Journal of Cleaner Production 94 (2015) 294–303

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Identification of the driving force of waste generation using a high-resolution waste input–output table

Meng-i Liao [a], Pi-cheng Chen [a], Hwong-wen Ma [a, *], Shinichiro Nakamura [b]

[a] Graduate Institute of Environmental Engineering, National Taiwan University, 71 Chou-Shan Road, Taipei 106, Taiwan, ROC
[b] Graduate School of Economics, Waseda University, 1-6-1Nishi-Waseda, Tokyo 169-8050, Japan

A R T I C L E I N F O

Article history:
Received 7 January 2013
Received in revised form
24 August 2014
Accepted 1 February 2015
Available online 10 February 2015

Keywords:
Waste input–output table
Waste generation
Sustainable consumption and production
Final demand

A B S T R A C T

Effective strategic planning for industrial waste management requires sound knowledge of the waste streams in an economy. Based on an input–output analysis with an extended function to consider the entire life cycle of a product, waste input–output (WIO) analysis plays an important role in describing the driving forces behind the generation of industrial waste. In this study, we compile a high-resolution WIO table for Taiwan that traces the flow of waste streams covering almost all types of waste emitted from industries into corresponding waste treatments and that identifies the driving force of waste in the economic system. In addition, we generate a detailed breakdown of the final demand categories into sub-categories to clarify consumption patterns or lifestyles that produce specific waste streams. The results show that export is the main driving force generating industrial waste. This dominance is obvious for "waste acidic etchants" and "copper and copper compounds", of which the electronic parts and components sector is the largest generator. In addition, this study reveals the industries that create the substantial demand for incinerators and landfills. This article illuminates the diagnostic features of the high-resolution WIO table and provides useful insights for linking the WIO and supply chain analysis approaching sustainable consumption and production.

1. Introduction

1.1. Driving forces of waste generation

The perspective of waste management is moving from "end-of pipe" strategies toward a more holistic perspective of sustainable consumption and production, a key effort of the United Nations Environment Programme for current and future policy (UNEP, 2002). This effort addresses not only the producer's responsibility of considering direct emissions from various production processes but also the effects of the consumer in driving indirect emissions through different consumption patterns. Regarding waste management issues, the process-based life cycle approach is frequently used to evaluate the waste generation of a product, from the extraction of raw materials to final disposal. However, it is difficult to identify the driving forces of different types of waste that are embodied in the economic system (Vergragt et al., 2014). Analyzing the mechanisms or factors of waste production that accompany various economic activities is important for developing sustainable waste management strategies and approaching sustainable consumption and production throughout the lifecycle of products.

The interpretation for the contribution of various driving forces to waste generation can have an implication of "footprints". Nakamura and Kondo provided a definition of "waste footprints" as "the amount of waste for treatment that was generated directly and indirectly to deliver a unit of its product to the final demand" (Nakamura and Kondo, 2009). The input–output technique is a viable tool for assessing the direct and indirect effects of consumption and production in an economic system (Hendrickson et al., 2006). Although the conventional input–output analysis (IOA) was originally developed to represent the monetary flows of goods and services between sectors, several environmentally extended input–output methods have incorporated environmental extensions for different environmental issues, such as energy consumption and CO_2 emissions (Jiang et al., 2014), total environmental impacts of consumption (Huppes et al., 2006), material flow and climate impacts (Seppälä et al., 2011) sustainable consumption (Hertwich, 2005), sustainability assessment

* Corresponding author. Tel.: +886 2 2363 0406; fax: +886 2 2392 8830.
E-mail address: hwma@ntu.edu.tw (H.-w. Ma).

