Waste input-output model at substance level

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Abstract

This paper proposes a waste input-output model at the substance level (WIOS) that considers the substance composition of wastes. Because the change of substance composition in the waste treatment processes potentially affects the life cycle inventory of waste treatment, the proposed model is expected to obtain more accurate results than the hybrid models that did not consider the substance composition. In addition, this model provides a method to trace the substances of waste in treatment processes by using hybrid input-output model. For illustration, the WIOS is applied to wastewater treatment. The calculation result shows that the change of substance composition significantly affects the total environmental loads caused by wastewater treatment. This result is different with the simulation result given by

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current existing hybrid input-output models that did not consider the change of substance composition in wastewater.

Keywords: hybrid, waste treatment, substance, input-output model

1 Introduction

In the field of life cycle assessment (LCA), as the change of substance composition in the waste treatment process potentially affects the inventory results of waste treatment, modeling this change is an important issue. For instance, the inputs of the auxiliary fuel to the incinerator of sludge depend on the composition of wastewater (Metcalf & Eddy, inc, 2003). Thus, in the studies of process-based LCA of waste treatment, such as Finnveden et al. (1995), Tanaka and Matsuto (1998), and Köhler et al. (2007), the substance composition of waste was considered. Additionally, Huang et al. (1999), Galan and Grossmann (1998), Hernandez-Suarez et al. (2004), and Lim et al. (2008), use the mathematical structure to analyze the treatment processes of substances in wastewater. However, the boundary selection problem of process-based LCA has been an important obstacle for comparative assessment to be disclosed to the public (Geneva, 1997). Under this background, hybrid LCA based on the input-output analysis (IOA) is introduced to ease the arbitrariness of the definition of system boundary (Suh, 2004; Suh et al., 2004). As the authors' knowledge, few studies of hybrid LCA of waste treatment, however, modeled the composition of substance contained in the waste. This is because the processes added to input-output sectors were normally classified by the treatment methods but not the composition of waste.

Waste input-output model (WIO) proposed by Nakamura and Kondo (2002) is an asymmetric model that considers both waste and treatment processes. Importantly, it needs not keep a one-to-one corresponding relationship between waste types and treatment processes. This mathematical structure provides a starting point to consider the substances in the treatment processes, if we define the substances as "wastes". Until now, the currently existing WIO did not go to the substance level. A potential uncertainty of this type of treatment is that in the linear WIO, the input coefficients of a given process were not influenced by the composition of waste. The authors of WIO noticed this problem and proposed nonlinearity by an engineering model (Nakamura and Kondo, 2002; Kondo and Nakamura, 2005). However, although the complication of Japanese WIO table (Nakamura and Kondo, 2002) and few studies about the WIO (Kondo and Nakamura, 2005) considered the nonlinearity by using the engineering model of the municipal solid waste management (Tanaka and Matsuto, 1998), most of the applications based on WIO, such as Takase et al. (2005) and Lin (2009), still remain in the linear part.

Under this background, this paper proposes a new method based on linear WIO to consider the composition of waste, named waste input-output model at the substance level (WIOS). The principle of the model is to disaggregate the waste into the substance level. For instance, instead of considering iron scrap as a whole, this model considers iron, carbon, and phosphorus, separately. This principle is similar to the substance flow analysis in the context of the material flow analysis (Brunner and Rechberger, 2004). Thus, the significance of the new method is not limited to the acquirement of accurate results for the life cycle inventory of waste treatment. Tracing the substance flows by using hybrid IO model is another feature of this model.

Wastewater is characterized by the wide range of its composition, especially in extreme cases, e.g., the storm (Metcalf & Eddy, inc, 2003). In the hybrid IO models given by Duchin (1990) and Lin (2009), wastewater is pre-classified by the composition, the change of the composition of one pre-defined wastewater type, however, has not been considered. Because of the changeability of the wastewater composition, this paper illustrates our method by applying it to the wastewater treatment system. We introduce the framework and compilation method in section 2. Next, the application of the compilation method is described with the German data of wastewater treatment in section 3. Finally, discussion are presented.

