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Constructing joint production chains: An enterprise input-output approach for alternative energy use

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ABSTRACT

Although there is already an extensive literature on waste and end-of-life (EOL) product recycling methods, the contribution of such methods to the environmental sustainability of entire production chains (PC) seems to have been ignored. Since many PCs belonging to diverse sectors have become more interconnected through recycling, the above mentioned problem is of vital importance to promoting cooperation among the actors of these PCs.

The aim of this paper is to propose several sustainable PC combinations, namely joint production chains (JPCs), and to foresee how potential environmental effects can be mitigated by linking these PCs. To this end, in this paper an enterprise input-output (EIO) model is introduced to evaluate the potential environmental benefits of cooperative actions taken by the actors in these joint production chains (JPC). Moreover, it is aimed that the proposed model serves as a material planning tool for the companies involved in JPCs.

Two main cases are investigated from structural perspective: (i) waste to main product substitution and (ii) EOL product to main product substitution. The proposed model provides dynamicity to input-output coefficients, thereby facilitating the calculation of the impacts of resource use change that stems from waste/main product recycling. This makes the model a novel material planning tool for modelling possible alternative material/energy use scenarios.

Two empirical case examples from second-generation bioenergy PC and EOL tires PC validate the constructed model to demonstrate its applicability.

The results indicate that the proposed model is able to compute not only the direct influence of recycling but also its indirect and resultant consequences on the all processes carried out by the involved actors. Substantial savings of energy and natural resources, and reductions in waste and CO_2 emissions are found in the case examples. The model is particularly useful for implementing policy shifts, planning future material purchasing strategies, and foreseeing the necessary actor involvement to reach complete material substitution for companies.

1. Introduction

In the recent, environmentally conscious manufacturing (ECM), product recovery, and energy recovery have acquired a strong relevance enforced by governmental regulations and customer perspectives on the environment (Gungor and Gupta, 1999).

The consumption of fossil fuels and other natural resources, increasing pollution, and overflowing waste sites have stimulated the necessity for both the design and manufacturing of environmentally friendly products and for 3R (reduce, reuse, recycle) processes to recover the utilisable parts of end-of-life (EOL) products and wastes produced during various production processes.

By the introduction of the ECM concept into various business areas, production chains (PCs) have become extended and more interconnected. In addition, the increased threat of legal liability (Snir, 2001) has been forcing companies to consider waste and EOL products for creating value. The materials obtained from waste and EOL product recycling and remanufacturing are being used in PCs resulting in mutual benefits for the involved companies. The involvement of enterprises requires cooperation not only with the upstream and downstream PC actors but also with the potential partners not used to working together and operating in other PCs.

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Hence, 3R activities gathered various PCs from traditionally separate sectors. In this context, a joint production chain (JPC) can be defined as a unique supply chain constructed via the use of recovered materials and energy sources from 3R activities included in PCs which initially have no relationship in terms of material and energy flows.

So far the use and reuse of materials has been addressed in the literature. In the value chain and supply chain management literature, various terms are introduced within the sustainability context, such as reverse supply chains (i.e. the chain of end-of-life main product recovery, Guide and Van Wassenhove, 2002; Prahinski and Kocabasoglu, 2006), closed-loop supply chains (i.e. chains consisting of a traditional and a reverse supply chain, Krikke et al., 2004; Guide and Van Wassenhove, 2006) or supply loops (i.e. product end-of life management strategies fulfilling the criteria of value recovery and the use of recovered materials in forward chains, Geyer and Jackson, 2004). However, JPCs are not addressed in this literature.

Although companies have technological skills on recovering materials, they generally have difficulty in anticipating the overall benefits of linking PCs. This represents an obstacle to cooperation initiatives which mostly originate in the lack of knowledge about the profile of potential partners (e.g. production structure, used primary inputs, waste composition). Corbett and Kleindorfer (2001) notice that extended PCs lead to more interconnection, so widening the complexity of the system. This would increase the difficulty of tracing all inputs, outputs, and the associated impacts of their use in various processes, which is crucial to design the extended chain and to plan its future material and energy flows. This is also critical to anticipate the associated economic returns of JPCs since waste or EOL products are not produced upon demand but appear as a secondary output of production activities.

Above-sketched problem calls for a dynamic planning tool which is able to trace the primary inputs, main products, energy, and waste streams within JPCs. Bailey et al. (2004) state that the useful capability of input-output (IO) approach that distinguishes it from other methods is that it dissects complicated systems of physical flows and effectively traces the path of flows. In this paper, we adopt the enterprise input-output (EIO) modelling which is an effective approach for computing environmental payoffs of single firms, PCs, or industrial zones at production process level (see Section 2.1. for IO and EIO literature).

