Reuse	copier paper	-0.0987
16	Copier Manufacture	copier parts	0.0955
17	Copier Parts Production	copier parts	-0.0929
18	Copier Parts Production	CO2	0.0929
19	Copier Usage	used copier paper	0.0840
20	Copy Paper Reuse	used copier paper	-0.0840
…	…	…	…
82	Coal Mining	heavy oil	0.0001

[Datum 1]: In the process of ‘Copier Usage’, one copier is inputted and the service of 5 years’ copier use is outputted. The 1st datum in Table 5.3 means when keeping all the other data in the product system as constant, increasing the outputted flow of ‘copier use’ in the process of ‘Copier Usage’ by 1%, the final cumulative CO_2 emission will be decreased by 1%. Therefore, it will be quite effective in decreasing CO_2 emission to prolong the lifetime of a copier in the stage of production or to use the copier with much care to extend the usable time.

[Datum 2]: When keeping all the other data to be constant, if the consumed copier paper in the process of ‘Copier Usage’ is increased by 1%, the final cumulative CO_2 emission will be increased by 0.49355%. Therefore, it is advocated to save the used copier paper so as to reduce the CO_2 emission. If it is possible, using the both sides of copier paper will be very environmentally beneficial.

[Datum 3]: When keeping all the other data to be constant, if the produced copier paper in the process of 'Copier Paper Production' is increased by 1%, the final cumulative CO_2 emission will be decreased by 0.39484%. So, improving the producing efficiency of copier paper production is also important in reducing CO_2 emission.

The other data of sensitivity can be interpreted in the same way.

In addition, from the sensitivity analysis result, it is known that when the precision of sensitivity is set to be 10^{-4}, among hundreds of process data, only 82 data have influences on CO_2 emission. Therefore, when we are to study the uncertainty of the final CO_2 emission, which are propagating from the uncertainties of process data, only these 82 data are needed to investigate.

§ 5.2.4.3 The environmental influence of the reuse rate and the recycling rate of copier paper

It has mentioned that improving the reuse rate of the recycling rate of copier paper will be quite effective in decreasing the CO_2 emission. Herein, the influence of the reuse rate and the recycling rate of copier paper is studied and discussed in detail.

By changing the parameter of the reuse rate of copier paper, the CO_2 emissions corresponding to different reuse rates are calculated and the result is shown in Fig. 5.9. Here, the recycling rate of copier paper is set to be the present value of 27%.

From Fig. 5.9, we can see that the CO_2 emission decreases when the reuse rate of copier paper is increased. At present, the reuse rate is 20%. If the reuse rate is increased to 30%, the CO_2 emission will be decreased to 1370.832 kg, it is reduced by about 7%. So, it is confirmed that the reuse rate of copier paper is a sensitive item to CO_2 emission.

In the same way, the environmental influence of recycling rate of copier paper is shown in Fig. 5.10. The reuse rate is set to be the present value of 20%. The present recycling rate is 27%. If the recycling rate is increased to 37%, the CO_2 emission will be decreased to 1440.959 kg. It is reduced by about 2.5%.

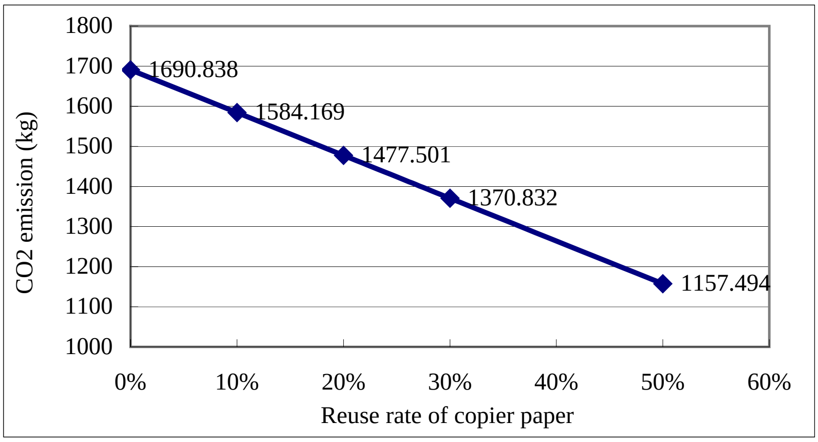


Fig. 5. 9 The influence of the reuse rate of copier paper to CO2 emission

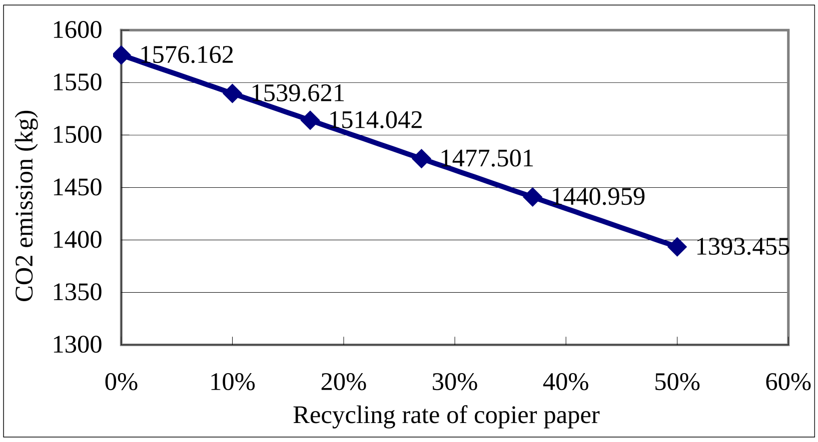


Fig. 5. 10 The influence of the recycling rate of copier paper to CO2 emission

§ 5.2.5 Uncertainty analysis in the LCA case study of copier

In the JLCA database [6], some data about the uncertainty of the process data of copier production are provided as well. In this section, the uncertainty of GWP propagated from those uncertain data are studied. The standard deviations provided by JLCA database are inputted into EMLCA and the uncertainty of GWP is calculated by using the approximate calculation method based on the central limit theorem. The result is shown in Table 5.4. For instance, the mean of GWP(20years) is 1498.497 kg-CO_2 and the standard deviation is 152.477 kg-CO_2.

Table 5. 4 Uncertainty analysis result by using the approximate calculation method

GWP (20 years) (Unit: kg-CO2)		GWP (100 years) (Unit: kg-CO2)	
Mean	Standard deviation	Mean	Standard deviation
1498.497	152.477	1486.614	152.382

Furthermore, it is assumed that all the uncertain data are normal distribution and the uncertainty of the final expected GWP is analyzed by using Monte Carlo simulation method. The trial number of Monte Carlo simulation is set to be 10000. Then, the probability distribution charts of GWP(20years) and GWP(100years) are shown in Fig. 5.11 and Fig. 5.12. Some statistic values of the result are shown in Table 5.5.

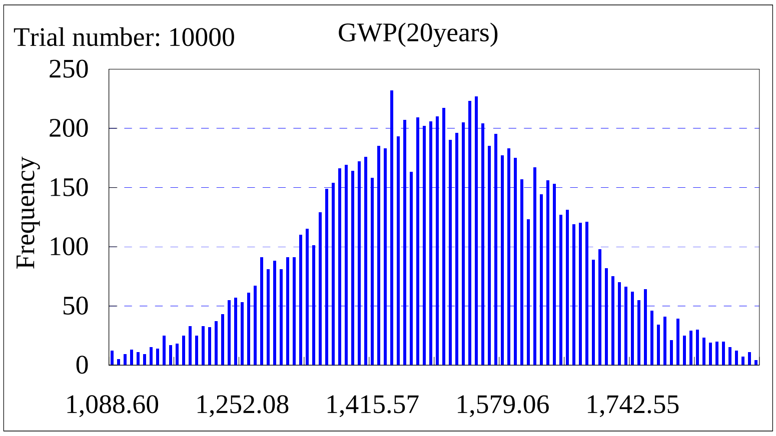


Fig. 5. 11 Probability distribution of GWP(20years) in the LCA case study of copier

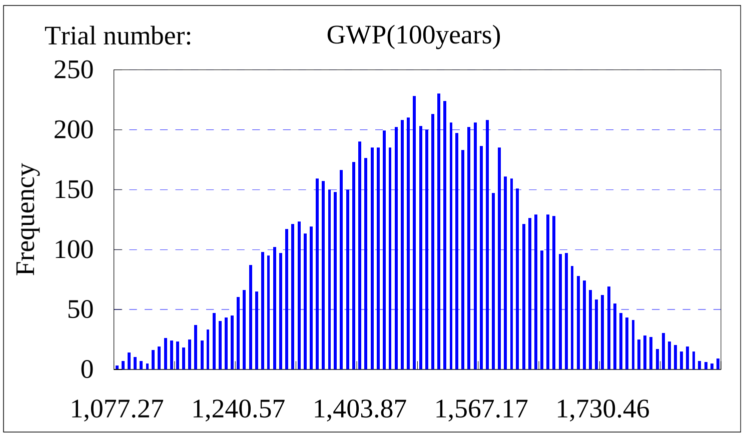


Fig. 5. 12 Probability distribution of GWP(100years) in the LCA case study of copier

Table 5. 5 Statistic of the GWP(20years) and GWP(100years)

Statistic	GWP(20years)	GWP(100years)
Trial number	10000.000	10000.000
Mean	1501.053	1485.843
Standard deviation	156.825	154.652
Variance	24594.113	23917.363
Coefficient of variance	0.104	0.104
Lower range bound	875.413	821.193
Upperrange bound	2213.540	2104.739
Range	1338.126	1283.546

From Fig. 5.11 and Fig. 5.12, it is known that the GWP(20years) and GWP(100years) can both be approximately regarded as normal distribution. From Table 5.5, we can see that the mean and the standard deviation of GWP(20years) are 1501.053 kg-CO_2 and 156.825 kg-CO_2 respectively, and those of GWP(100years) are 1485.843 kg-CO_2 and 154.652 kg-CO_2 respectively. These results are very close to the ones analyzed by the approximate calculation method, which are shown in Table 5.4. Therefore, it is confirmed again that the approximate calculation method of uncertainty, which is based on the central limit theorem, can give a reliable result of the uncertainty analysis in a practical LCA case study.

§ 5.2.6 Conclusions of the LCA case study of copier

In section 5.2, a practical LCA case study of copier is carried out. In the case study, it is confirmed again that the coefficient matrix composed by defining functional flow in each unit process is necessarily a square matrix. By carrying out the rate sensitivity analysis, the influence of each process datum on the final CO_2 emission is assessed quantitatively and the essential data are specified. In the sensitivity analysis, it is known that the influences of the coefficient matrix and the environmental load matrix are both taken into account.

Furthermore, the uncertainty of the final LCA result is studied by using the approximate calculation method based on the central limit theorem and the Monte Carlo simulation method respectively. By comparing the two results of uncertainty analysis, it is confirmed that the approximate calculation method can give us a reliable result of uncertainty analysis in practical LCA case studies.

5.3 LCA Case Study of The Maintenance Of Railway Track

In section 5.2, we practically used the matrix-based LCA methodologies to the LCA case study of a product (copier). Furthermore, it is expected to practically use the methodologies to an LCA case study of service as well. In this section, an LCA case study of the maintenance of railway track is carried out. In the case study, how the matrix method is applied to an LCA case study of service is shown.

Recent years, some LCA studies about the railway system have been carried out [22-24]. The Railway Technical Research Institute Of Japan has executed the LCA study on six components of railway system respectively: constructions, track, overhead catenaries, traffic signals, stations and trains [22, 23]. In the research, the CO_2 emissions associated with different component systems are calculated. However, most of those studies are based on the cumulative method of multiplying per unit environmental load value by the material quantity, while not the real process analysis. Further analysis of the railway system, such as sensitivity analysis etc., has not been carried out yet. Therefore, it is rather difficult to provide enough information so as to achieve the environmental improvements of the railway system.

In this section, the environmental assessment of the maintenance track is carried out. Firstly, all the components of the maintenance of track, which were expressed by per unit environmental load values in the conventional studies, are compiled to process expression. After that, the maintenance system of track for LCA is constructed. Using the general-purpose LCA system – EMLCA, the environmental loads associated with one year’s maintenance of railway track are calculated. By carrying out sensitivity analysis, the essential items in the maintenance system, which have huge influences on the final cumulative environmental loads, are specified and discussed. Finally, the analysis results are used to support and assist the decision making for the environmental improvements in the railway system.

