Resources, Conservation & Recycling 139 (2018) 326–332

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Toward an integrated model of the circular economy: Dynamic waste input–output

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ARTICLE INFO

Keywords:
Scrap
Alloy
Refinery
Resource efficiency
Input–output economics

ABSTRACT

Since its development at the end of the previous century, the waste input–output (WIO) model has been extended to wide areas of industrial ecology including material flow analysis (MFA), life-cycle costing (LCC), regional analysis, and linear programming (LP)-based technology selection. To our knowledge, the dynamics of waste generation and recycling is an area of possible conceptual extension that remains least explored. Building upon our recent work on dynamic MFA, in this work, we develop a dynamic WIO (dWIO) model that fully considers the issue of quality in recycling that involves mixing, dissipation, and contamination.

1. Introduction

Building upon the Leontief–Duchin environmental input–output (EIO) model (Leontief, 1970; Duchin, 1990), Nakamura (1999) and Nakamura and Kondo (2002) developed the waste input–output (WIO) model to incorporate the end-of-life phase of products involving waste management and recycling into IO, making IO applicable to all the phases of a product's life, which are production, use, and end of life (EoL). Whereas only a numerical example was presented by Duchin (1990), Nakamura and Kondo (2002) developed the first real WIO account table based on a Japanese IO table that involves 78 producing sectors, 34 waste types, and 5 waste treatment sectors. A system engineering model of waste incineration was used to represent the quantitative relationships among waste composition, the amounts of inputs required for incineration, and the residues generated. The development of WIO data and their publication in the Internet have resulted in numerous applications in Japan (Kondo and Nakamura, 2004; Kagawa et al., 2007; Tsukui et al., 2015). Furthermore, WIO has been adopted as the format for compiling the flows referring to waste and waste management by the Government of Japan (Ministry of the Environment, Government of Japan, 2017). Applications to countries/regions outside Japan include Salemdeeb et al. (2016) for the UK, Liao et al. (2015) and Chen et al. (2017) for Taiwan, Fry et al. (2016) for Australia, and Tisserant et al. (2017) for 48 world regions.

Conceptual extensions of WIO have been made, among others, to life-cycle costing (LCC), material flow analysis (MFA), optimization models involving alternative technologies, and regional analysis. Based on the duality of quantity and cost/price models in standard IO, Nakamura and Kondo (2006b) developed the cost-and-price counterpart of WIO, called the WIO-cost model. Consideration of the EoL costs including recycling distinguishes the WIO-cost model from the standard IO-cost model. This feature makes it an IO-based tool applicable to LCC (Nakamura and Kondo, 2006a; Rebitzer and Nakamura, 2008; Settanni, 2008; Heijungs et al., 2013).

While MFA is conceptually closely related to IO (Scholz, 2011, p. 314), the use of standard IO tables, which are based on monetary units, appears to have delayed its introduction into MFA studies. For instance, the well-known textbook on MFA by Paul Brunner (Brunner and Rechberger, 2004) makes no mention of IO, though attempts have been made to develop IO tables based on physical units, the physical input–output table (PIOT), for establishing links between IO and MFA (Statistisches Bundesamt, 2001; Giljum and Hubacek, 2009). However, Weisz and Duchin (2006) showed that, under standard conditions in the IO-cost model, a PIOT can be readily obtained from its monetary counterpart, eliminating the need for developing a PIOT from scratch, which is a challenging endeavor. Along the line of Weisz and Duchin (2006), Nakamura and Nakajima (2005) and Nakamura et al. (2007) developed a WIO-based method, WIO-MFA, to estimate the material content of products, that is, the masses of materials forming products, which can be used to transform a monetary IO into a PIOT in terms of the masses of the materials of concern. The basic idea behind this tool is simple and has been widely used since the 1970s at the latest (Carter, 1970). WIO-MFA is distinguished by its exploitation of triangular properties of the IO matrix (Simpson and Tsukui, 1965), which allows calculating embodied materials without double-counting. Explicit consideration of losses (in metal smelting, manufacturing, waste

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https://doi.org/10.1016/j.resconrec.2018.07.016
Received 28 February 2018; Received in revised form 21 June 2018; Accepted 14 July 2018

management, and recycling) establishes close links of this method with WIO. The latest applications of WIO-MFA include alloys for metal networks in the US economy (Ohno et al., 2016), inter-sectoral bisphenol A (BPA) flows in the Chinese economy (Jiang et al., 2017), and aluminum flows in the US economy (Chen et al., 2016).

The relaxation of the rigid square technology matrix with a rectangular one allowing for the possibility of technology choice dates back to the 1950s, when the so-called "substitution theorem" was a topic of active discussion among leading economic theorists of that time (Koopmans, 1951). The linear nature of IO makes this relaxation a typical linear programming (LP) problem. Within the context of WIO, its LP-based extension, WIO-LP, was first introduced by Kondo and Nakamura (2005) to consider the optimum selection of recycling/treatment technologies for waste electric and electronics equipment (WEEE). Subsequently, WIO-LP was used by Lin (2011) to identify the Pareto frontier with regard to wastewater treatment, and by Ohno et al. (2017) to identify the optimal allocation of EoL vehicle (ELV) parts to scrap categories for minimizing the emissions associated with metal production.

