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Building waste management core indicators through Spatial Material Flow Analysis: Net recovery and transport intensity indexes

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ABSTRACT

In this paper, the material and spatial characterization of the flows within a municipal solid waste (MSW) management system are combined through a Network-Based Spatial Material Flow Analysis. Using this information, two core indicators are developed for the bio-waste fraction, the Net Recovery Index (NRI) and the Transport Intensity Index (TII), which are aimed at assessing progress towards policy-related sustainable MSW management strategies and objectives. The NRI approaches the capacity of a MSW management system for converting waste into resources through a systematic metabolic approach, whereas the TII addresses efficiency in terms of the transport requirements to manage a specific waste flow throughout the entire MSW management life cycle. Therefore, both indicators could be useful in assessing key MSW management policy strategies, such as the consecution of higher recycling levels (sustainability principle) or the minimization of transport by locating treatment facilities closer to generation sources (proximity principle). To apply this methodological approach, the bio-waste management system of the region of Catalonia (Spain) has been chosen as a case study. Results show the adequacy of both indicators for identifying those points within the system with higher capacity to compromise its environmental, economic and social performance and therefore establishing clear targets for policy prioritization. Moreover, this methodological approach permits scenario building, which could be useful in assessing the outcomes of hypothetical scenarios, thus proving its adequacy for strategic planning.

1. Introduction

Socioeconomic systems could be described by the "industrial metabolism" (Ayres, 1989) or "social metabolism" (Fischer-Kowalski, 1998; Haberl, 2001) approach, in which such systems 'metabolise' resources (materials and energy) to produce goods and services and 'excrete' wastes in the form of discarded materials, pollution (material wastes) and dissipated heat (energy waste) (Matthews et al., 2000). Wastes are therefore an unavoidable by-product of industrial production (Baumgartner and Arons, 2003). Even with high-efficiency recycling systems, there will be always a certain amount of waste for thermodynamic reasons (Ayres and Kneese, 1969; Georgescu-Roegen, 1971; Ayres, 1978), and this waste will require management.

Waste management is a "complex process involving a wide range of technologies and disciplines carried out within existing legal, social and environmental guidelines that protect the public and the environment's health and that are economically acceptable" (Tchobanoglous et al., 1993). Thus, decisions regarding waste management should not only be technologically acceptable but should also consider environmental and social perspectives. These premises have led to the design of integrated models of waste management (IMWM), which are designed to minimise environmental and social impacts and reduce economic costs (Daskalopoulos et al., 1998; Berger et al., 1999; Morrissey and Browne, 2004).

Building IMWM first requires metabolic data about the system, namely, the agents involved and their physical interrelations, as well as characterization of the material flows. In this sense, material flow analysis (MFA) is an appropriate methodology to fulfil this

Abbreviations: BTPC, biological treatment plant by composting; BTPAD, biological treatment plant by anaerobic digestion; CWA, Catalan Waste Agency; DtD, door-to-door; GHG, greenhouse gases; MBTP, mechanical biological treatment plants; MBTPC, mechanical biological treatment plant by composting; MBTPAD, mechanical biological treatment plant by anaerobic digestion; MFA, material flow analysis; MPW, municipal pruning waste; MSW, municipal solid waste; MUW, municipal unsorted waste; NRI, Net Recovery Index; OFMW, organic fraction of municipal waste; IMWM, integrated models of waste management; IUW, industrial unsorted waste; PIOT, physical input-output table; SMFA, Spatial Material Flow Analysis; TII, Transport Intensity Index.

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need. MFA permits the tracking of specific material flows through a socioeconomic system and provides a method to identify sources of generation and account for hidden flows and sinks that could remain unexplained through a more traditional end-of-pipe approach (Brunner and Rechberger, 2004). In addition, with MFA, the entire waste management hierarchy can be addressed, and the key steps for prevention or recycling policies can be identified.

There are five main types of MFA (substance flow analysis, specific material MFA, bulk MFA, economically extended-MFA and economy-wide MFA) (Brunner and Rechberger, 2004). However, although they are suitable for spatial modelling, analyses are generally performed with non-spatial models (Roy et al., 2005). Overcoming this knowledge gap has been attempted through the integration of spatial allocation, which is the process of defining and assigning different spatial attributes to discrete spatial units or objects (Duh and Brown, 2007) and the grouping of discrete spatial units into larger clusters according to specified data (Shirabe, 2005). The spatial allocation of material flows has led to the construction of Spatial Material Flow Analysis (SMFA) models (Kytzia, 2000; Luck et al., 2001; Roy et al., 2005; Druckman and Jackson, 2008), which allow (1) multilevel spatial planning, (2) the joining of bottom-up (by grouping bottom-level spatial units into larger clusters) and top-down (through the allocation of spatial attributes to bottom-level spatial units) approaches and (3) the prediction of future scenarios that enable planning due to the indirect and temporal nature of the spatial attributes (Roy et al., 2005; Kavouras, 2001).