2 The model

2.1 Structure of the waste input output model at the substance level

In WIOS, we disaggregate the waste into the substance level. The input-s and by-products of treatment processes are related to both waste types and substances contained in the waste. For instance, the treatment of organic carbon in raw wastewater is different from that in the effluent from the first treatment. Substances in different processes are considered as d-ifferent types of wastes in this model. Therefore, all the combinations of substances and wastes after treatment processes are considered. As shown in table **??**, we take into consideration the combinations of the substance 1 to substance n_s and waste 1 to waste n_w, as the added row sectors. In the following part of this paper, we called these combinations waste-substances. Meanwhile, the quantity of wastes is potentially related to the inputs. For instance, the volume of wastewater is related to the electricity usage by the pump facility of the treatment plant. Thus, the "quantity" is also considered as a "substance". Furthermore, we consider all the combinations of substances and treatment processes, because the substance in the different waste is treated by the different treatment processes. As shown in table **??**, under each substance there are all the treatment processes, from "treatment 1" to "treatment n_t", as the added column sectors.

Table 1 shows the framework of WIOS. $A_{I,I}$ is the input coefficient matrix of production sectors, whose (i, j)-component refers to the input from production sector i per unit of output of production sector j. $A_{I,II}$ is the input coefficient matrix of treatment processes, which measures the inputs used by different treatment processes for the treatment of one unit of waste-substance. $G_{W,I}$ refers to the waste-substance generated by one unit of output of production sectors, while $G_{W,II}$ denotes to the waste-substance generated by one unit of treatment. $X_{I,F}$ is the final demand for production sectors and $W_{W,F}$ is the waste-substance generated by the final demand sectors. The environmental loads are recorded by $R_{\cdot,\cdot}$.

The WIOS also needs not to keep a one-to-one corresponding relationship between types of waste-substances and the treatment processes. In accordance with WIO, we defined an allocation matrix S to allocate waste-substances to treatment processes. Table 2 shows the framework of the allocation matrix. In order to be consistent with table 1, we still take the combinations of substances and waste after treatment processes and the combinations of substances and treatment processes as the first row and first column respectively in table 2. The allocation matrix in the WIOS thus can be seen as the combination of the allocation matrix of each waste-substance. Every allocation matrix of the waste-substance has the same structure and characteristics with that of the WIO. The whole allocation matrix S also has these features including the element in the matrix is non-negative and the sum of each column is equal to unity.

The WIOS is based on the linear WIO, introduced by Nakamura and

Kondo (2002), so the mathematical structure is the same with that of WIO.[1] The environmental loads caused by given exogenous final demand and waste-substance generation are obtained by

$$e = \begin{pmatrix} R_I & R_{II} \end{pmatrix} \left(I - \begin{pmatrix} A_{I,I} & A_{I,II} \\ SG_{W,I} & SG_{W,II} \end{pmatrix} \right)^{-1} \begin{pmatrix} X_{I,F} \\ SW_{W,F} \end{pmatrix} \quad (1)$$

It should be noted that the principle of the classification of the wastes and the treatment processes of the WIOS is different with the WIO. The former focuses on the substance level. When we apply the WIOS to the LCA of waste treatment, $W_{W,F}$ is considered as the amount of waste into the gate of the waste treatment plant.

[1] It should be noted that in the general IOA cases, we are discussing the non-singularity of (I-A). Similarly, in the context of WIO or WIOS, we are discussing the non-singularity of $\left(I - \begin{pmatrix} A_{I,I} & A_{I,II} \\ SG_{W,I} & SG_{W,II} \end{pmatrix} \right)$ rather than $\begin{pmatrix} A_{I,I} & A_{I,II} \\ SG_{W,I} & SG_{W,II} \end{pmatrix}$. The identities in I with regard to economic sectors refer to one unit of production of economic sectors, similarly the identities with regards to the treatment processes refer to treatment of one unit of waste. The proof of the solvability of equation 1 is the same with that of $x = (I - A)^{-1} f$ in the general IOA. Actually, the WIO structure can potentially avoid the negative elements in A, which can let the matrix to satisfy the nonnegative condition of Nikkaido theorem (Nakamura and Kondo, 2009).