This LCA case study of track maintenance system is a cooperative research of East Japan Railway Company and The University of Tokyo.

§ 5.3.1 Construction of the maintenance system of railway track

§ 5.3.1.1 Object and goal definition

Here, the object of the LCA is the railway track maintenance of different railway line in Tokyo. The track to study is composed of 3 parts: rail, sleeper and ballast, as shown in Fig. 5.13. The structure of the track for LCA is shown in Fig. 5.14.

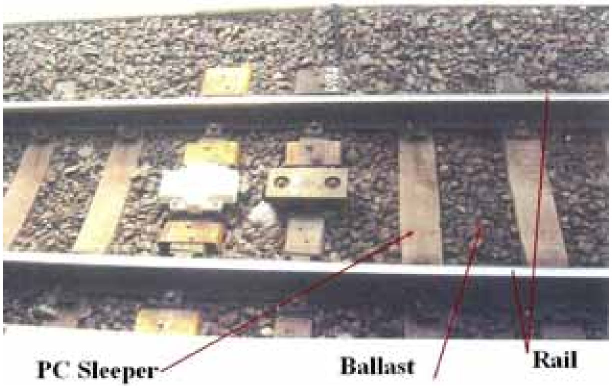


Fig. 5. 13 Components of the railway track for LCA

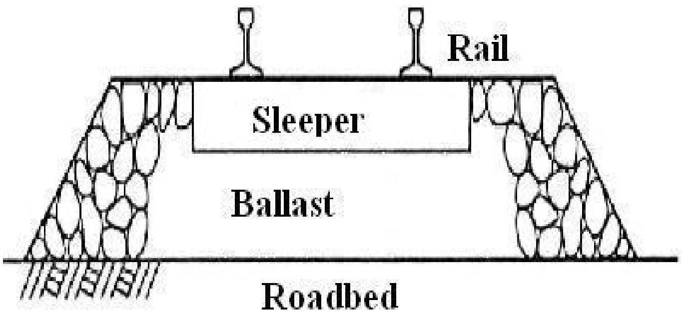


Fig. 5. 14 Structure of the railway track for LCA

The goal of the LCA case study is to carry out a reliable environmental assessment of the present track maintenance. Concretely, we are to calculate the environmental loads associated with the maintenance of railway track per year. By carrying out sensitivity analysis, the essential items in the maintenance system, which have huge influences on the final cumulative environmental loads, are specified and discussed so as to decrease the environmental load. At the present stage, as the environmental load, only CO_2 emission is taken into account while other environmental loads are expected to be taken account of in future research.

§ 5.3.1.2 Classification of the railway lines

In order to classify the structures and equipments of the railway lines in Japan, according to the volumes of transportation, importance and the viewpoint of economics, the railway track lines are divided into four classes. The LCI analysis is carried out according to these defined classes of railways. The classification of the railway lines and the selected railway line for each class are shown in Table 5.6.

	1st class	2nd class	3rd class	4th class
Volume range of transportation (million ton/year)	20~	10~20	5~10	~5
Selected railway line for LCA	Yamate Line Chuo Line	Tohoku Line	Uetsu Line	Suigun Line

Table 5. 6 Classification of the railway lines

§ 5.3.1.3 Construction of the maintenance system of track

As the previous preparing stage of the LCA analysis, the maintenance system of railway track is constructed. After that, the nenessary data for the maintenance systems are collected. On the whole, the maintenance system of railway track is composed of four maintenance operations as shown in Fig. 5.15. The detailed structure of each maintenance operation is established respectively.

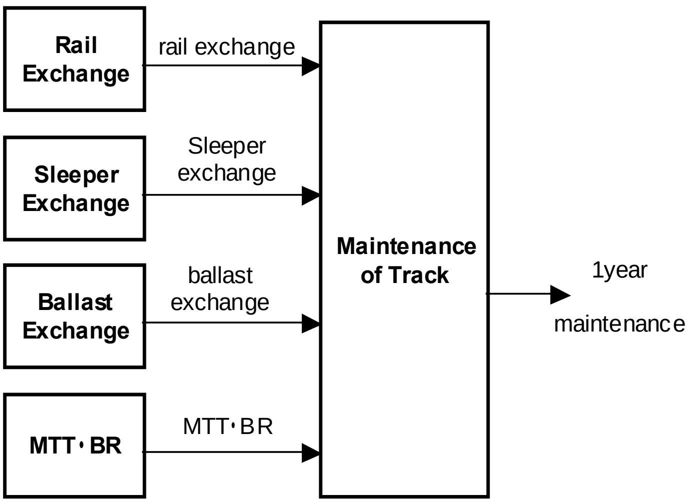


Fig. 5. 15 The sketch construction of the maintenance system of present track

(1). Rail Exchange

In the operation of rail exchange, new rails are transported to the track to exchange the old ones, which have been damaged to some extent and cannot be used any longer. In most cases, not only one kind of rails is laid on the roadbed of the railway lines. Here, in the tracks to study, 60K and 50N rails are two main used rails. The weight of the former rail is about 60 kg per meter and that of the later one is about 50 kg per meter. In the track maintenance system for LCA, these two rails are used to exchange the old ones. Therefore, the production processes of the rails are introduced into the track maintenance system, as shown in Fig. 5.16. New 60K rail and new 50N rail are inputted into the process of 'Rail Exchange', and the used 60K rail and used 50N rail are outputted from the process of 'Rail Exchange'.

[Rail Reuse]:

In present situations, all the exchanged rails from track are treated as waste rails and sold out. However, through some special treatments such as grinding etc., some of the exchanged rails could be laid on track again and reused. Therefore, processes of 'Rail(60K) Reuse' and 'Rail(50N) Reuse' are composed and introduced into the track maintenance system for LCA. The used rails from the rail exchange process are inputted into the rail reuse processes; then, some of them are outputted as rails, which are usable, and the other ones are outputted as waste rails. At present, the values of the outputted rails from the rail reuse processes are set to be zero. While, by changing the parameters, the influences of rail reuse to the final LCA result could be learned.

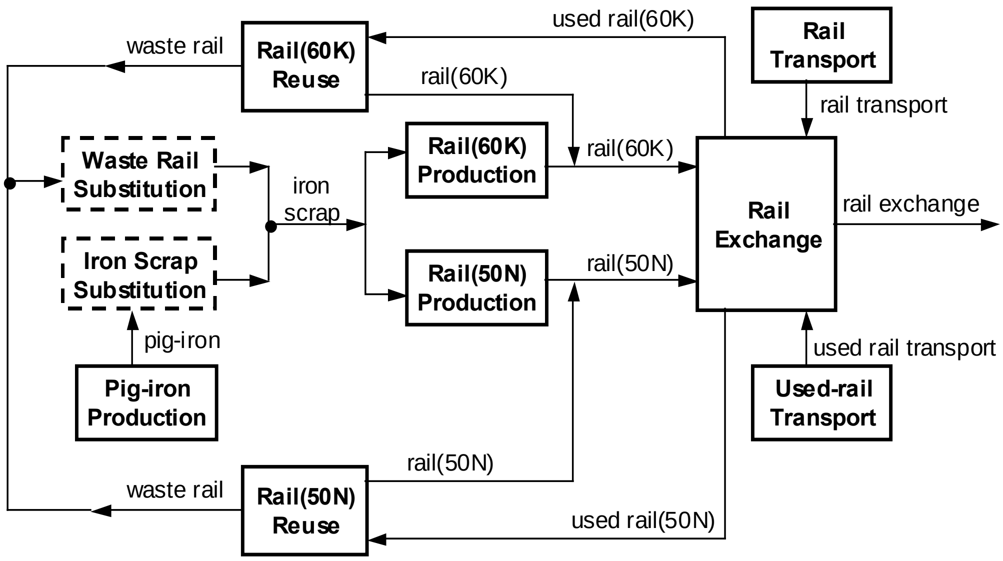


Fig. 5. 16 Rail exchange system in the track maintenance system for LCA

[Rail Recycling]:

The waste rail is a highly recyclable material, and in practice, it is highly recycled in our society. As the disposal of the waste rails after being sold, some of them are used as structure material for building, and some of them are melted and used as raw material of iron for producing other iron products. In a word, the exported waste rail from the track maintenance system services functions in other product systems. Therefore, it is unavoidable to take the environmental loads corresponding to the waste rails into account. Based on the track maintenance system, it is needed to allocate the total cumulative environmental loads to the track maintenance and the outputted waste rails. Herein, in order to simplify the allocation problem, it is assumed that all the waste rails are melted and used as raw material of iron.

On the other hand, in the processes of rail production, iron scraps are inputted into the processes as raw materials to produce rails. Since iron scraps are valuable materials, it is necessary to take the environmental loads corresponding to the iron scraps into account as well. According to ISO standards 14041, it is recommended that the allocation in LCA should be avoided if it is possible. Therefore, in this LCA study about track maintenance, it is assumed that the waste rails are recycled as iron scraps inside the track maintenance system. That manes the necessary iron scraps in the process of rail production are substituted by waste rails. Then, a recycling process is introduced into the track maintenance system, which is named as ‘Waste Rail Substitution’, as shown in Fig. 5.16. The recycling rate is set as 100%, which means that if 1 kg waste rail is inputted into the substitution process, 1 kg iron scrap will be outputted from the process. Of course, by changing the value of outputted iron scrap, the environmental influence of the recycling rate can be studied.

Further more, it is not necessary that all the outputted waste rails could be completely used as iron scraps for rail production. The amount of outputted waste rails from the rail reuse processes will not necessarily be equal to that of the required iron scraps in the rail production processes. The outputted waste rails will be insufficient to supply enough iron scraps to produce rails, or the outputted waste rails will be superfluous for supplying the required iron scraps. When the waste rails are insufficient to supply enough iron scraps, it is assumed that pig iron is introduced into the system to supply iron scraps. Therefore, pig-iron production process and another substitution process are introduced into the maintenance system. The process of ‘Iron Scrap Substitution’ is composed of 1 kg inputted pig iron and 1 kg outputted iron scrap. On the contrary, when the waste rails are superfluous, some of the waste rails will be exported out of the maintenance system. By using the matrix method for LCI analysis, the calculated process values of the processes of ‘Pig-iron Production’ and ‘Iron Scrap Substitution’ will be negative. Thus, the allocation problem about the superfluous waste rails can be resolved.

[Rail and used-rail transports]

In the maintenance operation of rail exchange, new rails are needed to be transported to the railway line and the used rails are needed to be transported away from the rail line. Therefore, two processes of ‘Rail Transport’ and ‘Used-rail Transport’ are composed and introduced into the maintenance system.

(2). Sleeper Exchange:

The sleeper used in the railway is composed of prestressed concrete (PC) sleeper and wooden sleeper. In the 1st ~ 3rd class railway lines, most of the used sleepers are PC sleepers, while in the 4th class railway lines, most of them are wooden sleepers. Compared with wooden sleeper, PC sleeper is more durable and the exchange period is longer. Therefore, in the railway lines, whose volumes of transportation are large, PC sleepers are most used.

The composition of the sleeper exchange in the track maintenance system is shown in Fig. 5.17. The disposal of the waste sleepers is not considered in this study. Both the new sleepers and the waste sleepers are transported by truck, therefore, service of truck transport is inputted into the process of ‘Sleeper Exchange’. PC sleeper is produced by using concrete and reinforcing bar. Furthermore, many materials such as coal etc. are needed to produce concrete and reinforcing bar. These materials’ production processes are also included in the track maintenance system, although they are not shown in Fig. 5.17.

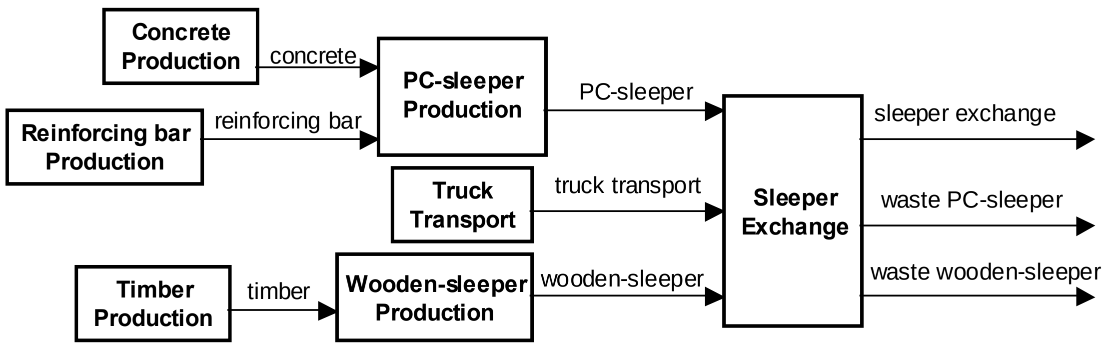


Fig. 5. 17 Sleeper exchange system in the track maintenance system for LCA

(3). Ballast Exchange:

The disposal of the waste ballasts is not considered in this study. Both the inputted and the outputted ballasts are transported by truck.

