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Analysis of uncertainty in material flow analysis

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ABSTRACT

Material flow analysis (MFA) is a method of depicting the flow of materials in the anthroposphere and the environment to support environmental management. However, MFA results can contain uncertainties that may be related to the investigation method, calculation process, data quality, data source, or study assumptions. Uncertainty is already an important consideration in tools for environmental management; for example, Life Cycle Analysis (LCA) has prompted research discussions related to the uncertainty in databases, periods and characteristic factors. However, few studies have addressed the uncertainty in MFA. The uncertainty issue in MFA is increasingly important to policy makers coping with resource management issues. The objectives of this research are to perform uncertainty analysis for data sets of different materials in MFA and to compare the results of two important uncertainty analysis methods, the Hedbrant and Sörme (HS) method and Monte Carlo (MC) simulation. In addition, we provide suggestions for research regarding MFA uncertainty analyses in the future.

The uncertainty range and likely values of flow data can vary considerably based on the HS method or MC simulation. After analyzing the relationship between the uncertainty range and flow data, likely values can be derived via comparisons of uncertainty method processes, and the uncertainty analysis results of the HS may deviate greatly from those of the MC method. In this scenario, MC simulation is needed to analyze MFA uncertainty, although it requires greater efforts. The results presented here provide new insights and recommendations for further MFA research.

1. Introduction

Material flow analysis (MFA) is a method widely used in environmental management and can be applied to material input and output process analyses, material use and stock calculations and hotspot assessments (Zhang, 2013). MFA has also been adopted in many resource management studies, and such analyses can provide new research findings and information for policymakers. Additionally, the method can clarify the structure, processes and flows in a system of materials, and the results can be combined with other tools, such as health risk assessments (Cumo et al., 2012) to conduct more detailed studies. Moreover, MFA has been used in socioeconomic metabolism studies and industrial ecology research as a scientific support tool for environmental policy and management over the past decade (Patrício et al., 2015).

The MFA process involves (1) defining a system boundary, (2) capturing the system structure and flows, (3) investigating database and calculation, and (4) analyzing material system processes and performing system balances (Brunner and Ma, 2004). However, uncertainties can occur in the third step that arise from the investigation methods, calculation processes, data quality, data resources, or study assumptions. For example, differences in data resources or insufficient information could introduce substantial uncertainty into the analysis results.

Most of the literature on MFA has indicated that uncertainty has a significant effect on the analysis results, although studies have also demonstrated the difficulty of identifying a solution or qualifying the range of uncertainty. For example, database quality was a substantial source of uncertainty in a study of copper flows in the United States (Spatari et al., 2005), and differences in the data resources and data quality have generated uncertainty, as highlighted in many MFA studies (Chen and Graedel, 2012; Fujimori and Matsuoka, 2007; Gloser et al., 2013; Kahhat and Williams, 2012; Kalmykova et al., 2012; Laner and Cencic, 2013; Liang et al., 2012; Liu et al., 2007; Ma et al., 2012; Schmid Neset et al., 2008; Senthilkumar et al., 2012). Few studies have discussed how to systematically analyze MFA uncertainty issues (Laner et al., 2014; Rechberger et al., 2014). Although these studies have highlighted

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MFA uncertainty issues, these issues require in-depth analysis in future research. Moreover, few studies have presented methods of assessing uncertainty in MFA using case studies. Four methods of assessing uncertainty in MFA have been discussed.

1.1. Uncertainty determined by experience or previous research

This method is usually applied in research when the source of uncertainty has been identified and parameters or functions can be derived from the literature to calibrate the results. For example, a research study of the main element flows in Demark included initial assumptions on the minimum and maximum percentage of each flow and then investigated the results to ensure that the data fell within the proper range (Hansen and Lassen, 2003). Research into the copper flows in several countries using MFA produced different percentages for the uncertainty ranges of different flows, and the accuracy of the results was compared in the discussion sections of the published studies (Graedel et al., 2004). The uncertainty ranges can vary due to different material system structures and flows, as has been highlighted in many MFA studies (Bonnin et al., 2013; Chancerel et al., 2009; Lifset et al., 2012; Månsson et al., 2009; Montangero et al., 2007; Ott and Rechberger, 2012). The method appears to be more logical because the uncertainty range should differ at different material system levels and in different areas. However, the method is limited because of the difficulty associated with obtaining correct local parameters for each flow.