Among other possible applications (particularly planning-related) and SMFA models have proven to be an indispensable tool to properly weight transport impacts within an IMWM, the relevance of which has been challenged by many authors both from environmental (Salhofer et al., 2007; Larsen et al., 2009) and economic (Palmer et al., 1997; Ecotec, 2001) perspectives. Spatial allocation of the agents involved permits an accurate estimation of the distances that waste flows cover via the performance of a network analysis. With network analysis, problems involving complex systems of interconnected linear features can be solved, such as determining the distance of an optimal route between two locations through a transport system.

Thus, the combination of spatial and material information can facilitate an understanding of MSW management systems, which could aid the identification of surface-hidden flows and their capacity to compromise environmental or economic performance. This could be the case for secondary waste flows, which are defined as those wastes generated by waste treatment facilities during the processing of waste and include both wastes for disposal and for recovery (Eurostat, 2010). In some regions, such as the European Union, secondary waste flows are expected to grow in coming years as treatment processes also increase as a response to European Regulations (EC, 2011). Therefore, environmental and economic impacts from the transport and treatment stages are also expected to increase. Moreover, as emissions from treatment facilities decrease due to technological improvements, emissions related to transport will play a relatively more important role. There are several quantitative and qualitative factors that determine secondary waste, such as the level of impurities found in MSW (particularly bio-waste and packaging), collection schemes, agents (municipalities, treatment and disposal facilities, etc.) geographical distribution, technologies and operational techniques, among others. The disclosure of these flows can thus favour the redesign of MSW management systems through a more holistic approach.

Among other applications, accurate waste flow accountability and spatial characterization could permit the construction of a set of core indicators to assess the real performance of the system in terms of material and energy recovery, as well as its transport intensity. Waste management core indicators are defined as those aimed at addressing policy-related issues, as well as monitoring the effectiveness of the specific policies implemented (EEA, 2005). Therefore, these indicators could be useful in assessing key MSW management policy strategies and objectives, such as the attainment of higher recycling levels (sustainability principle) or the minimization of transport requirements (proximity principle) (EC, 2008a). Nevertheless, at present these indicators usually appear either as rough approximations on official waste statistics or are unavailable. For example, regarding recovery indexes, within the European context, Eurostat uses the "difference methodology", by which recovery levels of MSW are calculated as the difference between the generated amount minus the amount landfilled and incinerated (Eurostat, 2010). This methodology, however, does not consider waste exported or energy recovery from incinerators or controlled landfills with biogas recovery. Moreover, the comparison between the "difference methodology" and the actual levels has revealed significant differences (both infra and overestimating) (Fischer and Werge, 2009), which could expose methodological inadequacies. Waste transport intensity indicators have even more scope for improvement as there are still no official methodological guidelines to provide this type of information.

Bio-waste is one type of waste in which the calculation of net recovery and transport intensity indicators could be particularly useful because these indicators can expose weak points within a waste management system. From an environmental perspective, the amount of bio-waste being landfilled is one of the most critical points, due to the significant GHG-related emissions derived from the anaerobic degradation that occurs in landfills (Themelis and Ulloa, 2007; Bingemer and Crutzen, 1987). In addition, these indicators could aid in assessing other weak points, such as the rate of secondary waste generation, low levels of self-management (for example, through home and community composting), inadequate geographical distribution of plants (according to the proximity principle) or low-efficiency operational techniques performed in treatment facilities.

The aim of this paper is to perform a Network-Based Spatial Material Flow Analysis of a MSW management system, with a dual objective: first, to accurately characterise waste flows, both in terms of mass and spatial attributes, as a means to better understand system flow behaviour and provide a set of information that could be a starting point for further environmental, economic and social assessment; second, to use these data to build core indicators that would allow the verification of MSW management sustainability performance according to the efficiency of the system in converting waste into products as well as the transport intensity required to do so. Additionally, the paper aims to verify the indicators' suitability for comparing different MSW management scenarios. The chosen case study corresponds to the municipal bio-waste management system of the region of Catalonia (Spain). The chosen system is characterised as small enough to permit systematic accounting of flows without jeopardising its comprehensibility and broad enough to be representative of a significant diversity of treatment technologies and operational techniques.

2. Methodology

Following the objectives set out, the methodology used in the present study can be divided in two sections. The first section addresses the development of a Network-Based Spatial Material Flow Analysis, which has been performed in three main steps: (1) MFA based in an agent-oriented Physical Input-Output Table (PIOT), (2) agent spatial allocation and (3) network analysis. Using material flow accounting and spatial characterization as inputs, the second section addresses the construction of two indicators: the net recovery and transport intensity indexes. Although