(4). MTT·BR (Multiple Tie Tamper & Ballast Regulate):

In the maintenance operation of Multiple Tie Tamper & Ballast Regulate, only the consumed light oil is taken into account.

Composing the maintenance operations shown above, the common track maintenance system, which is practicable to each class of railway line, is constructed on the whole, as shown in Fig. 5.18. Some detailed processes, such as electricity production etc., are not shown in Fig. 5.18, since it will make the structure too complicated. Furthermore, it is known that when producing reinforcing bar, iron scarps are used as raw material. Therefore, the waste rails are recycled inside the maintenance system to provide iron scraps not only for producing rail but also for producing reinforcing bar and so on.

Data collection for the maintenance system of track

The data about the maintenance operation of track are provided by the East Japan Railway Company. The data about the production of fundamental material and energy are taken from the LCA database of Life Cycle Assessment Society of Japan (JLCA database) [6]. The detail about the data collection for the maintenance system of present track is shown in Table 5.7. The production processes of 60K rail and 50N rail are compiled by using the process data of shaped steel production. Being different from the unit of track, the unit of rail is set as Rkm. Then, obviously, there are 2 Rkm rails laid on 1 km track.

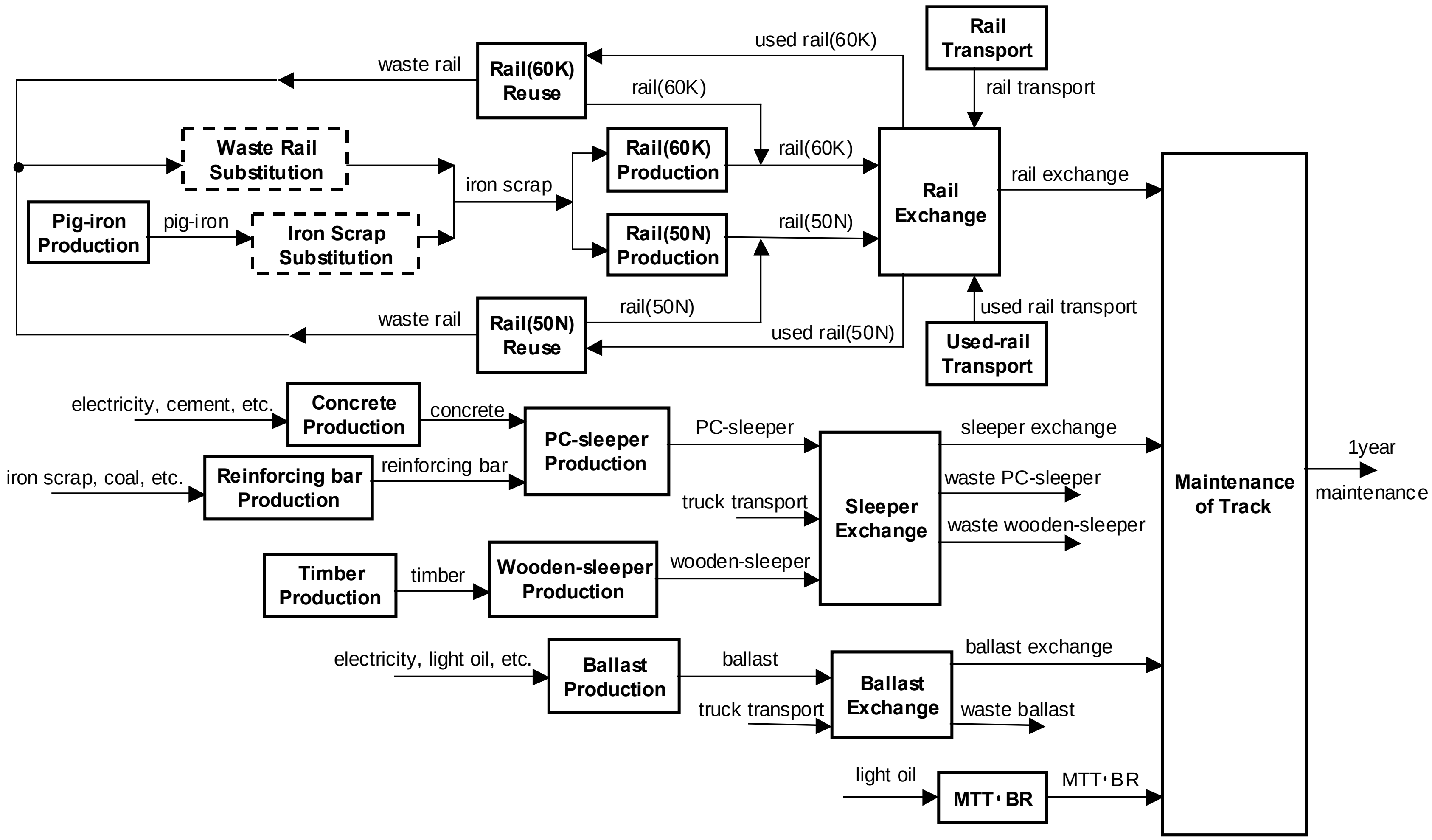


Fig. 5. 18 The common flow figure of the track maintenance system for LCA

Table 5. 7 Data collection for the maintenance system of present track

	Process	Functional Flow	Unit	Data Source
1	Maintenance of Track	maintenance	year	--
2	Rail Exchange	rail exchange	year	East JR 2002-2004 average
3	Rail Transport	rail transport	t	East JR 2002-2004 average
4	Used-rail Transport	used-rail transport	t	East JR 2002-2004 average
5	MC Transport	MC transport	t	East JR 2002-2004 average
6	Sleeper Exchange	sleeper exchange	year	East JR 2002-2004 average
7	Ballast Exchange	ballast exchange	year	East JR 2002-2004 average
8	MTT·BR	MTT·BR	year	East JR 2002-2004 average
9	Rail(60K) Production	rail(60K)	Rkm	JLCA database (2003) Shaped Steel Substitution
10	Rail(50N) Production	rail(50N)	Rkm	JLCA database (2003) Shaped Steel Substitution
11	Rail(60K) Reuse	used rail(60K)	Rkm	--
12	Rail(50N) Reuse	used rail(50N)	Rkm	--
13	Transport by Freighter	transport by freighter	t·km	JLCA database (2005) Coastal Shipping
14	Transport by Barge	transport by barge	t·km	JLCA database (2005) Coastal Shipping
15	Transport by Locomotive	transport by locomotive	t·km	JLCA database (2002) Cargo Railway Transport
16	Transport by Truck	transport by truck	t·km	JLCA database (2005) 10 Ton Truck Transport
17	Light Oil Production	light oil	l	JLCA database (2000)
18	PC-sleeper Production	PC-sleeper	piece	East JR
19	Wooden-sleeper Production	wooden-sleeper	piece	East JR
20	Ballast Production	ballast	m3	JLCA database (2005) Crushed Stone Substitution
21	Waste Rail Substitution	waste rail	kg	--
22	Electricity Production	electricity	kWh	JLCA database (2003)
23	Crude Oil Production	crude oil	l	JLCA database (2003)
24	Concrete Production	concrete	kg	JLCA database (2005)
25	Reinforcing bar	reinforcing bar	kg	JLCA database (2003)
26	Timber Production	timeber	kg	Scientific&Industrial Daily Report (1999)
27	Iron Scrap Substitution	iron scrap	kg	--
28	Pig-iron Production	pig-iron	kg	The Society of Non-Traditional Technology,
29	A Heavy Oil Production	A heavy oil	l	JLCA database (2003)
30	Coal Production	coal	kg	JLCA database (2005) Average Data
31	LPG Production	LPG	kg	JLCA database (2005) Average Data
32	LNG Production	LNG	kg	JLCA database (2005)
33	Cement Production	cement	kg	JLCA database (2005) Portland cement
34	Sandstone Production	sandstone	kg	JLCA database (2005)
35	Limestone Production	limestone	kg	JLCA database (1999)
36	Gasoline Production	gasoline	l	JLCA database (2003)
37	Kerosene Production	kerosene	l	JLCA database (2003)
38	C Heavy Oil Production	C heavy oil	l	JLCA database (2003)
39	Industry Water	industry water	l	JLCA database (2005)

§ 5.3.2 Environmental assessment of the present track maintenance system

Based on the maintenance system of railway track established in section 5.3.1, the CO_2 emission per year's maintenance is calculated. The CO_2 emissions associated with the track maintenances of different line classes are compared. Moreover, the contributions of the unit processes in the established track maintenance system are analyzed, and the essential unit processes are identified.

§ 5.3.2.1 CO_2 emission associated with the maintenance of railway track

The definition of the functional flow in each process is shown in Table 5.7. At present, all the used rails are sold out to another company, therefore, no rail is reused in the track maintenance system and the reuse rate is set to be zero. The recycling rate of the waste rail is set to be 100%. Then, the coefficient matrix **A** is composed of the functional flows, and the environmental load **B**, the surplus flow matrix **C** and the system boundary vector **α** are composed as well. By using the matrix method, the CO_2 emissions associated with one year's track maintenance of different railway lines are calculated, and the results in Table 5.8 and Fig. 5.19. Using the IOA method together, the rate of matrix analysis (AI) of the LCI result, which is proposed in chapter 4, is calculated as well.

Table 5. 8 CO_2 emissions per one year's track maintenance of different railway lines

		Track length (km)	CO2 emission (ton/year)	CO2 emission (ton/year·km)	Rate of matrix analysis (AI)
1st class	Yamate Line	41.2	246.031	5.972	99.98%
	Chuo Line	63.9	528.534	8.271	99.97%
2nd class	Tohoku Line	414.5	1641.608	3.960	99.95%
3rd class	Uetsu Line	266.5	788.229	2.958	99.94%
4th class	Suigun Line	135.0	285.615	2.116	99.94%

In Table 5.8, all the rates of matrix analysis are more than 99.9%, therefore, it is known that the LCI results of CO_2 emission are accurate enough. Consequently, no further treatment about the surplus flows in the maintenance system is needed.

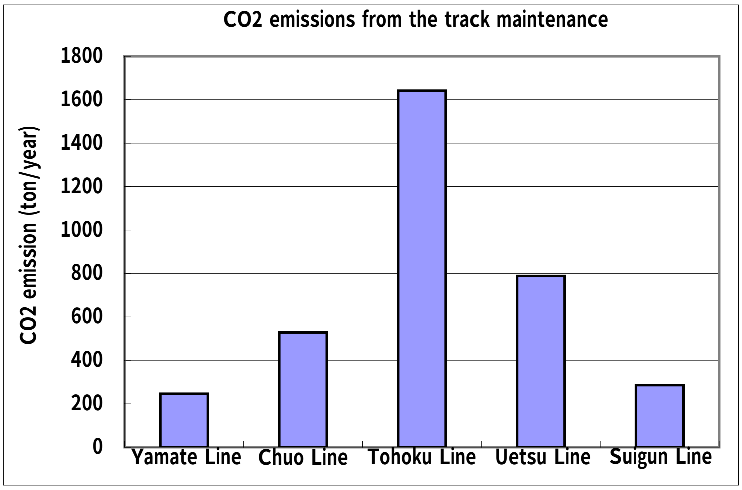


Fig. 5. 19 Comparison of the CO_2 emissions associated with the track maintenance systems (a)

For further comparison of the different railway line classes, by dividing the total amount of CO_2 emission by the track length, the CO_2 emissions per unit length of track maintenance are calculated. The results are shown in Fig. 5.20.

