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Vehicle routing for the eco-efficient collection of household plastic waste

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ABSTRACT

Plastic waste is a special category of municipal solid waste. Plastic waste collection is featured with various alternatives of collection methods (curbside/drop-off) and separation methods (source-/post-separation). In the Netherlands, the collection routes of plastic waste are the same as those of other waste, although plastic is different than other waste in terms of volume to weight ratio. This paper aims for redesigning the collection routes and compares the collection options of plastic waste using eco-efficiency as performance indicator. Eco-efficiency concerns the trade-off between environmental impacts, social issues and costs. The collection problem is modeled as a vehicle routing problem. A tabu search heuristic is used to improve the routes. Collection alternatives are compared by a scenario study approach. Real distances between locations are calculated with MapPoint. The scenario study is conducted based on real case data of the Dutch municipality Wageningen. Scenarios are designed according to the collection alternatives with different assumptions in collection method, vehicle type, collection frequency and collection points, etc. Results show that the current collection routes can be improved in terms of eco-efficiency performance by using our method. The source-separation drop-off collection scenario has the best performance for plastic collection assuming householders take the waste to the drop-off points in a sustainable manner. The model also shows to be an efficient decision support tool to investigate the impacts of future changes such as alternative vehicle type and different response rates.

1. Introduction

Plastic waste is a special category of municipal solid waste. Plastics, as packaging material, have substantial benefits in terms of their low weight, durability and lower cost relative to many other material types (Andrady and Neal, 2009). This feature makes plastic material favorable for all kinds of packaging use, however makes it difficult for recycling. Separation and sorting of plastic is more complicated than for other waste types due to a large variety in composition. Two alternatives for the collection of waste are possible, either at a central collection point in the neighborhood (drop-off collection) or at the curbside on the street outside the house (curbside collection). There are also two methods for the separation of waste: source-separation and post-separation. Source-separated plastics is separated from other waste at households. Post-separated plastics is mixed and collected together with other waste. Separation of plastics from other waste happens later in a separation center. Trade-offs between these collection options are in terms of costs, facility requirement and householder's involvement. Municipalities need a comparison between these collection options for plastic waste to make a decision on which collection method to invest in.

The collection cost of the various options is the most primary measurement to support this decision making process. Besides, due to the increasing environmental concerns, another important measurement that should be taken into account together with costs is the environmental and social performance of the collection options. Plastic waste collection should be eco-efficient. The concept of eco-efficiency is based on the concept of creating more goods and services while using fewer resources and creating less waste and pollution (WBCSD, 2000). Waste recycling is sustainable in itself as it avoids landfills (Carlson, 2001). Moreover, from a sustainable logistics perspective, there is also a requirement of conducting the activities in a sustainable manner, that is paying attention to environmental impacts and social well-being in

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addition to cost minimization (Quariguasi Frota Neto et al., 2009). Thus the eco-efficient performance of the collection options should be tested, together with the potentials to further reduce environmental impact. The continuous improvement in waste recycling in terms of householder's behavior and the technology input requires a design of collection that can cope with future changes. Therefore the capability of these collection options to meet future demand should also be investigated.

This research starts from current practice and redesigns the collection of various options based on the case of the Netherlands. Each Dutch municipality (more than 400 in total) has to decide which collection method to adopt. There is no obligation on which separation method to take although the government prefers the source-separation. Recently, source-separated plastic waste recycling is promoted with tax incentives and free waste bags distributed to households with a "Plastic Hero" icon printed on each bag. However, there are also municipalities conducting post-separation and believing that it is more efficient. In the future, municipalities are facing the choice of investing in an alternative collection system or make improvements of the current system. It is also difficult to predict how capable these alternatives are in dealing with future changes in plastic recycling. Therefore, the purpose of this research is to compare different options of collection alternatives with an improved eco-efficiency performance, and to explore the potentials for coping with future development. "Eco-efficiency" in waste collection means to deliver the collection service that satisfies the needs of householders while progressively reducing environmental impacts. Based on the current collection practice of a representative Dutch municipality, heuristics are used to improve the current collection routes. A scenario study approach is used in the analysis to compare different collection alternatives. Scenarios are designed with various collection methods in combination with the possible separation methods. Results are compared to provide decision support for choosing suitable collection options for municipalities.