3 An application of WIOS to wastewater treatment

3.1 Data and model design

In this study, we apply WIOS to wastewater treatment as an illustration. The inventory data given by Köhler et al. (2007) at the substance level are used to construct the WIOS for the wastewater treatment of Ciba Secialty Chemicals in Germany, along with the technical coefficient matrix for production sectors given by German IO table of 2007 (Statistisches Bundesamt Deutschland, 2007), which includes 59 production sectors. Meanwhile, the total organic carbon (TOC) release of production sectors are estimated from elementary flow data of unit-processes given by Ecoinvent database (Frischknecht et al., 2005). The wastewater treatment plant (WWTP) analyzed in Köhler et al. (2007), which established in 2003, consists of an extraction process, a nanofiltration process, and a mechanical-biological treatment process. The extraction process is used to remove the recalcitrant organic pollutants. The nanofiltration process is a pure physical separation process to remove organic pollutants. The mechanical-biological treatment process is operated to microbiologically decompose organic substances and remove nitrogen compounds. In the treatment process, however, the wastewater classified by the concentration of TOC, so we have two types of wastewater — wastewater (TOC <5g/L) and wastewater (TOC 9g/L-10g/L). Because the inputs and outputs of the mechanical-biological treatment process of the effluent from the extraction and nanofiltration processes are different, we consider them as different processes. According to this, in our model, we define 4 treatment processes, which are extraction, nanofiltration, mechanical-biological treatment E, and mechanical-biological treatment N. Mechanical-biological treatment process E refers to the treatment process after the extraction process while mechanical-biological treatment process N refers to treatment process after the nanofiltration processes. When the concentration of TOC in the wastewater is less than 5g/L, the first path is used to treat it, which includes the nanofiltration process and the mechanical-biological treatment process N. When the concentration of TOC is more than 9g/L but less than 10g/L, the second path is used to treat it, which includes the extraction process and the mechanical-biological treatment process E. It should be noted that the calculation structure of WIOS is a linear model. In the application, we use the WIOS to show the environmental loads due to two types of wastewater. They are considered as two scenarios using the same model structure. Because of the usage of different allocation matrices, the change in the application can be considered as a nonlinear process.

7 types of substances are considered. They are wastewater volume, $TOC_{refractory}$, $TOC_{degradable}$, $NH_4^+ - N$, $NO_3^- - N$, $NO_2^- - N$, and $PO_4^{3-} - P$. TOC measures the amount of carbon bound in an organic compound and is often used as a non-specific indicator of water quality or cleanliness of pharmaceutical manufacturing equipment (Association et al., 1912). Two types of TOC are

considered in this paper: $\mathrm{TOC}_{\mathrm{refractory}}$ and $\mathrm{TOC}_{\mathrm{degradable}}$. Meanwhile we take TOC discharged by the production sectors and treatment processes as the indicator to measure the environmental loads.

In summary, 59 production sectors, 7 substances, and 4 treatment processes are considered in our application. As the space is limited, an aggregated version, which includes 3 production sectors, 7 substances, and 4 treatment processes, is shown in table 3. As mentioned above, $A_{I,II}$ measures the input for one unit of waste-substance of of each process in monetary terms. Because the process data we used from the paper of Köhler et al. (2007) is measured in physical terms, we obtain the data of the prices of each input through the paper of Smith and Varbanov (2005) and the database of IChemE Education Subject Group (2002). In order to treat one kg of $\mathrm{TOC}_{\mathrm{refractory}}$, 0.073 Euros inputs from the secondary industry is used by the extraction process. In this paper, we assume that the wastewater generated by production sectors are treated by themselves instead of entering the WWTP under study. Thus, the middle-left part of table 3, which refers to the waste-substance generation coefficient of production sectors, $G_{W,I}$, are zeros. Meanwhile, their TOC release after treatment is considered as environmental loads, which is recorded in R_I. The generation coefficient of waste-substances from treatment processes is used to record the substance generation by one unit of treatment. One minus the above-mentioned coefficient equals the removal rate of treatment processes. For instance, 3.5 % of $\mathrm{TOC}_{\mathrm{refractory}}$ is remained after the extraction process. This indicates that 96.5 % of $\mathrm{TOC}_{\mathrm{refractory}}$ is removed by the extraction process. It should be noted that the volume of wastewater does not change in the treatment processes. As our model is a hybrid model that includes IO, the production of upstream inputs is include in the system boundary. The downstream treatment processes, such as sludge treatment was not considered in this application.