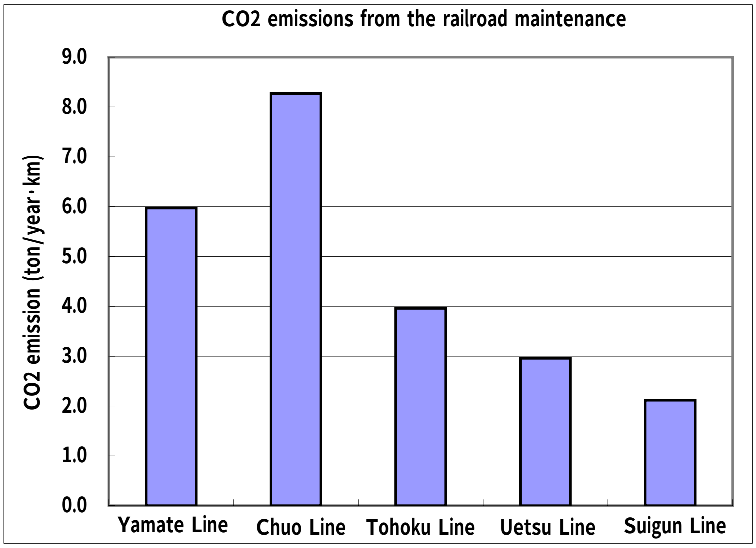


Fig. 5. 20 Comparison of the CO_2 emissions associated with the track maintenance systems (b)

Discussion:

From Table 5.8 and Fig. 5.19, it is known that the total amount of CO_2 emission associated with the track maintenance of Tohoku Line is the most (about 1642 ton/year); while those associated with the track maintenance of Yamate Line is the least (about 246 ton/year). It is because that Tohoku

Line is the longest railway line among the study objects. From this viewpoint, when aiming to decrease the CO_2 emission from track maintenance, the focus of the study should be put on Tohoku Line. On the other hand, although Suigun Line is much longer than Yamate Line, the CO_2 emissions are on the same level.

From Fig. 5.20, the CO_2 emissions per unit length of track maintenance can be learned. Obviously, the CO_2 emissions of track maintenance of the 1st line class are the most. When the line class level goes lower, the maintenance associated CO_2 emission per unit length will go smaller. It is because that the volumes of transportation of the high class railway lines are large, therefore, the more maintenance per unit length are needed on the railway lines. From Table 5.8, it can be seen that the CO_2 emissions per unit length of track maintenance of Chuo Line is about 8.3 ton/year·km, while that of Suigun Line is about 2.1 ton/year·km. The former is about 4 times of the latter.

Moreover, although both Yamate Line and Chuo Line belong to 1st line class and their average volumes of transportation are both about 43.9 million tons, the maintenance associated CO_2 emission of the former one is about 72% of the CO_2 emission of the latter one. The reason is that a rather long part of the track of Yamate Line has been rebuilt to be low-maintenance track [24]. Therefore, the sleeper exchange, ballast exchange and MTT are almost not needed in the track maintenance of Yamate Line, while only rail exchange is needed. It can also explain why the total amount of CO_2 emissions of Yamate Line and Suigun Line are on the same level.

§ 5.3.2.2 Contributions of the processes in the maintenance system of track

In the previous section, the final cumulative CO_2 emission associated with the track maintenance system is calculated. In order to decrease the CO_2 emission, it is important to study the CO_2 contributions of the processes in the track maintenance system. The analyzed results of the CO_2 contributions of the processes are shown in the following table and figures. The horizontal axis shows the process names and the vertical axis shows the CO_2 emission from each process. The processes are prioritized according to their contributions of CO_2 emission from from large to small.

Table 5. 9 CO_2 contributions of the processes in the track maintenance systems

	Rail Production	Pig-iron Production	Transport	Cement Production	MTT・BR	Ballast Production	Electricity Production
Yamate Line	283.606	-66.076	25.459	1.148	0.085	0.643	0.600
Chuo Line	510.269	-118.307	52.231	36.350	30.828	7.172	4.517
Tohoku Line	1511.978	-352.134	228.506	14.123	148.984	47.885	23.419
Uetsu Line	707.920	-164.954	90.709	1.739	95.996	28.780	16.526
Suigun Line	252.504	-58.847	39.472	0.000	27.178	15.059	6.019

The cement production in the results may be regarded as PC-sleeper production, since most of the cement is used for PC-sleeper production. The CO_2 emission associated with pig-iron production is negative, therefore, it is known that the superfluous waste rails are exported out of the track maintenance system. The CO_2 emission corresponding to the superfluous waste rails may be subtracted from the final LCI result by the negative pig-iron production.

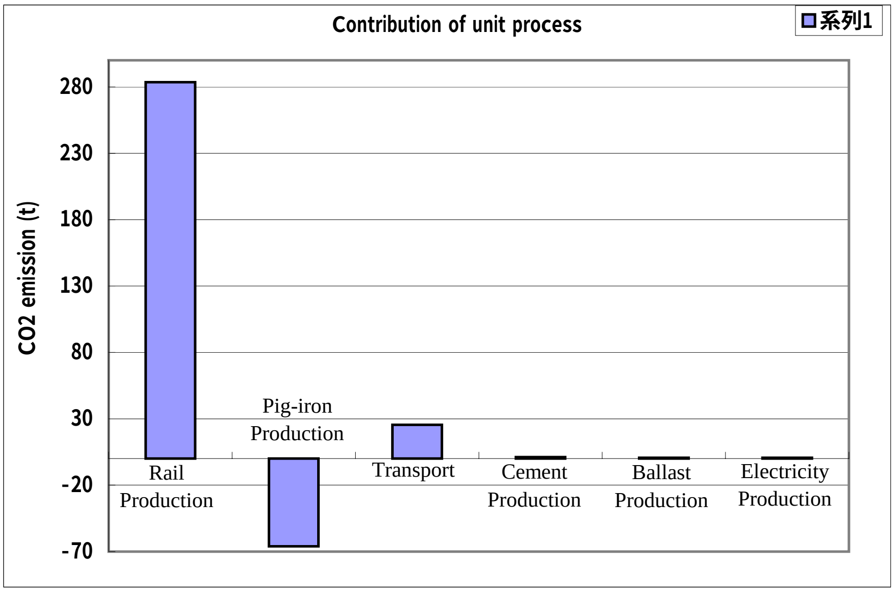


Fig. 5. 21 Contributions of processes in the track maintenance system of Yamate Line

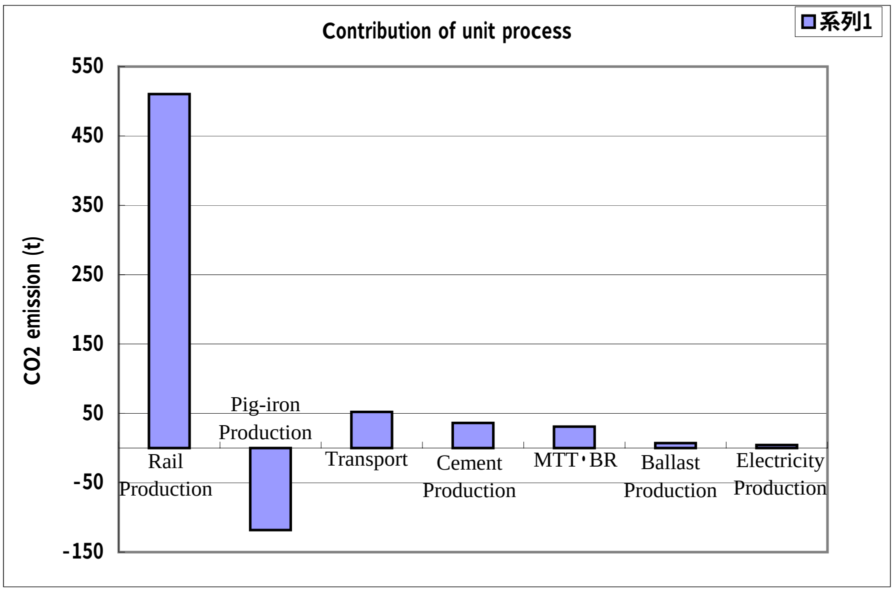


Fig. 5. 22 Contributions of processes in the track maintenance system of Chuo Line

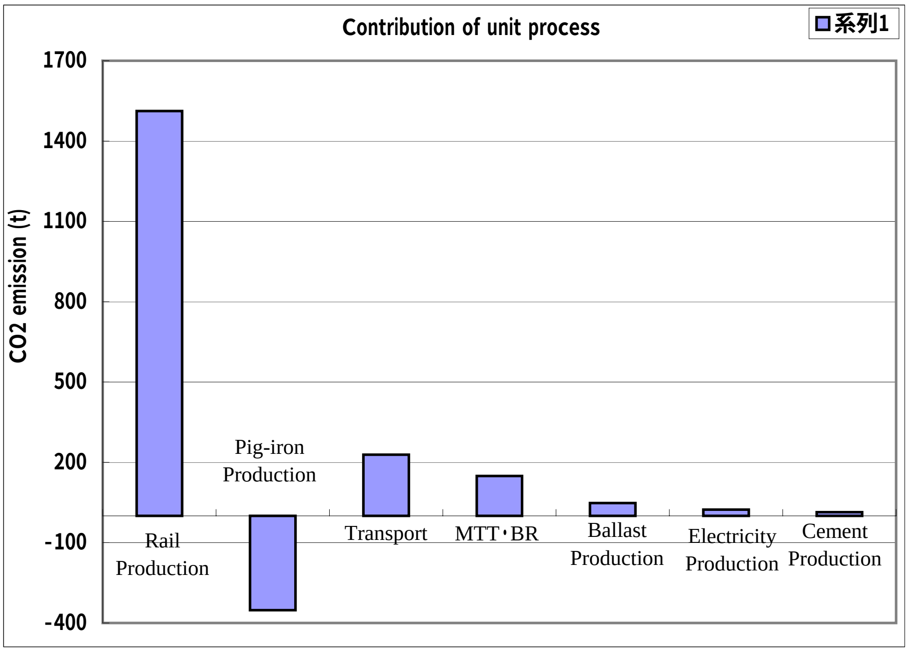


Fig. 5. 23 Contributions of processes in the track maintenance system of Tohoku Line

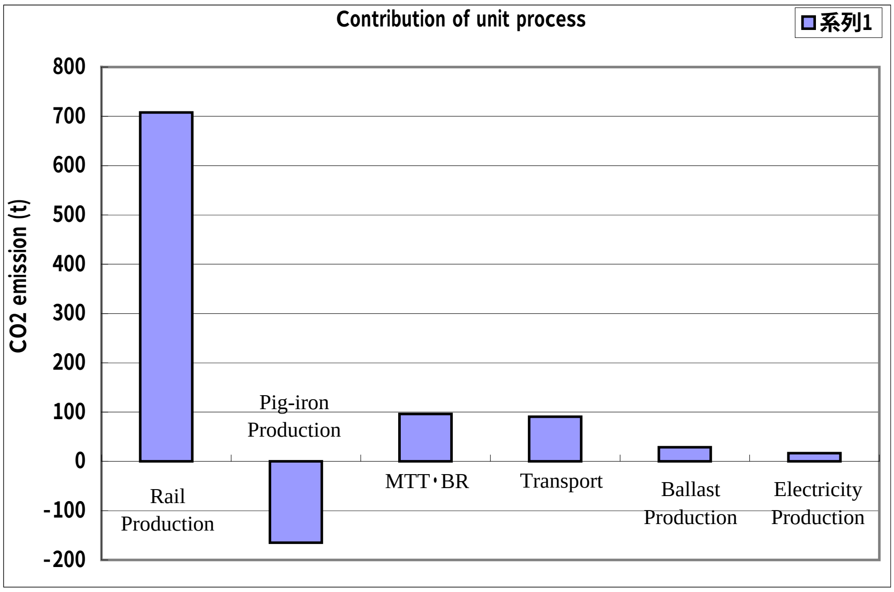


Fig. 5. 24 Contributions of processes in the track maintenance system of Uetsu Line

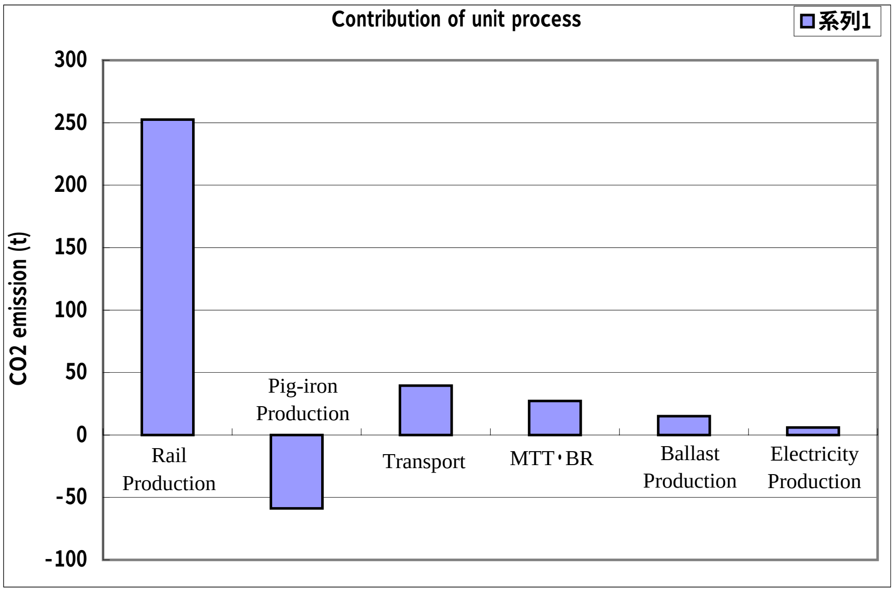


Fig. 5. 25 Contributions of processes in the track maintenance system of Suigun Line

Discussion:

From Fig. 5.21~5.25, it is obvious that ‘Rail Production’ is the most important process. Therefore, when aiming to decrease the CO_2 emission, it will be effective to reduce the CO_2 emission from the rail production or decrease the amount of used rails in the maintenance system. Moreover, from the figures, it is known that ‘Pig-iron Production’ is the secondly important process. Therefore, it is important to have a further investigation about the disposal of waste rails. In addition, the processes of ‘Transport’, ‘MTT·BR’ and ‘Ballast Production’ etc. are also important ones, from which it is considerable to exchange the transporting method or save consumed light oil in MTT·BR so as to reduce the final cumulative CO_2 emission in the maintenance system.

