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Household food waste collection: Building service networks through neighborhood expansion

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A B S T R A C T

In this paper we develop a residential food waste collection analysis and modeling framework that captures transportation costs faced by service providers in their initial stages of service provision. With this framework and model, we gain insights into network transportation costs and investigate possible service expansion scenarios faced by these organizations. We solve a vehicle routing problem (VRP) formulated for the residential neighborhood context using a heuristic approach developed. The scenarios considered follow a narrative where service providers start with an initial neighborhood or community and expands to incorporate other communities and their households. The results indicate that increasing household participation, decreases the travel time and cost per household, up to a critical threshold, beyond which we see marginal time and cost improvements. Additionally, the results indicate different outcomes in expansion scenarios depending on the household density of incorporated neighborhoods. As household participation and density increases, the travel time per household in the network decreases. However, at approximately 10–20 households per km^2, the decrease in travel time per household is marginal, suggesting a lowerbound household density threshold. Finally, we show in food waste collection, networks share common scaling effects with respect to travel time and costs, regardless of the number of nodes and links.

1. Introduction

Food waste collection and recycling is an important issue in waste management that has gained interest in recent years due to the environmental impacts of food degradation in landfills (Edwards et al., 2017; Laurent et al., 2014). The United States (US) generated 63 million tons of food waste in 2015, of which approximately 40% originates from consumer-facing businesses and 43% from residences (ReFED, 2017). However, implementation of programs to recycle this food waste is slow due to high transportation costs and the relatively low market value of products created from current recycling processes (ReFED, 2017). States including Massachusetts, Connecticut, and Rhode Island have passed legislation to speed up program development by mandating diversion of food waste to recycling facilities from larger consumer-facing businesses (Manson, 2017), but residential food waste diversion has been ignored in state-level policy and legislation. This lack of interest in diverting residential food waste from landfills is problematic if states wish to continue reducing the environmental impact of their waste management systems.

As of 2014, only 200 municipalities in the US have some form of residential food waste collection in place through municipal mandates or private waste collection businesses (Yepsen, 2015). Increased costs for the addition of curbside food waste collection brings considerable challenges that have mostly been overcome by political will (Yepsen, 2014), which is unsustainable from a long-term economic perspective. In order to reduce waste collection program costs, economies of scale are critical (Bohm et al., 2010). Achieving these economies of scale may be difficult for food waste collection due to lower generation rates compared to municipal solid waste (MSW) and recyclable material (New York State Department of Environmental Conservation, 2010).

A main focus of previous waste collection models in the literature is to increase collection efficiency by optimizing routing and scheduling for networks at the urban scale (Arribas et al., 2010; Or and Curi, 1993). Urban residential waste collection poses significant methodological challenges due to the large number of individual waste bins to be collected. Also, these models neglect food waste generated by suburban areas. Larger regional networks that encompass both urban and suburban areas include many logistic dimensions such as transfer stations, time constraints, and bin types (Das and Bhattacharyya, 2015; Nuortio et al., 2006; Son and Louati, 2016). Some studies focus on specific waste materials,

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such as recyclables, to understand the dynamics that specific waste types confer to the collection system (Bing et al., 2014; Rousta et al., 2015). This practice may parallel dynamics seen in the food waste collection system.

Relatively few studies focus specifically on the collection of source-separated household food waste. Franchetti and Dellinger (2014) and Edwards et al. (2016) study the economic and environmental effects that an additional waste collection stream will have on the collection system. However, these studies each examine large, mature collection networks and systems, assuming all households participate in the collection service. Realistically, households in communities have varying values regarding recycling of food waste; therefore, not everyone is willing to participate in or pay for the additional service. National surveys in the US focusing on household attitudes toward food waste indicate that the majority of people still throw away food even though they feel guilty about their actions (Neff et al., 2015; Qi and Roe, 2016). Therefore, understanding the effects of participant spatial density on service cost is important for implementing collection services sustainably.

The overarching objective of this study is to provide system-level insights for expanding food waste collection. This objective is twofold. First, improvements to transportation costs for small start-up scale networks and the implications as service grows and more households incorporated in the network are examined. Second, the feasibility of expanding small scale residential food waste collection services is assessed by calculating travel and collections costs associated with adding new communities. As communities join the collection network, travel time and cost per household are expected to decrease, indicating positive returns to scale.