3.2 Result

By using equation 1, we calculate the total TOC release (the environmental loads) caused by the treatment of raw wastewater with different TOC concentration. The results are illustrated in figure **??** and **??**. In these figures, the exogenous variables $\mathrm{TOC}_{\mathrm{refractory}}$ and $\mathrm{TOC}_{\mathrm{degradable}}$ are shown in x-axis and y-axis, respectively. As the wastewater is treated by two different pathes due to the range of TOC concentration, we use two figures to illustrate the results. Figure **??** is the environmental load of wastewater (TOC<5g/L), while figure **??** is that of the wastewater (TOC 9g/L-10g/L). The slopes of the two figures illustrate that different concentration of TOC causes different environmental loads. This is significantly different with the model that did not consider the change of the concentration of substance in the wastewater, such as Duchin (1990) and Lin (2009, 2011). In those models, because the environmental loads are not affected by the composition of substances, if we draw the same figure, a horizontal surface will be shown.

The environmental load is related not only with the substances but also the volume of wastewater. Fixed other factors, we changed the volume of wastewater from 0.5 billion m^3 to 1 billion m^3. With the increase of the volume, the environmental loads of the two figures are both larger than before. The change of volume affects both the level of environmental loads and the slopes of the surfaces. When the volume of wastewater doubles, the environmental loads related to the volume double. As a result, the slopes of the surfaces are larger than before. As an exogenous factor, the technology will also affect the model. When the treatment methods changes from above-mentioned path 1 to path 2 because of the change of TOC concentration, both the slopes and the level of the surfaces are changed.

4 Conclusion and discussion

The principle of our new model is to disaggregate wastes into the substance level and define them as the new "waste" in WIOS, by using the unit-process data at the substance level provided by the academic researches and reports, such as Tanaka and Matsuto (1998) and Köhler et al. (2007). Meanwhile, the total volume or mass of the waste is still related to the inputs to the treatment activities. For instance the electricity for secondary wastewater treatment is related to the total quantity of wastewater. Thus, the proposed model focus not only on the substance composition of wastes but also the quantity of the wastes.

The WIOS can measure the treatment processes and environmental loads in a more accurate way. Meanwhile, the WIOS traces the source and destination of crucial substances, which is highly useful in the waste management (Brunner and Ma, 2009). By using the data given by Köhler et al. (2007) and German IO table of 2007, we build the WIOS for wastewater treatment. The result shows that the environmental load is affected by the concentration of TOC. This is significantly different with the simulation result given by the hybrid model that did not take the concentration into account.

The WIOS can be considered as an extension of WIO, which involves the engineering model(e.g. the engineering model of wastewater (Köhler et al., 2007) or the engineering model of municipal solid waste management (Tanaka and Matsuto, 1998)) into the linear calculation system. In other words, the WIOS decides the composition of waste and the use of treatment inputs endogenously by involving an engineering model at substance level. As a limitation of the current WIOS, the generation of wastewater by the economic sectors was not considered. Because the wastewater is disaggregated into substance level in the WIOS, if data is available, technically we can consider the composition change of the wastewater due to the production of the treatment inputs.

A number of limitations of this study and future research areas are due. First, the application of WIOS needs high quality data at the substance level. When we want to apply the WIOS to other examples, such as analyzing the amounts of crude oil input and ash generation per unit of waste at an incineration process that are generally affected by the composition of waste, the engineering model or data about this topic at substance level is necessary.

Modeling the most relevant substances separately and the others as a whole is a solution of the data quality problem. Second, in some cases the effects of substances are not independent (Metcalf & Eddy, inc, 2003). A model that is able to consider this situation is an important future direction. Third, in the application of WIOS to wastewater only one type of environmental loads was considered, inclusion of other environmental loads such as the release of $NH_4^+ - N$, CO_2, and heavy metals is another future direction.

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