In the track maintenance system of Yamate Line, due to the construction of low-maintenance track, there are few CO_2 emission from the processes of ‘MTT·BR’ and ‘Ballast Production’ etc. and most of the CO_2 emission concentrates on the production, disposal and transport about rails.

§ 5.3.3 Environmental improvements of the maintenance system of track

In section 5.3.2, the CO_2 emission associated with the present track maintenance per year is calculated. In this section, discussion is focused on the environmental improvements of the track maintenance system; namely how the CO_2 emission could be decreased. Since the maintenance of railway track is expressed by a series of processes and the matrxi model has been established by defining funtional flow in each process, the matrix-based sensitivity analysis can be easily carried out. Furthermore, in the matrix-based LCI analysis, it is very convenient as well to study the influences of some paramters on the final LCI result. Herein, the influences of the reuse rate of used rail and the recycling rate of waste rail on the final CO_2 emission are studied.

§ 5.3.3.1 Sensitivity analysis of the track maintenance system

Firstly, using the function of sensitivity analysis in EMLCA, the sensitivity analysis of the track maintenance system is carried out. By the sensitivity analysis result, it is easy to specify the essential process data, whose influences on the final LCI result are larege. It is easy to determine the priority of the process data as well. The sensitivity analysis results of the track maintenances are shown as follows.

Table 5. 10 Sensitivity analysis results of track maintenance system of Chuo Line

	PROCESS	FLOW	VALUE	UNIT	SENSITIVITY
1	Rail Exchange	Rail (60K)	Rkm	-12.388	1.52837
2	Rail (60K) Production	Rail (60K)	Rkm	1	-1.52837
3	Rail (60K) Production	CO2	kg	40614.4	0.95194
4	Railroad Maintenance	Rail exchange	year	-1	0.82948
5	Waste Rail Substitution	Iron scrap	kg	1	-0.80935
6	Waste Rail Substitution	Waste rail	kg	-1	0.80935
7	Rail (60K) Reuse	Waste rail	kg	60800	-0.79803
8	Rail (60K) Reuse	Used rail (60K)	Rkm	-1	0.79803
9	Rail Exchange	Used rail (60K)	Rkm	12.388	-0.79803
10	Rail (60K) Production	Iron scrap	kg	-43897.6	0.57618
…	…	…	…	…	…

In Table 5.10, the sensitivity analysis results of the track maintenance system of Chuo Line are shown. The data of the results are prioritized from large to small in the table and they are interpreted as follows.

[Datum 1]: In the rail exchange operation of the maintenance of Chuo Line, 12.388 km rails(60K) are exchanged per year. It means that 12.388 km new rails(60K) are needed to import into the maintenance system every year. The sensitivity of the imported new rails(60K) to the final CO_2 emission is calculated to be 1.52837. It means that if the imported new rails(60K) are increased by 1% when the other process data are set to be constant, the final CO_2 emission will be increased by 1.52837%. On the contrary, if the imported new rails(60K) are decreased by 1%, the final CO_2 emission will be decreased by 1.52837%. Since this datum of sensitivity is the largest one, it will be most effective to decrease the amount of exchange rail in the maintenance system so as to reduce the final cumulative CO_2 emission.

[Datum 2]: In the process of 60K rail production, keeping the other data as constant, when the outputted 60K rail could be increased by 1%, the final CO_2 emission will be decreased by 1.52873%. From this datum, it is known that in order to reduce the CO_2 emission, it is important to increase the producing efficiency of 60K in the production process.

[Datum 3]: In the process of 60K rail production, keeping the other data as constant, when the CO_2 emission could be decreased by 1%, the final CO_2 emission will be decreased by 0.95194%.

[Datum 4]: In the process of 'Track Maintenance', when the other data are set to be constant, if the inputted maintenance operation of rail exchange is decreased by 1%, the final CO_2 emission will be decreased by 0.82948%. It shows that, compared with other maintenance operations of sleeper exchange or ballast exchange, rail exchange has an absolutely more important influence on the final CO_2 emission.

[Datum 5]: In the process of 'Waste Rail Substitution', it is assumed that waste rail is inputted into the process and iron scrap is outputted from the process. The ration of the outputted iron scrap to the inputted waste rail shows the recycling rate of waste rail. In the present maintenance system, 1 kg waste rail is inputted into and 1 kg iron scrap is outputted from the process, which means that the recycling rate is set to be 100%. Herein, the sensitivity of the outputted iron scrap shows the influence of the recycling rate to the final CO_2 emission. From the datum, it is known that if the recycling rate of waste rail is increased by 1%, then, the final CO_2 emission will be decreased by 0.80935%. Therefore, the recycling rate of waste rail has a significant influence on the final CO_2 emission.

Datum 6 in Table 5.10 has the same meaning with datum 5. The other data of the sensitivity analysis result could be interpreted in the same way. In conclusion, to do more effort about rail, such as reducing the CO_2 emission associated with rail production and increasing the recycling rate of waste rail etc., will have a great effect in decreasing the final cumulative CO_2 emission in the track maintenance system. However, not all the data of sensitivity analysis result can support the environmental improvement. It means that not each datum of sensitivity analysis result has a practical meaning. Therefore, judgments of the LCA practitioner are needed in the result's interpretation.

The sensitivity analysis of the other track maintenance systems are also carried out. The interpretation of the results is abridged here.

Herein, rate sensitivity analysis about the railraod maintenance system is carried out and the results are shown. The sensitivity analysis studies the influences of the small variations of process data to the final CO_2 emission. If the process data fluctuate in a large range, there might be a big error on the sensitivity analysis result. Therefore, in order to clarify the influences of some special parameters and operations in the maintenance system to the final CO_2 emission, further investigations are performed in the following sections.

§ 5.3.3.2 The environmental influence of rail reuse

In practice, all of the used rail outputted from the process of 'Rail Exchange' are treated as waste rail. It menas that no used rail is reused at present. However, in the maintenance system of track for LCA, the processes of rail reuse are still compiled, which are shown in red line in Fig. 6.26. The reuse ratios of the used rail of '60K' and '50N' are assumed to be the same, and represented by the parameter x. At present, it is is set to be zero. As shown in Fig. 6.26, when 1 Rkm used rail(60K) are outputted from the process of 'Rail Exchange' and x Rkm of them are reused, 60800*(1-x) kg waste rail will be generated. Basing on the reuse process of rail(60K), 1 Rkm used rail(60K) are inputted, and x Rkm rail(60K) and 60800*(1-x) kg waste rail are outputted.

On the spreadsheet of Microsoft Excel, if the relationships among the cells are determined by formula forms, then, the values in the cells may change automatically according to the relative cell values. Using this character, in EMLCA, all other connecting parameters (such as the amount of transport etc.) will change when reuse ratio x changes. Therefore, by changing the parameter of x, the influence of the rail reuse ratio on the final CO_2 emission can be studied.

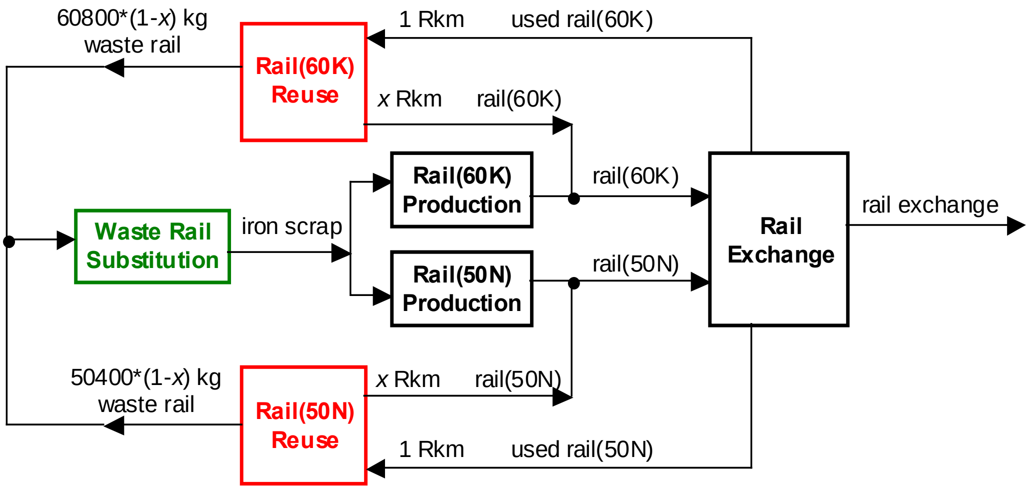


Fig. 5. 26 The flow chart for rail reuse in the maintenance system of track

The recycling rate of waste rail is set as zero. Setting the reuse ratio to be 0%, 2%, 5%, ···, by calculating the consequent CO_2 emissions, the influence of the rail reuse ratio on the final CO_2 emission is studied. The results are shown in Table 5.11.

Table 5. 11 The influence of reuse ratio of used rail to the final CO_2 emission

Final CO2 emission Unit: ton	1st Class Line		2nd Class Line	3rd Class Line	4th Class Line
Rail Reuse Rate	Yamate Line	Chuo Line	Tohoku Line	Uetsu Line	Suigun Line
0%	246.031	528.534	1641.608	788.229	285.615
2%	241.681	520.704	1618.408	777.366	281.741
5%	235.155	508.960	1583.608	761.072	275.929
10%	224.280	489.385	1525.607	733.916	266.243
15%	213.404	469.811	1467.606	706.760	256.556
20%	202.529	450.237	1409.606	679.603	246.870
30%	180.778	411.088	1293.605	625.291	227.498

As an example, how the CO_2 emission is reduced accompanying with the increase of reuse rate of rail in the mantenance system of Yamate Line is shown in Fig. 5.27. The influences of reuse rate of rail on CO_2 emission's reduction in defferent railway lines are compared in Fig. 5.28.

