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Service area size assessment for evaluating the spatial scale of solid waste recovery chains: A territorial perspective

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ABSTRACT

Waste recovery is an integrated part of municipal solid waste management systems but its strategic planning is still challenging. In particular, the service area size of facilities is a sensitive issue since its calculation depends on various factors related to treatment technologies (output products) and territorial features (sources waste production and location). This work presents a systemic approach for the estimation of a chain's service area size, based on a balance between costs and recovery profits. The model assigns a recovery performance value to each source, which can be positive, neutral or negative. If it is positive, the source should be included in the facility's service area. Applied to the case of Montreal for food waste recovery by anaerobic digestion, the approach showed that at most 23 out of the 30 districts should be included in the service area, depending on the indicator, which represents around 127,000 t of waste recovered/year. Due to the systemic approach, these districts were not necessarily the closest to the facility. Moreover, for the Montreal case, changing the facility's location did not have a great influence on the optimal service area size, showing that the distance to the facility was not a decisive factor at this scale. However, replacing anaerobic digestion by a composting plant reduced the break-even transport distances and, thus, the number of sources worth collecting (around 68,500 t/year). In this way, the methodology, applied to different management strategies, gave a sense of the spatial dynamics involved in the recovery chain's design. The map of optimal supply obtained could be used to further analyse the feasibility of multi-site and/or multi-technology systems for the territory considered.

1. Introduction

The recovery of municipal solid waste is widely recognized as a step towards the welfare of society since it contributes to reducing waste sent to landfills and provides useful output products that can replace finite resources (Carvalho and Marques, 2014). However, its implementation at the municipal scale poses strategic, tactical and operational challenges. For example, selective collection, which improves the quality of the recovered products compared to mixed collection, also increases the share of collection and transport in the total waste management costs (Teixeira et al., 2014). It was also shown that the recovery benefits of some waste types can be compromised by transport distances that are too long (Merrild et al., 2012; Salhofer et al., 2007).

Therefore, at the strategic level, finding the optimal service area size is critical and has been widely addressed in the literature, as reported by Iakovou et al. (2010). For waste-to-energy or biomass-to-energy systems, the problem relies on the trade-offs between economies of scale achieved by large facilities and low transport costs of small-scale sites (Pantaleo et al., 2013). Indeed, when the plant size increases, unit treatment costs tend to decrease, whereas transport costs increase. Consequently, several studies proposed to find the optimal plant size as the result of a balance between unit treatment costs and transport costs (Gan and Smith, 2011; Leboreiro and Hilaly, 2011; Walla and Schneeberger, 2008). The transport model can be continuous, like in the aforementioned studies. In this case, the service area is characterised by a uniform waste density. The transport model can also be discrete to account for scattered biomass sources (Steubing et al., 2014). Another study addressed the economies of scale for anaerobic digestion facilities producing electricity from cattle farms waste (Pantaleo et al., 2013). The authors compared different scenarios of plant size and analysed the balance between net economic profits, transport and production costs, taking into account that electricity production's efficiency increases when the plant size increases. Economies of scale were also found in the literature

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for other recovery technologies like composting (Zhang and Matsuto, 2011). Overall, in these approaches, the optimal size problem is solved with a model relying on trade-off estimations between operational costs and revenues, by expanding the site's service area, whose centre is the facility. Other types of approaches aiming at allocating waste sources to different sites by minimizing transport costs can also address the problem. The optimization model is often combined with a location method, which may include site-specific data like road networks and resource availability maps using Geographic Information Systems (Bojesen et al., 2014; Sultana and Kumar, 2012). In some cases, such models are one module of a more comprehensive approach used to design waste management systems on the territory (Fiorucci et al., 2003; Khan et al., 2016).

However, in the context of waste recovery, profits need to be considered in the design model to ensure that long transport distances do not hamper the system's balance, which must remain positive. Moreover, the territory is often comprised of different areas with various waste densities and, thus, with various results in terms of global recovery performance. Therefore, a territory does not respond homogeneously to one waste recovery strategy. Some areas will constitute high-ranking sources whereas others will reduce the chain's global efficiency because their waste production is low or the distance to the facility is too high. Given this heterogeneity of the sources, the question that may be raised is how to decide which ones should be included in the recovery supply chain and which ones should be managed differently. Ultimately, answering this question leads to the estimation of the chain's service area size and the recovery performance for each source.