http://dx.doi.org/10.1016/j.jclepro.2015.02.002
0959-6526/

(Kucukvar et al., 2014) and multi environmental pressures for specific manufacturing sectors (Egilmez et al., 2013). To account for the issue of waste flows and waste management activities, Nakamura and Kondo developed the waste input–output (WIO) model to analyze waste streams based on the interdependence between goods sectors and waste treatment sectors, and published a paper regarding a detailed theoretical model in 2002 (Nakamura and Kondo, 2002a). Their recent treatises illuminate expansibility on the basis of WIO analysis, such as the integration of material flow analysis (MFA), called the WIO-MFA model. Nakamura et al. described the detailed framework of the linkage in their article (Nakamura et al., 2007) and estimated major final use categories of various metals (Nakamura and Nakajima, 2005) and PVC-embodying products (Nakamura et al., 2009). In addition, Nakajima applied the WIO-MFA model to connect with physical unit input–output analysis to address specific metals simultaneously (Nakajima et al., 2013). Nakajima also combined this model with statistical data to quantify the flows of substances embedded in trade products (Nakajima et al., 2011). The evaluation of the economic and environmental effects (particularly regarding CO_2 emissions and landfill consumption) of different consumption patterns (Takase et al., 2005) or waste management scenarios is another interesting topic in the WIO field. Empirical scenarios include specific combinations of waste treatments and recycling options (Nakamura and Kondo, 2002b), alternative lifecycle strategies of end-of-life electric home appliances (EL-EHA) (Kondo and Nakamura, 2004), and the quality of recovered materials from end-of-life vehicles (ELVs) (Nakamura et al., 2012). The model expands the analytical framework by using a multi-regional model associated with economic benefits and environmental externalities (Kagawa et al., 2007). The WIO model incorporates a new scheme of hybrid life-cycle assessment (LCA) (Nakamura and Kondo, 2002a) that integrates an economic IOA with LCA. Therefore, it is capable of characterizing the flow of different types of waste under a lifecycle perspective and of assessing the direct and indirect generation of waste derived from various types of demand. An additional price analysis provides insights into the extended LCA model, providing life-cycle cost analysis (LCC) to realize whether it is economically affordable to manufacture a product and to achieve sustainability (Nakamura and Kondo, 2006). To support prospective waste management for diverse species of industrial waste, a comprehensive analysis for the driving force of the specific waste generation should address the material cycle and the associated overall economic effects and environmental burdens (such as landfill consumption), which requires an understanding of the complicated inter-sector input–output relationship. Therefore, we highlight the implication of building a high resolution WIO model, which consists of more sophisticated waste types and waste treatments, and aim to trace the flows of detailed waste streams into their corresponding treatments in order to identify the waste embodied in those streams that is driven by each category of final demand.

In addition, the attribution of waste streams to industries supply and consumption demand is imperative to policy makers for waste management (Jensen et al., 2011). Lee investigated direct and indirect lead-containing waste discharge along the supply chain (Lee et al., 2012). Court illustrated the input–output framework can be used to identify waste hotspots in the supply chain (Court et al., 2014).

This study employed two components of the WIO model, which are input coefficient and waste generation coefficient, to evaluate the amount of upstream waste production embodied in the supply chain to the downstream. The extended concern of the WIO analysis to supply chain management may provide a broader perspective on sustainable consumption and production.

1.2. Developing a high-resolution WIO

The Taiwan WIO table is based on a waste database maintained by the Taiwan Environmental Protection Administration (Taiwan EPA). The database features a sophisticated scheme of waste classification. The impetus for designing such an extensive waste database was the urgency of the problem of insufficient landfill sites for extremely dense populations. To solve those problems, the Taiwan EPA initiated a zero industrial waste program in 2003 and declared its determination to approach zero waste production. For better waste monitoring and management, the Taiwan EPA established the “Industrial Waste Control Center” (IWCC) to maintain an online reporting system, which was the first online waste control data system in the world. The waste control data system maintains a waste database of more than 61,000 businesses. In the database, 23,000 registered businesses produced general industrial waste of more than one metric ton per month, on average, or hazardous industrial waste of more than four kilograms per month, on average. Each company is responsible for reporting its information online, including the use of raw materials, the volume of products, operating conditions, the amount and type of waste, storage methods, intermediate treatments, final disposal, and reuse management. This abundant information renders the database a high-resolution waste-monitoring database that will enhance the discrimination of a specific waste stream to building a high-resolution WIO model. Using a high-resolution WIO analysis to investigate the embodied waste of various drivers will enable the assessment of the influence of detailed final demand categories on the direct and indirect generation of specific waste species, which will therefore facilitate the practical planning of prospective waste management strategies.

This paper is structured as follows. Section 2 describes the conceptual framework of a WIO model and the compilation of a Taiwan WIO model. Section 3 presents the Taiwan WIO table with empirical data, and discusses the implication of this high resolution WIO model in supporting waste management. Section 4 summarizes the features of the Taiwan WIO table and provides directions for future research.

2. Methodology

2.1. The concept of a WIO model

Nakamura and Kondo developed the WIO model, which explicitly takes into account the flow of waste and the activities of waste management. The extension of conventional input–output analyses addresses all of the stages of products and takes into account various monetary flows with regard to waste management. A review of the prototype of the WIO model shows that the outputs of goods sectors and waste treatment sectors can be identified using the following equations (Nakamura and Kondo, 2002a):

$$x_I = A_{I,I}x_I + A_{I,II}x_{II} + X_{I,F} \quad (1)$$

$$x_{II} = A_{II,I}x_I + A_{II,II}x_{II} + X_{II,F} \quad (2)$$

$$w = G_{\cdot,I}x_I + G_{\cdot,II}x_{II} + W_{\cdot,F} \quad (3)$$

Let there be n^I goods sectors, n^{II} waste treatment sectors and n^w waste types. The symbol x_I stands for an output vector ($n^I \times 1$) of the goods sectors, and the symbolx_{II} denotes an output vector ($n^{II} \times 1$) of the waste treatment sectors; both x_I and x_{II} are the estimated monetary gross output.$A_{I,I}$,$A_{I,II}$,$A_{II,I}$ and $A_{II,II}$ represent the matrices of input coefficients. The symbols$G_{\cdot,I}$ and $G_{\cdot,II}$ indicate the matrices $n^w \times n^I$ and $n^w \times n^{II}$ of the net waste generation coefficients, which