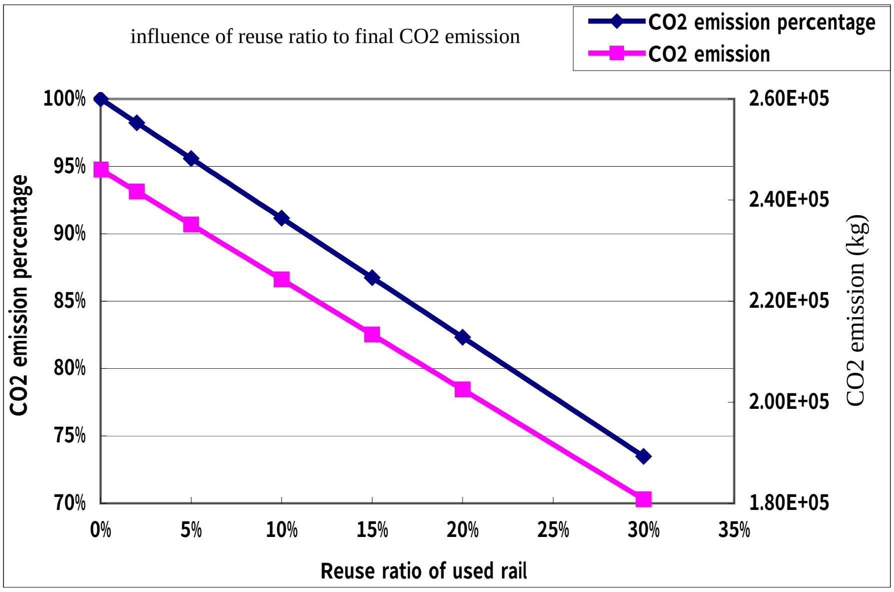


Fig. 5. 27 The influence of reuse ratio of used rail to the final CO_2 emission (Yamate Line)

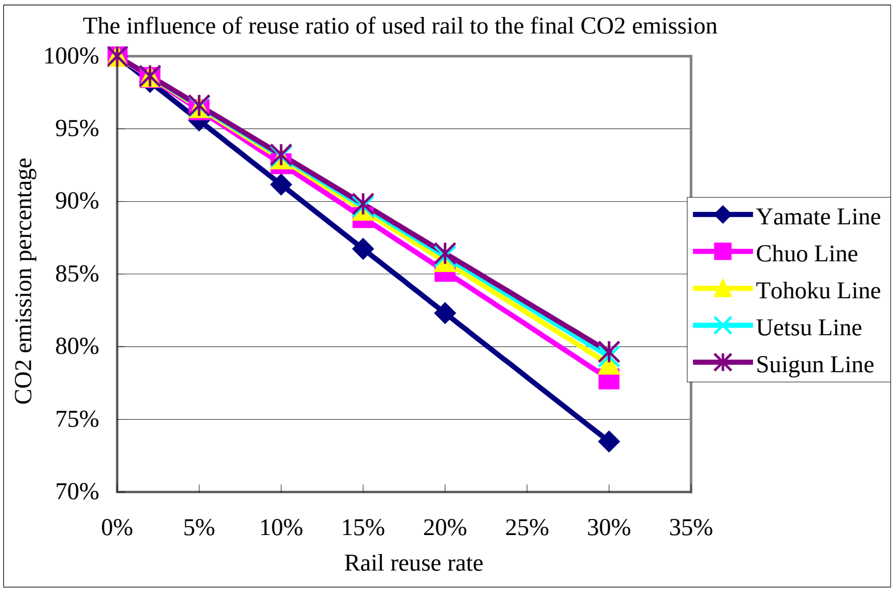


Fig. 5. 28 The influence of reuse ratio of used rail to the final CO_2 emission

Discussion:

Accompanying with the increase of reuse rate of rail in the track mantenance system, the CO_2 emission is decreased. In Fig. 5.27, when the reuse rate of rail is increased to 30% in the maintenance system of Yamate Line, the final CO_2 emission is decreased by about 26.5%. It means that the reuse rate of rail has a sensitive effect on the CO_2 emission. The slope of the blue line in Fig. 5.27 is about 0.884. This datum shows the sensitivity of the reuse rate of rail to the CO_2 emission. However, in the rate sensitivity analysis, which is shown in section 5.3.3.1, the sensitivity of the outputted flow of rail(60) to the CO_2 emission is calculated to be 0. Therefore, in some cases, sensitivity analysis result cannot provide us a complete and reliable enough information about the influence of the process data on the final LCI result. It is because that in the sensitivity analsis, it is assumed that the process data are indenpendent from each other and each of them could be changed independently keeping the other data as constant. While it is not correct in practical cases. Moreover, the sentisitivity analysisi is based on the first order approximation and it provides us a approximate result.

From Fig. 5.28, we can see that on the other railway lines, the reuse rate of rail is aslo an essential item in the maintenance systems. Therefore, techniques and methods about the treatment of used rail should be put more efforts to study and develope, so as to increase the reuse rate rail. The reuse rate of rail of Yamate Line has a more sensitive effective on the final CO_2 emission, since the maintenance operation of Yamate Line is almost only the rail exchange.

In the present environmental assessment of track maintenance, since the information about rail reuse could not be obtained, the reuse rate of rail is set to be zero. However, for a more correct and reliable LCI result of the track maintenance system, reuse rate of rail should be clarified in future research. Furthermore, since the quality of reused rail is worse than that of the new one, the situation of the reused rails should be strictly checked and more attentions should be paid to the safety of the railway line.

§ 5.3.3.3 The environmental influence of the recycling of waste rail

In the process of ‘Waste Rail Substitution’, only waste rails are inputted and only iron scraps are outputted. The ratio of the outputted iron scraps to the inputed waste rails represents the recycling rate of waste rail. Since iron is a highly recyclable material, at present track maintenance system, the recycling rate of waste rail is set to be 100%. However, the recycling rate of 100% is not a practical datum. Due to the lost in transport and abrasion in usage, the recycling rate of the iron of rail is difficult to reach 100%. Herein, setting the recycling rate of waste rail as 100%, 98%, 95%, ···, the influence of the recycling rate on the CO_2 emission is studied. The reuse rate of rail is set as zero. The results are shown in Table 5.12 and Fig. 5.29.

Table 5. 12 The influence of recycling ratio of waste rail to the final CO_2 emission

Final CO2 emission Unit:	1st Class Line		2nd Class Line	3rd Class Line	4th Class Line
Rail Recycling Rate	Yamate Line	Chuo Line	Tohoku Line	Uetsu Line	Suigun Line
100%	246.031	528.534	1641.608	788.229	285.615
98%	250.786	537.089	1666.959	800.098	289.849
95%	257.918	549.922	1704.984	817.902	296.199
90%	269.806	571.311	1768.361	847.575	306.783
80%	293.582	614.088	1895.113	906.922	327.951
70%	317.357	656.865	2021.866	966.268	349.119
50%	364.908	742.419	2275.371	1084.961	391.455

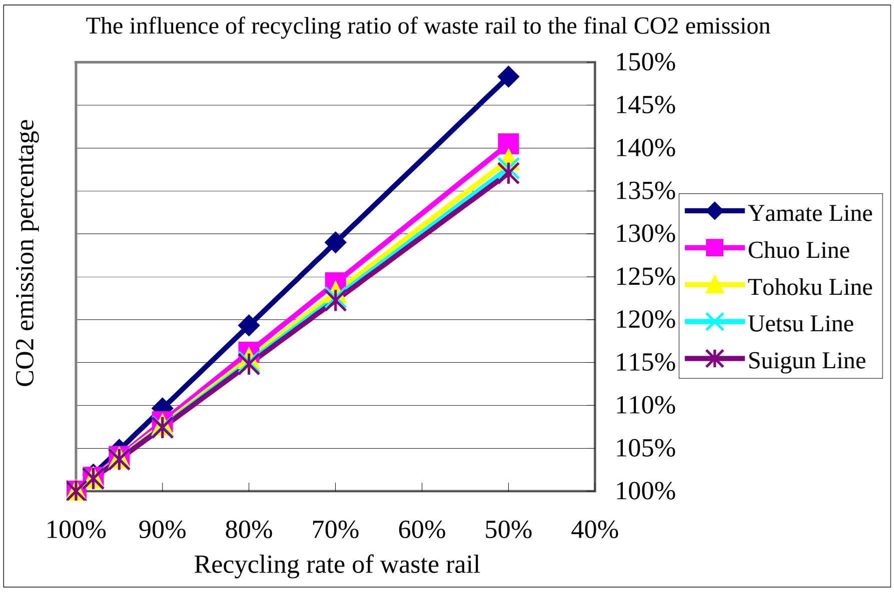


Fig. 5. 29 The influence of recycling ratio of waste rail to the final CO_2 emission

Discussion:

Accompanying with the decrease of the recycling rate of waste rail, the CO_2 emission is increased. For instance, in the maintenance system of Yamate Line, if the recycling rate of waste rails goes down to 90%, the CO_2 emission will be increased 9.66%. In the same way, in the maintenance system of other railway lines, when the recycling rate of waste rail is decreased, the CO_2 emission will be vastly increased. Therefore, it is known that the recycling rate of waste rail has a significant influence on the CO_2 emission. In order to obtain a correct and reliable LCI result, how the waste rails are disposed outside of the maintenance system should be further investigated.

§ 5.3.4 Conclusions of the LCA case study of track maintenance

In the case study of the maintenance of railway track, how the matrix method is applied to an LCA case study of service is shown. By establishing the matrix model of maintenance system of track and defining the functional flow in each unit process, the CO_2 emission associated with one year's track maintenance is calculated. Moreover, the rate of matrix analysis of the LCI result is also calculated to check whether further analysis about the surplus flows is needed. By carrying out sensitivity analysis, the opportunities to obtain environmental improvements are identified and evaluated.

As a result, it is confirmed that the developed matrix-based LCA methodologies can also be easily applied to the LCA study of services, if the operations of service are expresses to be a series of processes.

§ 5.4 Conclusions of Chapter 5

In this chapter, the matrix-based LCA methodologies are practically used to develop LCA software and carry out LCA case studies. By using the practical LCA case studies, the applicability of the matrix method for LCI analysis is examined.

Firstly, a general purpose LCA system-EMLCA is introduced, which adopts the matrix method and is established on worksheet. In EMLCA, all the operations and calculations of LCA analysis are based the matrix algebra and all the matrices are shown on sheet. Moreover, the Monte Carlo simulation for uncertainty analysis is greatly easy to carry out on EMLCA.

Secondly, an LCA case study of copier is carried out. In the case study of copier, it is confirmed that the coefficient matrix composed by defining functional flow in each unit process is necessarily a square matrix. Moreover, the sensitivity analysis is carried out, in which the influences of the coefficient matrix and the environmental load matrix are both included.

Thirdly, an LCA case study of the maintenance of railway track is carried out. By the case study, it is shown that the developed matrix-based LCA methodologies can also be applied to the LCA study of services, if the operations of service are expresses to be a series of processes.

In such a way, the applicability and effectiveness of the matrix-based LCA methodologies are examined. All the operations and calculations in the practical LCA case studies are carried out by using the general purpose LCA software- EMLCA. So that, the practicability and effectiveness of EMLCA are examined and proved.

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Appendix of chapter 5

Appendix 5.1 The coefficient matrix **A** and the boundary vector **α** in the LCA case study of copier

A	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	α
M1	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M2	-5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M3	-1044	-28.25	0	-14.66	0	0	1	0	0	0	0	0	0	-0.016	-1E-05	-0.204	0	-0.294	-0.301	-0.008	-0.218	-0.146	-0.445	-3E-04	-0.008	-0.008	-0.008	0	0
M4	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M5	-3E+05	0	0	0	0	0	0	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M6	288000	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M7	1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M8	0	-1	1	0	0	0.0272	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M9	0	-0.302	0	-0.03	0	0	0	0	0	0	0	0	0	-7E-05	0	0	0	-0.002	0	0	0	0	0	0	1	0	0	0	0
M10	0	-0.067	0	-0.008	0	0	-2E-04	0	0	0	0	0	0	0	-0.008	-0.015	0	0	-0.07	0	0	0	0	0	0	1	0	0	0
M11	0	-0.467	0	0	0	0	-0.014	0	0	0	0	0	-2E-04	-0.012	-0.038	-0.222	0	-0.105	-0.134	0	-0.049	0	-0.018	0	0	0	1	0	0
M12	0	-0.125	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
M13	0	0	0	-0.036	0	0	-0.002	0	0	0	0	0	0	0	1	-4E-04	0	-0.016	0	0	0	0	0	0	0	0	0	0	0
M14	0	0	0	-1.449	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
M15	0	0	0	-0.606	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
M16	0	0	0	-0.148	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
M17	0	0	0	-0.083	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
M18	0	0	0	0	0	0	-0.057	0	0	0	0	0	0	1	0	-0.248	-1.67	-0.001	0	0	0	0	0	0	0	0	0	0	0
M19	0	0	0	0	0	0	-0.012	0	0	0	0	0	0	0	0	-1E-03	-1.26	0	0	-1	0	0	0	0	-1	-1	-1	1	0
M20	0	0	0	0	0	0	-2.701	0	0	0	0	0	1	0	0	0	0	-0.087	0	0	0	0	0	-0.965	0	0	0	0	0
M21	0	0	0	0	0	0	0	0	0.8	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M22	0	0	0	0	0	0	0	0	0	2.92	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M23	0	0	0	0	0	0	0	0	0	0.27	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.02	0	0	0	0	-0.335	0.016	0	0	0	0	0
M25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.009	-0.992	1	0	0	0	0	0	0	0	0	0
M26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.184	1	0	0	0	0	0	0	0
M27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.057	0	1	0	0	0	0	0	0
M28	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5