To our knowledge, the area of possible conceptual extensions of WIO that remains least explored is the dynamics of waste generation and recycling. WIO in its original form is a static model and does not explain the dynamic process in which durable products become EoL products and are transformed into residues and/or recyclates. Among other limitations, it is not able to address issues of quality in recycling caused by the unintentional mixing of heterogeneous materials/substances that can result in function losses of dissipated materials and the contamination of recycled products (Nakamura et al., 2012). For the case involving alloys and metals, Nakamura et al. (2017) developed a dynamic MFA model, called MaTrace-alloy, that can trace the fate of metals over multiple life cycles under explicit consideration of thermodynamic constraints in metal refining processes. This paper presents a dynamic WIO (dWIO) integrating MaTrce-alloy and static WIO for the first time. The novelty of the dWIO is its capability of explicitly considering the following aspects of recycling: quality issues due to the unintentional mixing of materials, the supply-demand balance of secondary materials, and the flow of goods and services such as energy and chemicals, which are not of primary interest in typical material flow analyses.

2. Static WIO and its limits for dynamic analysis

2.1. Static WIO

Table 1 presents a schematic WIO account with n_1 producing sectors (each producing a single product), n_2 waste treatment sectors, $n_y = 1$ final demand sector, and n_w waste categories. The set of n_1 products is denoted by "1" and that of n_2 waste treatment sectors by "2." X_1 and y_1 refer to the flows of goods and services among production sectors and the final demand, respectively.

Characteristic to WIO is the occurrence of flows associated with waste and waste treatment, W_1, X_2, W_2, and w_y. W_1 refers to the flow of waste generated and/or absorbed by production sectors, with its (i, j) element, w_{ij}, taking a positive value if sector j generates waste i, but a negative value if sector j uses (recycles) waste i. Waste-treatment sectors transform waste from its initial forms into forms of smaller environmental/health impacts; incineration transforms organic waste into ash and emissions, while shredding transforms EoL appliances into metal scrap and waste plastics. W_2 refers to the flow of outputs that result from this transformation, while X_2 refers to the flow of goods and services that are needed for this transformation, such as electricity, gas, and chemicals. Also included in X_2 are products obtained from treatment processes, such as electricity from the waste heat of waste incineration facilities, which occur as negative inputs. Finally, w_y refers to the generation of waste from final demand, such as garbage, wastewater, and EoL products.

Table 1
A schematic WIO account.

	Products (n_1)	Waste treatment (n_2)	Final demand (n_y)
Products (n_1)	X_1	X_2	y_1
Waste (n_w)	W_1	W_2	w_y

Note: The *n*s in the parentheses refer to the number of sectors/categories.

Denoting by x_1 the quantity of n_1 products produced and by w the quantity of n_w waste for treatment, the following balance holds:

$$\begin{pmatrix} X_1 & X_2 \\ W_1 & W_2 \end{pmatrix}\begin{pmatrix} \iota_1 \\ \iota_2 \end{pmatrix} + \begin{pmatrix} y_1 \\ w_y \end{pmatrix} = \begin{pmatrix} x_1 \\ w \end{pmatrix}, \tag{1}$$

where ι_a refers to an $n_a \times 1$ vector of ones used for summation, where the symbol a represents a set of sectors, products, scrap, or waste. An increase in recycling increases the absolute value of negative elements in W, mostly W_1, and reduces w. Denoting by x_2 the activity level of treatment sectors (the quantity of waste treated in each treatment sector), the input coefficient matrices A and waste generation coefficients G are given by

$$A_1 = X_1 \hat{x}_1^{-1}, \quad A_2 = X_2 \hat{x}_2^{-1}, \tag{2}$$

$$G_1 = W_1 \hat{x}_1^{-1}, \quad G_2 = W_2 \hat{x}_2^{-1}, \tag{3}$$

where $\hat{v} = \mathrm{diag}(v)$ refers to the diagonal matrix, the (i, i)-element of which is the i-th element of a vector v. By using A and G obtained as a result, the balance (1) becomes

$$\begin{pmatrix} A_1 & A_2 \\ G_1 & G_2 \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} y_1 \\ w_y \end{pmatrix} = \begin{pmatrix} x_1 \\ w \end{pmatrix}. \tag{4}$$

By definition, the sum of waste for treatment is equal to the sum of waste treated

$$\iota_2^{\mathrm{T}} x_2 = \iota_{\mathrm{w}}^{\mathrm{T}} w, \tag{5}$$

where T is the transpose operator. This is the Duchin–Leontief environmental IO model of waste and waste management (Duchin, 1990).

However, (4) is not solvable unless each waste is exclusively submitted to a single treatment process; that is, $w = x_2$, which is a condition that hardly reflects the reality of waste management. For instance, any solid waste can be landfilled, while several treatment methods can be applied to a given waste: organic waste can be landfilled, incinerated, or composted. Nakamura (1999) and Nakamura and Kondo (2002) solved this problem by introducing the allocation matrix S of order $n_2 \times n_w$ that allocates waste to treatment processes:

$$x_2 = \mathrm{S\,w}. \tag{6}$$

Because waste has to be treated in one way or another (even including illegal dumping if it be regarded as a treatment method), $\iota_2^{\mathrm{T}} S = \iota_{\mathrm{w}}^{\mathrm{T}}$ holds. Note that S is needed to obtain x_2 from w. The application of S transforms (4) into a solvable form, the WIO quantity model:

$$\begin{pmatrix} A_1 & A_2 \\ \mathrm{SG}_1 & \mathrm{SG}_2 \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} y_1 \\ Sw_y \end{pmatrix} = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}, \tag{7}$$

with the solution

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} I - A_1 & -A_2 \\ -SG_1 & I - SG_2 \end{pmatrix}^{-1}\begin{pmatrix} y_1 \\ Sw_y \end{pmatrix}. \tag{8}$$

2.2. Limits of static WIO for dynamic analysis

The WIO outlined above is a static model because it does not involve any index referring to different times: it is not a system of difference/differential equations. Noting that w_y emerges over time, dynamics could be introduced into WIO via the explicit representation of its