Then, from an IO perspective, we categorise and analyse JPCs in two groups: (1) JPCs incorporating waste recycling, and (2) JPCs incorporating EOL main product recycling. A dynamic EIO model with two stages is proposed in this paper, i.e. initial non-cooperation stage and cooperation for JPC construction stage. In the cooperation phase, waste or EOL product is recycled and reused within the JPC, causing changes in material and energy flows of traditional production processes and their associated environmental impact. The EIO model allows us to anticipate such changes being capable of predicting the future impacts of resource use change in production processes. Besides, such a tool would allow companies to forecast the required waste quantities and anticipate the necessary number of potential partners for complete resource substitution (i.e. total amount of a waste or an EOL main product of a PC substitutes the total amount of a specific main input of another PC). Similarly, it can also be used for reaching targeted substitution rates which may be planned by governments (e.g. land use change for energy-containing crops cultivation in a region). Therefore, it is also beneficial for policy-makers and governmental bodies – particularly those involved in environmental law-making – to monitor the timely advancements for environmental targets. The applicability of the model is demonstrated in two empirical case examples from bioenergy and cement PCs, each representing one category of JPCs.

This paper's remainder is as follows. Section 2 provides a short introduction to IO and EIO models followed by the model description for JPCs. In Section 3, two empirical case examples are analysed. Results, findings, and shortcomings of the paper are discussed in Section 4. The paper concludes by summarizing the methodological, managerial, political, and practical contributions, and recommending future research in Section 5.

2. Enterprise input-output (EIO) model for joint production chains

Input-Output (IO) models are firstly used by Wassily Leontief as an accounting system which is characterised by a double-entry bookkeeping principle that emphasises general equilibrium phenomena (Leontief, 1936). Hence, it is firstly based on IO tables as an accounting tool. Ten Raa (2006) supports that this is a main tool that helps us to answer different questions that pertain the economy as a whole such as the efficiency and productivity, or how these measures are affected when environmental constraints are taken into account. For an introduction to IO modelling see Miller and Blair (2009), for a broad selection of seminal papers, see Kurz et al. (1998).

In the late 1990s and early 2000s, Enterprise Input-Output (EIO) approach was also introduced as a tool to analyse all sorts of questions within a production unit (Lin and Polenske, 1998), an enterprise (e.g. Marangoni and Fezzi, 2002), a group of enterprises (e.g. Marangoni et al., 2004), and industrial districts (e.g. Albino et al., 2003), or a supply chain (Grubbström and Tang, 2000). In particular, Polenske and McMichael (2002) built an IO model for a coke making plant and assessed the economic and energy requirements of using alternative coke making technologies. Albino et al. (2003) analysed backward impacts of wooden waste recycling in an upholstery industrial district. In addition, EIO models are used as a planning tool for analysing the complex structure of global and local supply chains, in terms of materials, energy, and pollutants flows (Albino et al., 2002).

IO models have also been used as environmental and footprint accounting tools in different sectors. Particularly, Chen et al. (2011) evaluate the carbon emissions of wastewater treatment in a constructed wetland which performs notably better than a conventional water treatment system. Within energy use context, Kühtz et al. (2010) compare two ceramic production lines characterised by intensive energy use in Italy and China. Yazan et al. (2011) integrate physical and monetary IO modelling to measure economic and environmental performance of bioenergy production chains. Such models are also applicable at regional, national and international levels for policy-making (e.g. Chen and Zhang, 2010). For example, Chen and Chen (2013) use multi regional input-output (MRIO) models to quantify the virtual water footprints of sectors and countries providing a global picture of water consumption. Similarly, Chen and Han (2015) compare production- and consumption-based arable land-use at a global supply chain level revealing the global role of single countries from a trade perspective.

Waste input-output (WIO) models are also developed to compare life cycle strategies of products (Kondo and Nakamura, 2004); to compute the life cycle costs of appliances (Nakamura and Kondo, 2006); and to measure environmental impacts of waste treatment (Lin, 2009). Similarly, Yang et al. (2012) evaluate the greenhouse gas (GHG) emissions of a rural biogas system using a life cycle assessment (LCA) approach.

From a physical point of view, a production chain (PC) can be considered as an IO system (Storper and Harrison, 1992) that describes the product flows existing among production processes. Next subsection describes the EIO modelling for single PCs.