P1: Copier Usage	P2: Copier Manufacture	P3: Copier Parts Production	P4: Copier Consumable Production	P5: Transport Of Copier	P6: Used Copier Disposal	P7: Electricity Production
P8: Copy Paper Production	P9: Copy Paper Reuse	P10: Copy Paper Recycling	P11: Paper Reproduction	P12: Waste-paper Treatment	P13: LNG Production	P14: Coal Mining
P15: LPG Production	P16: Paper Production	P17: Aluminum Production	P18: ABS Resin Pellet Production	P19: Polyethylene Production	P20: Naphtha Production	P21: Polyester Resin Production
P22: Phthalic Acid Production	P23: Glycerin Production	P24: City Gas Production	P25: Kerosene Production	P26: Light Oil Production	P27: Heavy Oil Production	P28: Crude Oil Production

M1: copier	M2: copier consumable	M3: electricity	M4: transport	M5: copier paper	M6: used copier paper	M7: used copier
M8: copier parts	M9: kerosene	M10: light oil	M11: heavy oil	M12: paper	M13: LPG	M14: polyester resin
M15: polyethylene	M16: aluminum	M17: ABS resin pellet	M18: coal	M19: crude oil	M20: LNG	M21: recycling paper
M22: waste paper	M23: reproduced paper	M24: city gas	M25: naphtha	M26: phthalic acid	M27: glycerin	M28: copier use

Appendix 5.2 The environmental load matrix **B** in the LCA case study of copier (Unit: g)

A	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28
CO2	0	2541	141040	200.2	4140	17150	353	2.532	0	0	0.014	0.4	9.96	78.8	297.1	1069.9	9601	1492.1	980.35	101.85	149	307	711.44	0.0665	62.979	91.051	145.39	79.933
NOx	0	1928	0	196.45	0	0	0.18	0	0	0	0	0	0	0.355	0.717	1.308	18	1.2183	0.942	0.079	0.093	0	0.188	4E-05	0.048	0.071	0.113	0.92
SOx	0	3040	0	31.963	0	0	0.14	0	0	0	0	0	0	0.681	1.53	1.22	58	0.2538	0.217	0.098	0.098	0	0.0184	0	0.06	0.087	0.14	1.343
BOD	0	0.2	0	4.229	0	0	0	0	0	0	0	0	0	0	0	3.586	0.0015	0.1352	0.024	0	0	0	0	0	0	0	0	0
COD	0	0.4	0	6.164	0	0	0.00015	0	0	0	0	0	0	0	0	8.9	0.038	0.5849	0.034	0	0.032	0	0	0	0	0	0	0
T-P	0	0.066	0	0.007	0	0	0	0	0	0	0	0	0	0	0	0.0512	0	0.0328	0.003	0	0	0	0	0	0	0	0	0
T-N	0	2.1	0	0.195	0	0	0	0	0	0	0	0	0	0	0	0.2913	0	0.945	0.094	0	0	0	0	0	0	0	0	0
SS	0	0.2	0	0.061	0	0	6.2E-05	0	0	0	0	0	0	0	0	3.437	1.2	0.2239	0.016	0	0	0	0	0	0	0	0	0
HFC	0	0	0	0	0	0	1.3E-05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2O	0	0	0	0	0	0	0.0021	0	0	0	0	0	0	0	0	0.045	0	0	0.0002	0	0	0	0	0	0	0	0	0
SF6	0	0	0	0	0	0	4.4E-05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dust	0	0	0	0	0	0	0.0074	0	0	0	0	0	0	0.0508	0.097	0.277	58	0.0396	0.793	0	0	0	0	0	0	0	0	0
CH4	0	0	0	0	0	0	0	0	0	0	0	0	0.0143	3.99	0.895	0.129	0	0.0026	0.005	0	0	0	0	0.0009	0	0	0	0
CO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4543	0	0	0	0	0	0	0	0	0	0
HC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.757	1.929	0	0	0	0	0	0	0	0	0

Appendix 5.3 The calculated inverse matrix of the coefficient matrix **A** in the LCA case study of copier

A-1																												
	-1E-17	-9E-18	-2E-19	0	0	-1E-21	0	0	-3E-18	-3E-18	-6E-18	4E-18	2E-19	3E-18	9E-19	7E-19	-2E-17	-4E-18	0	5E-21	0	-3E-22	0	-4E-18	-3E-18	6E-20	-5E-19	0.2
	1	6E-17	-4E-18	0	0	1E-20	0	0	-3E-18	-3E-18	-6E-18	4E-18	2E-19	-2E-17	-2E-19	7E-19	4E-16	-4E-18	0	-7E-19	-1E-36	6E-21	0	6E-17	-3E-18	2E-20	2E-17	0.2
	1	2E-16	-1E-18	0	0	1E-20	0.0272	1	-3E-18	-3E-18	-6E-18	5E-18	2E-19	-1E-17	-2E-18	7E-19	4E-16	-4E-18	0	-7E-19	-1E-36	6E-21	0	6E-17	-3E-18	4E-19	2E-17	0.1946
	-3E-17	1	-1E-18	0	0	3E-37	0	0	-2E-17	-2E-17	-4E-17	2E-17	1E-19	-8E-17	9E-18	3E-18	-1E-17	-5E-19	0	-6E-21	-1E-37	2E-37	0	-3E-18	-2E-17	1E-19	-2E-18	1
	-1E-17	-9E-18	-2E-19	1	0	-1E-21	0	0	-3E-18	-3E-18	-6E-18	4E-18	2E-19	3E-18	9E-19	7E-19	-2E-17	-4E-18	0	5E-21	0	-3E-22	0	-4E-18	-3E-18	6E-20	-5E-19	0.2
	-1E-17	-9E-18	-2E-19	0	0	-1E-21	-1	0	-3E-18	-3E-18	-6E-18	4E-18	2E-19	3E-18	9E-19	7E-19	-2E-17	-4E-18	0	5E-21	0	-3E-22	0	-4E-18	-3E-18	6E-20	-5E-19	0.2
	28.314	15.289	1.001	0	0	-7E-19	0	0	0.0075	0.0075	0.0075	0.2099	0.0004	0.2712	0.3103	0.0261	0.3289	0.0156	0	1E-06	-6E-23	-2E-19	0	0.0167	0.0075	0.1461	0.451	229.96
	-3E-12	-2E-12	-5E-14	0	1	0.2	0	0	-7E-13	-7E-13	-1E-12	1E-12	6E-14	6E-13	2E-13	2E-13	-4E-12	-9E-13	0	1E-15	0	-8E-17	0	-1E-12	-7E-13	1E-14	-1E-13	46080
	-4E-12	-3E-12	-6E-14	0	0	-1	0	0	-9E-13	-9E-13	-2E-12	1E-12	7E-14	7E-13	3E-13	2E-13	-5E-12	-1E-12	0	1E-15	0	-1E-16	0	-1E-12	-9E-13	2E-14	-2E-13	57600
	-3E-12	-2E-12	-5E-14	0	0	-0.8	0	0	-7E-13	-7E-13	-1E-12	1E-12	6E-14	6E-13	2E-13	2E-13	-4E-12	-9E-13	0	1E-15	-1	-8E-17	0	-1E-12	-7E-13	1E-14	-1E-13	46080
	-9E-13	-6E-13	-1E-14	0	0	-0.216	0	0	-2E-13	-2E-13	-4E-13	3E-13	1E-14	2E-13	6E-14	5E-14	-1E-12	-2E-13	0	3E-16	-0.27	-1E-17	-1	-3E-13	-2E-13	4E-15	-3E-14	12442
	-1E-11	-6E-12	-1E-13	0	0	-2.336	0	0	-2E-12	-2E-12	-4E-12	3E-12	2E-13	2E-12	6E-13	5E-13	-1E-11	-3E-12	0	3E-15	-2.92	-1	0	-3E-12	-2E-12	4E-14	-4E-13	134554
	76.462	53.103	2.7032	0	0	-2E-18	0	0	0.0203	0.0203	0.0203	0.5669	0.001	1.8867	0.8379	0.0705	123.08	0.0422	0	1	-2E-22	-5E-19	0	60.492	0.0203	0.3947	21.47	632.83
	1.6509	1.1219	0.0573	0	0	-4E-20	0	0	0.0004	0.0004	0.0004	0.2602	2E-05	0.0155	0.0178	1.6715	0.0198	1.0009	0	7E-08	-4E-24	-1E-20	0	0.001	0.0004	0.0084	0.0258	13.41
	0.0487	0.0636	0.0017	0	0	-1E-21	0	0	1E-05	1E-05	1E-05	0.0008	1	0.0005	0.0005	4E-05	0.0166	3E-05	0	2E-09	-1E-25	-3E-22	0	3E-05	1E-05	0.0003	0.0008	0.4329
	0.125	5E-18	-5E-20	0	0	-8E-23	0	0	-4E-19	-4E-19	9E-19	1	1E-19	6E-18	4E-19	8E-19	1E-17	2E-19	0	7E-21	-4E-39	-2E-23	0	7E-18	-4E-19	4E-20	2E-18	0.025
	-2E-16	0.148	-6E-18	0	0	0	0	0	0	0	-4E-16	-9E-17	6E-18	-9E-17	-2E-16	1	0	-4E-18	0	-2E-20	0	6E-37	0	-7E-18	0	-7E-19	-1E-17	0.148
	-4E-18	0.083	-8E-20	0	0	-1E-38	0	0	-1E-18	-1E-18	3E-18	1E-19	-2E-20	-5E-18	1E-18	3E-19	1	4E-20	0	-1E-22	-1E-38	5E-39	0	0	-1E-18	1E-20	0	0.083
	-2E-17	0.606	-7E-19	0	0	2E-37	0	0	-9E-18	-9E-18	-3E-17	1E-17	9E-20	-6E-17	1	2E-18	-8E-18	-3E-19	0	-4E-21	-9E-38	1E-37	0	-2E-18	-9E-18	8E-20	-1E-18	0.606
	-2E-17	0.6016	-7E-19	0	0	2E-37	0	0	-9E-18	-9E-18	-3E-17	1E-17	9E-20	-6E-17	0.9916	2E-18	0.0086	-3E-19	0	-3E-21	-9E-38	1E-37	0	-2E-18	1	8E-20	-1E-18	0.6016
	-5E-17	1.449	-2E-18	0	0	4E-37	0	0	-2E-17	-2E-17	-6E-17	3E-17	2E-19	1	1E-17	5E-18	-2E-17	-7E-19	0	-8E-21	-2E-37	2E-37	0	-4E-18	-2E-17	2E-19	-3E-18	1.449
	-1E-17	0.2666	-6E-19	0	0	1E-37	0	0	-4E-18	-4E-18	1E-17	-1E-18	3E-19	0.184	1E-18	7E-19	-5E-18	-8E-20	0	-3E-21	-4E-38	5E-38	0	-7E-19	-4E-18	1	-5E-19	0.2666
	5E-18	0.0826	-1E-19	0	0	2E-38	0	0	-1E-18	-1E-18	7E-19	9E-19	1E-19	0.057	1E-18	2E-19	-2E-18	-5E-20	0	-5E-22	-1E-38	2E-38	0	4E-20	-1E-18	3E-21	1	0.0826
	-4E-16	12.241	-1E-17	0	0	-9E-37	0	0	-2E-16	-2E-16	4E-16	4E-17	4E-19	1.1968	2E-16	4E-17	126.59	5E-18	0	-2E-20	-2E-36	1E-36	0	62.67	-2E-16	1E-18	20.997	12.241
	0.3021	0.0304	4E-06	0	0	-7E-21	0	0	1	3E-08	3E-08	2E-05	1E-09	1E-06	1E-06	0.0001	0.0025	7E-05	0	5E-12	-7E-21	-5E-23	0	7E-08	3E-08	6E-07	2E-06	0.0916
	0.0763	0.0549	0.0003	0	0	-2E-22	0	0	2E-06	1	2E-06	0.0155	0.0081	7E-05	0.0702	7E-06	0.0002	4E-06	0	3E-10	-2E-21	-5E-22	0	4E-06	2E-06	4E-05	0.0001	0.1242
	0.9259	0.4014	0.0152	0	0	-5E-21	0	0	0.0001	0.0001	1.0001	0.228	0.0376	0.0544	0.1385	0.0208	0.1314	0.0125	0	0.0002	-1E-24	-3E-21	0	0.0105	0.0001	0.0022	0.0285	3.7665
	1.6552	1.4642	0.0279	0	0	-2E-20	0	0	1.0002	1.0002	1.0002	0.2471	0.0457	0.0578	1.2042	1.2813	0.1469	0.0127	1	0.0002	-8E-21	-6E-21	0	0.0107	1.0002	0.0041	0.0342	7.6196