The collection of plastic waste is modeled as a Vehicle Routing Problem (VRP). A tabu search algorithm is proposed to solve the model. The current collection routes are used as initial solution and the algorithm improves the routes with an objective of minimizing total cost. Emissions from driving and idling of vehicles are transferred to a cost factor that is added to the total cost. The costs considered in the model, therefore, consist of transportation cost, labor cost and emission cost. In order to model the problem in a realistic manner, distance matrices between locations are generated by Microsoft MapPoint (Microsoft, 2012). In this way, the distance input of the model can reflect the actual shortest driving distances between each pair of locations in the chosen geographic area.

The remainder of the paper is organized as follows. In Section 2, we present the scientific relevance of the research. In Section 3, we describe the problem and formulate the model. Section 4 presents the scenarios and present the data we use in the modeling. Section 5 presents the algorithm we use to obtain the results as presented in Section 6. Section 7 presents the sensitivity analysis and discussion. Conclusions are stated in Section 8.

2. Scientific relevance

The collection of municipal plastic waste is within the scope of reverse logistics (Fleischmann et al., 1997). Redesign of the collection routes for municipal plastic waste is essentially a vehicle routing problem. The Vehicle Routing Problem (VRP) can be described as the problem of designing optimal delivery or collection routes from one or several depots to a number of geographically scattered demand points, subject to side constraints (Christofides, 1976). The VRP plays an important role in logistics with a large number of variants (Desrochers et al., 1990). A few VRP variants can be applied to waste collection problems. Waste collection can be divided into three categories: residential, commercial and skip waste collection (Benjamin, 2011). Residential waste is collected in front of the houses in small bins or garbage bags. The collection vehicles will collect all the waste along the streets which is often solved as an arc routing problem where demand is on arcs. Commercial collection (waste in restaurants, retail outlets and apartments in containers) and skip collection (waste in construction sites in big containers) problems are typically solved as node routing problems (demand on nodes) and the location of every customer is known. Waste collection involved in these strategies is point-to-point collection (Ramos et al., 2013). In practice, a combination of the two types of collection in the routing problem (demand on both arcs and nodes) also exists, which makes it a general routing problem (Beullens et al., 2004). For plastic waste collection, drop-off collection is a typical node-routing problem. In curbside collection, as in practice, householders aggregate their plastic bags with the close-by neighbors at curbside, collection points can be aggregated and also modeled as a node-routing problem.

Given the complexity of the problem, heuristics are usually used to efficiently solve VRP for waste collection problems. Karadimas et al. (2007) employed the ant colony algorithm for optimizing costs for different scenarios of urban solid waste management systems. A capacitated clustering-based algorithm is proposed by Kim et al. (2006) to solve their waste collection vehicle routing problem with time windows considering the route compactness and workload balancing of a solution. Benjamin and Beasley (2010) work on a waste collection vehicle routing model with time windows. They generate their initial solution with a method that fully utilizes a vehicle and improves the initial solution using an interchange procedure. Bautista et al. (2008) described their urban waste collection problem as a capacitated arc routing problem. They applied a transformation procedure of the problem into a node routing one and solved it with ant colony heuristics. Scheuerer (2006) used a tabu search heuristics for the truck and trailer routing problem and concluded that the tabu search obtained better solutions in comparison with the other construction heuristics used. Ismail and Md Yunos (2010) designed a reactive tabu search to solve the solid waste collection scheduling problem with a dynamic tabu list. The previous research shows Tabu search is an appropriate method to solve a waste collection vehicle routing problem. Thus, in our research, we also designed a Tabu search algorithm to solve our vehicle routing problem. This algorithm is featured with a combination of three types of moves and a reactive frequency indicator to favor moves with a better performance progressively.

A number of studies have been conducted on comparing waste collection options. Gallardo et al. (2010) investigated the extent to which clean materials are recovered of four different selective collection scenarios in Spain. They concluded that the best values were obtained from the system with paper/cardboard, glass and lightweight packaging (e.g. plastic packaging) at drop-off points, organic waste and mixed waste in curb-side bins. Dahlén et al. (2007) performed a sampling and composition analysis of different collection methods for sorted household waste in Sweden and concluded that with curb-side collection more metal, plastic and paper packaging was separated and sent to recycling. These studies investigated the differences between various waste types in the comparison. The focuses are mainly on collection alternatives. Whereas, our study takes a closer look into plastic waste in specific and takes into account the combined effect of collection and separation methods. We examine the different combinations of these methods with a vehicle routing model. The key performance indicator is eco-efficiency measured by a combination of transportation, labor and emission costs.