1.2. Hedbrant and Sörme (HS) method

This method was developed by Hedbrant and Sörme (2001) and can provide suggestions for the treatment of uncertainty caused by different data resources and limited data. The method provides the interval value for every data resource. Six levels are included in this study. At level zero, the source of information is scientific knowledge; therefore, no interval is used in this level. At level 1, the source of information is official statistics on a local level or information from authorities/construction or production facilities, and the interval at this level is 1.1. At level 2, the interval is 1.33, and the source of information is official statistics on local, regional and national levels. At level 3, the interval is 2, and the information is based on official statistics at the national level downscaled to the local level. At level 4, the interval is 4, and information is sourced from requests made by authorities/construction or production facilities. Finally, at level 5, the interval is 10, and the source of information is specific, such as the Cd content in Zn in a type of good, e.g., galvanized goods. For example, if a flow data value of '100 tons' is determined at the national level but used at the local scale, the interval value is two and the uncertainty range varies from 50 to 200.

This method has been used in some studies, but complications were encountered when this method was used to analyze the uncertainty range. A study of stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system used this method to analyze and qualify the uncertainty range caused by a lack of data and different data resources (Antikainen et al., 2005). The uncertainty range in this study could be more than 50% for each flow; thus, it could be difficult to establish resource management policies. Some other studies noted similar situations (Asmala and Saikku, 2010; Cooper and Carliell-Marquet, 2013; Patrício et al., 2015), and some doubts exist. For example, 'can the intervals be used for all materials?' and 'is this method suitable for different countries or areas?' Therefore, although the HS method is a simple method for understanding an uncertainty range, if the uncertainty range is too large, then the difficulty of creating management policies increases. Additionally, the suitability of this method for different countries and materials must be verified.

1.3. Monte Carlo simulation method

This method is used to analyze data uncertainty via a computational model. The simulation produces the probability distribution (e.g., normal, lognormal or beta distribution) and characteristics of the data, as well as the uncertainty range. It can also be used to perform data sensitivity analysis.

The Monte Carlo (MC) method can be best used if the dataset contains more than 30 records (Montangero and Belevi, 2008). The Monte Carlo method uses observation data to simulate the distribution, and then the uncertainty range is calculated. This method was used in a nutrient MFA study to perform a sensitivity analysis (Montangero and Belevi, 2008). This application is common in MFA research with sufficient data (Refsgaard et al., 2007; Schaffner et al., 2009; Tsai and Krogmann, 2013; Wu et al., 2014). The Monte Carlo method can provide the uncertainty range that is close to that of the observed data. However, because observation data are often limited in MFA, it is difficult to employ this method generally.

1.4. Combination of two or more methodologies

Each of the above uncertainty analysis methods has strengths and weaknesses. Thus, combining multiple methods can allow the advantages of each method to be exploited.

In one study, an MC simulation and the HS method were combined in the analysis of copper flows (Lin, 2012). The HS method was first applied to calculate the mean, minimum and maximum data values. Then, MC simulation was used to simulate the distribution and calculate the uncertainty range.

But the limitation of these uncertainty analysis methods would both exist. Thus use combination of two or more methodologies is more difficult in quantifying the uncertainty range of MFA results.

Overall, the HS method and MC simulation are mostly commonly used for uncertainty analysis in MFA. The MC simulation method provides the uncertainty range based on observation data and is deemed the preferred method. Thus, it is necessary to verify the uncertainty ranges provided by the HS method against the MC method. The uncertainty issue in MFA is increasingly important for policy makers to cope with resource management issues. This research performs uncertainty analyses of data sets for different uncertainty quantification methods and different materials in MFA. The results of the two uncertainty analysis methods, the Hedbrant and Sörme (HS) method and the Monte Carlo (MC) simulation method, are then compared. Moreover, we provide suggestions for research regarding MFA uncertainty analyses in the future.

2. Material and methods

2.1. Materials used in the study

A target material is normally a material that is frequently used or could cause health risks to humans or the environment. Cement, copper (Cu), nitrogen (N), phosphorous (P) and lead (Pb) are selected in this study after considering the available data and urban characteristics.

Cement is a material used in urban areas that persists for a long time. This material is an important resource in urban areas, but the associated waste could cause problems in the urban environment (Wang et al., 2016). There is approximately one million tons of cement input into Taipei City.

There is approximately 0.2 million tons of copper input into