論文の内容の要旨

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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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 manufactured and consumed, has increased the attention on developing the methods to comprehend and reduce these impacts. One of the techniques being developed for this purpose is Life Cycle Assessment (LCA). LCA is an increasingly important tool to evaluate the environmental impacts associated with products and services by taking into account the whole life cycle of from the cradle to the grave.

In recent years, LCA has become widely accepted and utilized all over the world and a lot of practical LCA case studies have come out. The LCA methodologies have been deeply developed, in which the matrix method is one of the effective methods for Life Cycle Inventory (LCI) analysis. Compared with other LCI analysis methods, the matrix method has many unique merits. For instance, 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 cumulative environmental loads in each process. By using the matrix method, it becomes easier to realize the sensitivity analysis and uncertainty analysis in LCA than other methods. Although the matrix method has many merits, it 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 that have not been resolved yet in the matrix method. For instance, there is yet no general and consistent method for matrices composition in LCI analysis.

In this thesis, the aim is to develop a complete, practical and effective matrix method for LCI analysis, which is easier to use in a practical LCA case study. Based on the developed 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, a general purpose LCA system is developed. Finally, by carrying out two practical LCA case studies of product and service, how the developed LCA methodologies and LCA software can be utilized is demonstrated. The practicability and effectiveness of the LCA methodologies and the software in a practical LCA case study is examined and confirmed as well.

The thesis is composed of total 6 chapters. The summary of each chapter is stated as follows.

Chapter 1: General introduction

In the first chapter, the background of the technique of environmental assessment based on LCA is simply introduced. The problems in the conventional LCA are discussed. The aim of the thesis is proposed and the structure of the thesis is shown as well.

Chapter 2: Development of a practical approach for matrix-based LCI analysis

In Chapter 2, firstly, the conventional matrix methods for LCI analysis are reviewed and the problems in them 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 $\boldsymbol{\gamma}$, 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 matrix method respectively. The practicability and effectiveness of the present matrix method are examined. By comparing the two kind of analysis, the merits of the present one is shown clearly as well. The concepts of ‘functional flow’ and ‘surplus flow’ are firstly defined in this thesis.

As a result, the matrix method for LCI analysis becomes more appropriate to deal with 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. It is the 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 as follows.

Chapter 3: Generalization of sensitivity and uncertainty analysis in the matrix-based LCI analysis

In this chapter, based on the matrix method proposed 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 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, from which 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 improved matrix method, the operations from LCI analysis to sensitivity and uncertainty analysis are connected to facilitate the LCA analysis.

Chapter 4: Development of a general and consistent method for system boundary definition in LCA

In this chapter, the matrix method for LCI analysis proposed in chapter 2 is combined with the conventional 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 product system boundary is proposed. A general procedure for system boundary definition in LCA is proposed as well. Using the combined method of the matrix method and IOA method, the system boundary is defined by an iterative process. Consequently, the product system for LCA 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 a desktop computer and a refrigerator are performed to demonstrate the applicability of the proposed method.

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

Chapter 5: Practical application of the matrix method for LCI Analysis

The matrix-based LCA methodologies developed above 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 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 the software in a practical case study of a product are examined and confirmed. The developed matrix-based LCA methodologies and the software can also be easily applied to the LCA case study of services, if the operations of service are expresses 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 which how the matrix-based LCA methodologies are applied to the LCA case study of services is shown. 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.

Chapter 6: Conclusions

In this chapter, the conclusions of the thesis are drawn and the possible directions of future research on LCA are stated.