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The price of byproducts: Distinguishing co-products from waste using the rectangular choice-of-technologies model

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ABSTRACT

The reuse or sale of byproducts is widespread throughout the global economy. Such byproducts are deemed co-products, while unused byproducts are considered waste. This distinction becomes less clear for waste products that can be turned into useable co-products, creating methodological problems for those studying reuse of byproducts using life cycle assessment, material flow analysis, and input-output analysis. Expanding upon the Rectangular Choice-of-Technologies (RCOT) framework (Duchin and Levine, 2011), this paper presents an approach for associating byproducts from the production process of a primary commodity with a distinct technology. This new RCOT method endogenously defines byproducts as co-products or waste depending on the technological and economic capacity to utilize them. By comparing the prices of utilized co-products to unused wastes, this framework provides an explicit way to relate these three concepts while also illustrating how changing economic conditions can change wastes into co-products, and vice-versa. We present a numerical example of this new method for distiller's grains byproducts from ethanol production.

1. Introduction

The production of any good orservice requires various physical inputs, including both raw resources and other produced goods. During the production process, portions of these physical inputs are utilized and become embedded in the final product or service, while others are not. Much of this unused portion is simply discarded and becomes unused waste, while other portions have valuable properties that are used for other goods or services. The same can be said during the use and disposal phase of a product, which, depending on its changing properties and characteristics, is either disposed as waste or transformed once again into another useable product.

Reducing the amount of waste and increasing the reuse of byproducts is generally considered a positive outcome in the sustainability community for a variety of reasons. Waste ends up in landfills and often has negative environmental impacts such as increased greenhouse gas emissions or reduced biodiversity and wildlife (Weng et al., 2015; Porter et al., 2016). In many cases, discarding materials or substances that have valuable properties necessitates the virgin extraction of new resources, which often requires more resource inputs than recycling (Dewulf et al., 2010; Yellishetty et al., 2011; Reck and Graedel, 2012). Strict dependence upon virgin resources can also be unstable, particularly when such resources are regionally scarce or concentrated, threatening the steady availability of essential goods and services (Nassar et al., 2015; Seekell et al., 2017). For these reasons, increasing the "circularity" of production processes through the simultaneous reduction of waste and the reuse of byproducts is being vigorously pursued by the sustainability community, and in particular those within the industrial ecology community (Haas et al., 2015; Ghisellini et al., 2016; Geissdoerfer et al., 2017; Kalmykova et al., 2017; Kirchherr et al., 2017; Bocken et al., 2017). Circular economy is also being pursued by governments, most notably in Europe where the 2018 Circular Economy Action Plan has wide-ranging measures for creating and promoting circular systems (European Commission, 2018).

The search to better quantify the positive and negative impacts of such circular systems has led to a large body work on the representation of byproducts, co-products, and waste within material flow analysis (MFA), life-cycle assessment (LCA), and input-output analysis (IOA). Input-output is often criticized for its inability to represent co-products since each sector and each production process is represented in terms of a single primary output, and such a sector is often aggregated to represent multiple products (Majeau-Bettez et al., 2017). This issue is related to the problem of associating distinct production processes to sectors when producing the input-output total requirements matrix from supply and use tables, which requires making either an industry or commodity technology assumption regarding the input structure of the

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same commodity produced in different industries (Miller and Blair, 2009). Suh et al. (2010) explains a third variation, the "by-product technology" model (Stone, 1961; Leontief and Ford, 1972), which assumes negative values for byproducts inseparable from a given primary production process.

Other methods to represent circular systems have been developed that allow the addition of co-products and waste to environmentally extended input-output analysis. For instance, Konijn et al. (1997) created IO-MFA approach that builds a physical input-output extension to a monetary input-output table for metals and describe primary and secondary activities associated with alternative production processes or activities. This approach has subsequently expanded in recent efforts to associate physical material accounts with multi-regional input-output tables (Schoer et al., 2013; Wiedmann et al., 2015). Still, the MRIO approach does not solve the aggregation problem, which becomes particularly problematic when measuring byproducts in physical units of different types (Merciai and Heijungs, 2014; Majeau-Bettez et al., 2016). Majeau-Bettez et al. (2014) explore variations of allocation assumptions in an IO-LCA framework with variations for linking co-products with explicit production technologies, specifically exploring the ability of various approaches to maintain traceability of co-products throughout a life-cycle network.

One of the more complete and comprehensive solutions to the treatment of byproducts is accomplished with the Waste Input-Output (WIO) model developed by Nakamura and Kondo (2002). WIO proposes a distinct waste matrix, with an allocation matrix that maps any number of wastes to waste treatment methods. This allocation matrix, which, like the MRIO environmental extension approach, is not required to be square and is measured in physical units, not only allows them to specify what products are cycled back into production processes, but distinguish different types of such cycles. For instance, they distinguish byproducts that are reused in the same production process that created them (type I) and byproducts that are cycled into other production processes (type II) (Nakamura and Kondo, 2009). This allows them to explore recycling networks and not just single loops within supply chains. The WIO approach also allows byproducts and waste to be represented in positive units in their allocation matrix, and Nakamura and Kondo clearly discuss the possibility of byproducts becoming waste depending upon their price, with a negative byproduct "price" making it a waste that has a cost of disposal (Nakamura and Kondo, 2002).