The objective of this paper is to present an approach to evaluate this performance for a heterogeneous territory. The evaluation is based on the sources contribution to the system's global efficiency. If the contribution is positive, the source should be included in the service area. In the second part of this paper, the general methodology for quantifying the sources contribution is presented. It takes into account collection, transport and treatment costs/impacts as well as the net profits induced by waste recovery. In the third part, the methodology is applied to the case of Montreal, Canada, for the source-separated food waste recovery by anaerobic digestion. Finally, two other management scenarios will be compared to the first case and a discussion of the results will be proposed.

2. Methodology

A conceptual model for the recovery supply chain was developed. As illustrated in Fig. 1, the territory was first divided into several sources that are individually responsible for waste collection and transport to the recovery facility.

In the next sections, the collection and transport model will be first described, followed by the recovery model.

2.1. Collection and transport model

The territory under study has been modelled on a GIS environment using the Qgis software. A grid was created to represent the road network with nodes accounting for sources and the recovery facility. The study is conducted at a municipal scale and a source represents one district. Geospatial information of actual roads was included such as their location and type. Three road types were distinguished to account for speed variations on the network. A road tortuosity factor of 1.2 was also applied because actual roads are not straight lines. It was calculated as the average value of the ratio actual road distance/length of the arc connecting two adjacent nodes of the grid. It matches values found in other studies for dense regions like Montreal (Pantaleo et al., 2013; Wright and Brown, 2007).

For a specific district i, costs and embedded energy calculations are divided into two steps: (1) collection and (2) transport. For the first step, a kerbside collection system exists in each district, where the trucks pick up organic waste in containers placed along the district's roads. In this paper, rather than finding an optimal value, waste collection costs were instead estimated in the following manner: trucks travel each road at least once a week, making the minimum total travel distance equal to the sum of the length of all roads in the district. Economic costs C_c^i (\$/week) and embedded energy E_c^i (MJ_{emb}/week) are based on diesel consumption of trucks during collection FC_c (L/km) and are calculated according to Eqs. (1) and (2) respectively:

$$C_c^i = \left(FC_c * \beta_{diesel} + \frac{C_h}{V_c}\right) * D_i \tag{1}$$

where β_{diesel} (\$/L) is the diesel price at the pump; C_h (\$/h) is the hourly costs of garbage trucks; V_c (km/h) is the average speed of trucks during collection; and D_i (km/week) is the sum of the length of all roads in the district i. C_h is a global cost value, including the salaries, maintenance and insurance costs related to the trucks.

$$E_c^i = FC_c * Emb_{diesel} * D_i \tag{2}$$

where Emb_{diesel} (MJ_{emb}/L) is the fossil fuels consumption (embedded energy) for the production of 1 L of diesel.

The second step is the calculation of transport-related economic costs C_t^i (\$/week) from the district to the recovery facility, estimated according to Eq. (3):

$$C_t^i = \sum_j \left[\left(FC_{t,j}(V_{t,j}, \alpha_i) * \beta_{diesel} + \frac{C_h}{V_{t,j}}\right) * d_j\right] * \alpha_i * \tau \tag{3}$$

where $FC_{t,j}$ (L/km) is the average fuel consumption of trucks on arc j which is on the path of district i to the recovery facility; $V_{t,j}$ (km/h) is the average driving velocity during transport on arc j; α_i ($week^{-1}$) is the ratio of the organic waste weight collected in the district i to the truck size; d_j (km) is the length of arc j; and τ is the tortuosity factor. Similarly, embedded energy consumption during transport E_t^i (MJ_{emb}/week) is calculated according to Eq. (4):

$$E_i^t = \sum_j [FC_{t,j}(V_{t,j}, \alpha_i) * d_j] * \alpha_i * \tau * Emb_{diesel} \tag{4}$$

Table 1 summarises the values of the parameters used in Eqs. (1)–(4).

Moreover, it was assumed that trucks have an unloaded weight of approximately 30 tonnes and a volume capacity of 29 m^3. As regards to their fuel consumption during transport, calculations are based on the results of the project MEET (Methodologies for Estimating air pollutant Emissions from Transport), considering trucks payload and velocity (Hickman et al., 1999; Zsigraiova et al., 2013). Funded by the European Commission, this project provides general formulas for the air pollutants and fuel consumption estimations of different transportation modes and types of vehicles. The trucks used for waste collection and transport are classified by MEET as diesel heavy-duty vehicles.

Since multiple routes from each district to the recovery facility are possible, the selected routes are the ones that minimize the transport costs defined in Eqs. (3) and (4). The optimization approach is further described in Tanguy et al. (2016).

2.2. Waste-to-biomethane recovery model

The anaerobic digestion (AD) of source-separated food waste to produce raw biogas involves several process stages: waste pretreatment, digestion and handling of the digestate. The use of the