2. Analysis and modeling framework

2.1. Analysis framework: decision-making for service expansion

The analysis and modeling framework developed reflects the decision-making process faced by start-up food waste collection services early in development. The problem is approached by developing a model and analysis framework that solves for the vehicle routing problem (VRP) given an a priori set of households and their spatial locations over participation levels that reflect expansion scenarios. A new solution to the VRP for each network expansion level (a new collection route) is obtained as more households and communities join.

The VRP is solved using the cluster first, route second heuristic (Laporte, 2009), which helps address the high computational resources required of large networks. Under this approach, destination nodes are clustered first based on their spatial proximity and the VRP is solved for each cluster. A second VRP is performed on the network of centroids of each cluster. For this study, the clusters are determined (a priori) based on pre-defined neighborhood boundaries, precluding the need for a clustering algorithm. The motivation behind this assumption is behavioral. Social interaction within communities or neighborhoods likely contribute more towards behaviors such as adoption of curbside composting services (Hopper and Nielsen, 1991; McMillan and Chavis, 1986).

The framework consists of two routing layers: (1) an intra-neighborhood vehicle routing and (2) inter-neighborhood vehicle routing. Fig. 1 illustrates this framework.

Each neighborhood represents a community seeking collection service. The first layer solves a VRP for a given neighborhood between households randomly selected to represent different levels of collection program participation. The collection vehicle must stop at each household and requires a set time duration for collecting the food waste. A solution to the first stage VRP will indicate the sequence of household stops, network links traversed, total traversal time, and quantity of collected waste is produced.

In the second layer, an inter-neighborhood VRP is solved for a network of centroids of the neighborhoods. Associated with each neighborhood centroid is a total waste collected at that neighborhood and travel time determined previously in the first (intra-neighborhood) layer. Similarly, the output to the inter-neighborhood VRP includes a collection route that indicates the sequence of stops and network link traversed between neighborhoods. This layer also produces the total time of the collection route and total quantity of food waste collected by the vehicle.

2.2. Vehicle routing problem (VRP) formulation

The VRP is formulated as a mixed-integer mathematical program and solved using the cluster first and route second heuristic (Laporte, 2009). The neighborhood residential waste collection problem is formulated as a capacitated VRP where the decision variables are:

x_{hij}^{k} – The shortest path travel times nodes h, i, and j for collection truck k.
y_{i}^{k} – The total quantity of food waste in the collection truck k including node i.
w_{j}^{k} – Mass of waste delivered to recycling facility j by collection truck k.
v_{j} – The total mass of food waste delivered to recycling facility j.

The formulation has the following objective function:

$$Min = \sum_{i\in(D,N)}\sum_{j\in(D',N)}\sum_{k\in K} c_{ij}x_{ij}^{k} + \sum_{j\in N} m_j \quad (1)$$

The objective function (1) minimizes the truck travel time between pickup $i \in D, N$ and drop-off $j \in D', N$ nodes over the set of vehicles $k \in K$ mobilized in the collection network by summing the travel time c_{ij} on each traversed link x_{ij}^{k} and the collection time at each pickup node m_j.

Subject to the constraints:

$$\sum_{h\in D}\sum_{i\in N} x_{hi}^{k} = 1 \;\forall k \in K \quad (2)$$

$$\sum_{i\in N} x_{hi}^{k} = \sum_{j\in N} x_{jh'}^{k} \;\forall k \in K,\; h \in D,\; h' \in D' \quad (3)$$

$$\sum_{h\in(D,N)} x_{hi}^{k} = \sum_{j\in(N,D')} x_{ij}^{k} \;\forall k \in K,\; i \in N \quad (4)$$

$$\sum_{i\in N} x_{ij}^{k} = \sum_{h'\in D'} x_{jh'}^{k} \;\forall k \in K \quad (5)$$

$$\sum_{k\in K}\sum_{j\in(N,F)} x_{ij}^{k} = 1 \;\forall i \in N \quad (6)$$

Constraints (2-6) provide the minimum cost flow constraints that simulate the behavior of the collection truck. The truck can only leave the depot once, all households or neighborhoods must be visited by only one truck, food waste must dropped off at the recycling facility, and the truck must return to the vehicle depot.

$$y_i^k \geqslant y_h^k + (q_i + Q)x_{hi}^k - Q \;\forall h \in (N,D),\; i \in N,\; k \in K \quad (7)$$

$$w_j^k \geqslant y_i^k - Q(1 - x_{ij}^k) \;\forall k \in K,\; i \in N,\; j \in D' \quad (8)$$

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