The most prominent limitation of all these approaches is the requirement that wastes must be matched with waste treatment *ex ante,* that is, what is deemed both the waste and the treatment option for that waste is determined upfront. Within LCA, this problem is being discussed in the context of attributional vs. consequential approaches (see Majeau-Bettez et al., 2017), and more broadly in the context of prospective or dynamic scenarios of the future (Nakamura and Kondo, 2002; Duchin et al., 2016; Pauliuk and Hertwich, 2016; Nassar et al., 2016). Yet without endogeneity of prices, byproducts must be defined as co-products or waste upfront. This not only is unrealistic, but without costs and prices associated with different waste management technologies for potentially utilizing byproducts, it remains difficult to assess where reducing waste makes the most sense (Bellemare et al., 2017).

This paper presents a solution by presenting the RCOT model with endogenous co-products and waste (RCOT with byproducts). This model is an extension of the RCOT model, an IO-based linear programming approach that allows the representation of distinct technologies for each commodity using any combination of physical or financial units (Duchin and Levine, 2011). Depending on relative technological costs and resource availability, theoretically defined as the comparative advantage of a particular technology in a particular region, this model determines which byproducts can be used economically (co-products) and which cannot (waste). RCOT with byproducts uses this unique capability to associate unique technologies with any number of byproducts also created during each technological process. The same choice-of-technology mechanisms also allows the definition of any number waste management or recycling technologies or processes for transporting, disposing or reusing these byproducts. The price information captured simultaneously in dual of the linear program, which further illustrates the financial rationale for why byproduct may become a waste instead of a coproduct.

This paper will also show how RCOT with byproducts solves many problems often associated with modeling byproducts in input-output analysis. Different degrees of companionability, or the degree of byproduct obtained at the same time as another product (Nassar et al., 2015), can be represented by defining any number of technologies for producing the same product, each with different associated byproduct quantities. Oversubstitution, or co-product production greater than the amount demanded (Suh et al., 2010), is impossible, for byproducts with value below the market price become wastes, even when produced using the same technology in the same region. The aggregation and mass balance problem (Merciai and Heijungs, 2014; Majeau-Bettez et al., 2016) is avoided by associating each technology with physical units in the primal LP solution and monetary units in the LP dual, which are solved simultaneously. We present this new method using an illustrative example for distiller's grains produced as a byproduct of ethanol production from maize.

2. RCOT with byproducts

The standard RCOT formulation shown by Duchin and Levine (2011) minimizes total factor costs in a given economy subject to a) production meeting final demand and b) factors of production not outstripping available resource use. The variables and parameters of the model, with dimensions listed in Table 1, constitute three equations:

$$\text{Minimize}\, z = \sum_i \boldsymbol{\pi}_i{}' \mathbf{F}_i \mathbf{x}_i \tag{1}$$

$$\text{s. t.} \ \sum_i (\mathbf{I} - \boldsymbol{A}_i)\mathbf{x}_i \geq \sum_{\text{i}} \mathbf{y}_{\text{i}} \tag{2}$$

$$\mathbf{F}_i \mathbf{x}_i \leq \mathbf{f}_i \ \ \forall\ i \tag{3}$$

Production $\mathbf{x}_i$ is characterized by a set of t technologies, with at least one technology for each n sector or commodity. Note that in previous RCOT studies, variables and parameters with dimension t are denoted with a star (*), although we forgo that convention here for simplicity. Factor use $\mathbf{F}_i$, or more generically resource use, defines the set of resources k are necessary to produce the commodity with each technology, and hence is dimension t. Factor prices π_i are a vector of resource prices $(k\ x\ 1)$ based on availability at the beginning of that year.

Without a demand to produce, however, minimizing factor costs will result in zero production. The first constraint therefore assures that demand for n commodities, both for final consumption ($\mathbf{y}_i$) and for production of those commodities ($\mathbf{A}_i\mathbf{x}_i$), is at least equal to total production. But regions can also only produce if they have enough resources available (with $\mathbf{A}_i$ having dimension $n\ x\ t$). The second constraint therefore assures that the sum of all factors used for production ($\mathbf{F}_i\mathbf{x}_i$) is less than or equal to than their given endowment of resources $\mathbf{f}_i$ (with $\mathbf{F}_i$ having dimension $k\ x\ t$). As all variations of the RCOT primal, just as in the standard input-output quantity model, units can be either physical or monetary for each commodity.

Yet in reality, each technological process does not only result in the output of a single commodity. Any number of byproducts (*bp*) are also produced, some which are useful elsewhere and some which are considered waste or pollution. To methodologically incorporate byproducts, we create a modified formulation of the standard RCOT model (with an updated list of variables, parameters, and dimensions provided in). Byproducts are explicitly represented with the addition of a byproduct matrix $\mathbf{BP}_i$ $(bp\ x\ t)$ that specifies the amount of each byproduct produced during the production of a commodity using a specific technology. Since the amounts of byproducts depend on the