Appendix 5.4 The calculated process vector **p** in the LCA case study of copier

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28
Process Value	1	1	0.97	5	1	1	1149.8	230400	288000	230400	62208	672768	3164.1	67.048	2.1644	0.125	0.74	0.415	3.03	3.0082	7.245	1.3331	0.413	61.207	0.4581	0.6209	18.832	38.098

Appendix 5.5 The calculated final environmental load vector **β** in the LCA case study of copier

Environmental load	CO2	NOx	SOx	BOD	COD	T-P	T-N	SS	HFC	N2O	SF6	Dust	CH4	CO	HC
Value (Unit: g)	1477500.52	3197.64352	3508.49086	21.9231751	33.1106724	0.1301119	3.78842484	2.03532577	0.01494752	2.4208299	0.0505916	57.4984132	314.792998	0.18855484	6.989025

Appendix 5.6 The sensitivity matrix to the CO_2 emission in the LCA cast study of copier

S	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28
M1	0.1048	-0.105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M2	0.0304	0	0	-0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M3	0.2754	0.0075	0	0.0193	0	0	-0.303	0	0	0	0	0	0	0.0003	8E-09	7E-06	0	3E-05	0.0002	6E-06	0.0004	5E-05	5E-05	4E-06	9E-07	1E-06	4E-05	0
M4	0.0028	0	0	0	-0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M5	0.4935	0	0	0	0	0	0	-0.395	-0.099	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M6	0.084	0	0	0	0	0	0	0	-0.084	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M7	0.009	0	0	0	0	-0.009	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M8	0	0.0955	-0.093	0	0	-0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M9	0	3E-05	0	1E-05	0	0	0	0	0	0	0	0	0	5E-07	0	0	0	1E-07	0	0	0	0	0	0	-5E-05	0	0	0
M10	0	8E-06	0	5E-06	0	0	3E-05	0	0	0	0	0	0	0	2E-06	2E-07	0	0	3E-05	0	0	0	0	0	0	-7E-05	0	0
M11	0	7E-05	0	0	0	0	0.0025	0	0	0	0	0	8E-05	0.0001	1E-05	4E-06	0	7E-06	6E-05	0	5E-05	0	1E-06	0	0	0	-0.003	0
M12	0	0.0001	0	0	0	0	0	0	0	0	0	0	0	0	0	-1E-04	0	0	0	0	0	0	0	0	0	0	0	0
M13	0	0	0	4E-05	0	0	0.0004	0	0	0	0	0	0	0	-4E-04	1E-08	0	1E-06	0	0	0	0	0	0	0	0	0	0
M14	0	0	0	0.0018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0	0	0	0	0	0
M15	0	0	0	0.0027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	0	0	0	0	0	0	0	0	0
M16	0	0	0	0.0049	0	0	0	0	0	0	0	0	0	0	0	0	-0.005	0	0	0	0	0	0	0	0	0	0	0
M17	0	0	0	0.0008	0	0	0	0	0	0	0	0	0	0	0	0	0	-8E-04	0	0	0	0	0	0	0	0	0	0
M18	0	0	0	0	0	0	0.0039	0	0	0	0	0	0	-0.004	0	2E-06	7E-05	2E-08	0	0	0	0	0	0	0	0	0	0
M19	0	0	0	0	0	0	0.0008	0	0	0	0	0	0	0	0	7E-09	5E-05	0	0	0.0002	0	0	0	0	2E-05	3E-05	0.001	-0.002
M20	0	0	0	0	0	0	0.021	0	0	0	0	0	-0.021	0	0	0	0	2E-07	0	0	0	0	0	0.0004	0	0	0	0
M21	0	0	0	0	0	0	0	0	0.1827	-0.183	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M22	0	0	0	0	0	0	0	0	0	0.1821	0	-0.182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M23	0	0	0	0	0	0	0	0	0	0.0006	-6E-04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0003	0	0	0	0	6E-05	-4E-04	0	0	0	0
M25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4E-07	0.0004	-4E-04	0	0	0	0	0	0	0	0
M26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0003	-3E-04	0	0	0	0	0	0
M27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0003	0	-3E-04	0	0	0	0	0
M28	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CO2	0	0.0017	0.0929	0.0007	0.0028	0.0116	0.2747	0.3948	0	0	0.0006	0.1821	0.0213	0.0036	0.0004	9E-05	0.0048	0.0004	0.002	0.0002	0.0007	0.0003	0.0002	3E-06	2E-05	4E-05	0.0019	0.0021

Chapter 6

Conclusions

§ 6.1 Conclusions

In this thesis, a general and effective matrix method for Life Cycle Inventory (LCI) analysis is developed. Based on the matrix method, the operations from LCI analysis to sensitivity and uncertainty analysis are connected to facilitate the LCA analysis. After that, using the developed LCA methodologies, a general purpose LCA software is developed and some practical LCA case studies are carried out. As a result, a complete study on the advanced technique of environmental assessment based on life cycle assessment using matrix method is carried out. All the studies in the thesis are based on the matrix method

Firstly, in Chapter 2, the conventional matrix method for LCI analysis is reviewed and the problems in it are investigated and discussed. After that, a new practical approach for matrix-based LCI analysis is proposed, which is suitable for all kinds of product systems. In the practical approach, all the process data are arranged in three matrices: the coefficient matrix **A**, the environmental load matrix **B** and the surplus flow matrix **C**. The coefficient matrix **A**, which is the most important one, is composed through defining only one functional flow in each unit process, so that, it is assured to be a square matrix. Based on the final surplus flow vector $\boldsymbol{\gamma}$, which is calculated by using the surplus flow matrix **C**, after confirming that the byproducts etc. are assuredly cross the system boundary and allocation is really needed, the allocation in LCI analysis is carried out. Consequently, the efficiency of the matrix method for LCI analysis is further improved. The general approach for allocation is discussed as well. Furthermore, an extend example of LCA case study is carried out by using the conventional matrix method and the present one respectively. The practicability and effectiveness of the present matrix method are examined. By comparing the two kinds of analysis, the merits of the present one is shown clearly as well.

As a result, the matrix method for LCI analysis becomes more appropriate to deal the complex product system with many recursive loops and recycling loops. It is more practicable and easier to use, especially for the practitioners who have few LCA experience and knowledge. Moreover, this practical approach can be easily carried out by computer program. It is the most basic algorithm of the studies in this thesis. Based on the basic matrix method for LCI analysis, further studies on LCI analysis methods are carried out in Chapter 3 and Chapter 4.

In Chapter 3, based on the matrix method proposed in Chapter 2, the algorithm of sensitivity and uncertainty analysis in matrix-based LCI is generalized. The sensitivity analysis adopts the rate sensitivity and quantitatively studies the influence of each process datum on the final cumulative environmental loads. Since all the process data have been arranged in three matrices according to the different properties, the sensitivity analysis based on the matrices becomes much more convenient and the sensitivity analysis result is easier to grasp as a whole. The uncertainty analysis studies the uncertainties of the final environmental loads, which are propagated from the uncertainties of process data. It is shown that the matrix method greatly supports the uncertainty analysis methods, which are based on the central limit theorem and the Monte Carlo simulation. Moreover, a general procedure for uncertainty analysis in LCI is proposed. The practicability and effectiveness of the uncertainty analysis methods and the general procedure are examined as well.

As a result, based on the improved matrix method, the operations from LCI analysis to sensitivity and uncertainty analysis are connected to facilitate the LCA analysis.

In Chapter 4, the matrix method for LCI analysis proposed in Chapter 2 is combined with the Input-Output Analysis (IOA) method through the final surplus flow vector $\boldsymbol{\gamma}$. Consequently, all the direct and indirect environmental loads associated with a product can be taken into account and the LCI analysis is completed. Continuatively, considering the cost performance and the result's accuracy in practical LCA case studies, a general and consistent method about how to define the appropriate product system boundary is proposed. The iterative calculation in the method uses the matrix method and the IOA method. By the method in this chapter, the product system of a product is composed of all the essential relevant unit processes, which provides the result of LCA with high accuracy. Furthermore, the product system is composed of only the essential relevant unit processes, which makes the LCA case study to be simplified and of low cost. Finally, as examples, case studies of desktop computer and refrigerator are performed to demonstrate the proposed method for system boundary definition, and the practicability and effectiveness of the method are examined.

As a result, by using the method for product system boundary definition based on the matrix method and IOA method, the accuracy of LCI result is improved. The problem of compromise between practicality and completeness in LCA is resolved.

In Chapter 5, the matrix-based LCA methodologies developed in Chapter 2, 3, and 4 are practically used. In the first place, using the methodologies, a general purpose LCA system is established on the spreadsheet of Excel and it is named as Excel Management LCA (EMLCA). The features of EMLCA are that all the operations and calculations of LCA analysis are based on the matrix algebra and all the matrices are shown on sheet, which makes it easy to manage and check the data. Moreover, the sensitivity analysis and uncertainty analysis are greatly easy to carry out on EMLCA.

Continuatively, an LCA case study of copier is carried out. In the case study of copier, how the matrix-based LCA methodologies are made good use of are demonstrated. The practicability and effectiveness of the methodologies and software in a practical case study of a product are examined and confirmed.

The developed matrix-based LCA methodologies and software can also be easily applied to the LCA case study of service, if the operations of service are expressed as a series of processes. As an LCA case study of service, the environmental assessment of the maintenance system of railway track is carried out by using the matrix-based LCA methodologies and software-EMLCA. By establishing the matrix model of railway track maintenance system, the environmental loads associated with one year's railroad maintenance are calculated. By carrying out sensitivity analysis, the opportunities to obtain environmental improvements are identified and evaluated.

Feature of the thesis:

All the studies in this thesis are based on the matrix method. The thesis covers the development of matrix-based LCA methodologies, the development of general purpose LCA software and the practical usage of the methodologies and software in practical LCA case studies.

Limitation of the thesis:

It is time consuming to derive the inverse matrix when the coefficient matrix becomes large. The matrix method is based on linear assumption; therefore it is not so suitable to the non-linear systems. In the matrix method proposed in this thesis, the definition of the functional flow of each unit process depends on the practitioner's judgment yet. However, by clarifying the purpose of introducing the process into the product system, the functional flow may be easily defined in each individual unit process.

§ 6.2 Possible direction of future research on LCA

In order to preserve the environment more effectively and efficiently, we should pay attention to not only industrial activities, but also ordinary life styles and the role of government. Recent years, new concepts of “Establishment of Recycling Society” and “Sustainable Development” have been proposed and emphasized, and some studies about them have been carried out [1-3]. Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for the provision of goods and services. Matrix-based LCA is such an effective tool, which can satisfy the requirement. Japan is intending to shift from the former 1R (Recycle) policy to 3R (Reduce, Reuse, Recycle) policy, in other words, to focus on not only recycling waste but also not producing as much waste by means of waste reduction and re-use of waste [1]. In a 3R- intent product system for LCA, there will be many reusing and recycling loops. In such a complex LCA case study, the matrix method will be much superior to other methods. Therefore, it is necessary to study further that how the matrix method for LCI analysis should be taken advantage of in the recycling society. How to popularize the matrix-based LCA method to preserve the environment more effectively and efficiently and to support the decision making in society is the future task.

On the other hand, in Chapter 3, it is mentioned that there are many sources of the uncertainty of LCI/LCA result. So far, there is yet no a method of uncertainty analysis, which could take all the sources into account as a whole. Therefore, we hope to develop such a method in future.

In LCI/LCA, the temporal and spatial influences on the final result are very important aspects. Although there have been some discussions about these problems [4, 5], much more studies are needed.

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Study On The Advanced Technique Of Environmental Assessment
Based On Life Cycle Assessment Using Matrix Method
（マトリックス法を用いたライフサイクルアセスメントによる環境影響評価技術の高度化に関する研究）

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