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A stochastic optimization framework for planning of waste collection and value recovery operations in smart and sustainable cities

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ABSTRACT

The concept of City 2.0 or smart city is offering new opportunities for handling waste management practices. The existing studies have started addressing waste management problems in smart cities mainly by focusing on the design of new sensor-based Internet of Things (IoT) technologies, and optimizing the routes for waste collection trucks with the aim of minimizing operational costs, energy consumption and transportation pollution emissions. In this study, the importance of value recovery from trash bins is highlighted. A stochastic optimization model based on chance-constrained programming is developed to optimize the planning of waste collection operations. The objective of the proposed optimization model is to minimize the total transportation cost while maximizing the recovery of value still embedded in waste bins. The value of collected waste is modeled as an uncertain parameter to reflect the uncertain value that can be recovered from each trash bin due to the uncertain condition and quality of waste. The application of the proposed model is shown by using a numerical example. The study opens new venues for incorporating the value recovery aspect into waste collection planning and development of new data acquisition technologies that enable municipalities to monitor the mix of recyclables embedded in individual trash bins.

1. Introduction

The smart city can be defined as a smart combination of infrastructure, activities and aware citizens with well performance in fundamental components such as smart economy, environment, mobility, quality of living and smart government (Giffinger et al., 2007). As urban population is growing very fast (Fazio et al., 2012), there is an urgent need for efficient utilization of resources in urban areas and mega cities. In order to manage advanced, newly emerging and fundamental needs, the use of smart infrastructure and capabilities offered by Industry 4.0 is considered as one solution (Balakrishna, 2012). The use of the wireless sensors and actuators will enable technologies such as Internet of Things (IoT) to reconstruct urban activities in smart cities in almost all aspects of daily life (Jara et al., 2014).

One fundamental challenge in improving the quality of life in urban area is the proper management of growing waste generated as a result of industrial development and consumers' consumption behaviors. Waste generation rate is growing rapidly due to the rise in the standards of living, rapid urbanization and developed economies (Minghua et al., 2009). In order to increase the quality of life for citizens and minimize negative environmental effects, the effective management of the waste becomes very critical.

Waste management practices deal with different activities ranging from waste collection, and waste separation to waste recovery and recycling. Various waste collection and recovery systems have been developed for effective management of different types of wastes during their entire lifecycles. Information and communication technologies (ICT) offer fundamental advantages for solving waste management issues when incorporated with existing systems. One example is the dynamic collection of waste due to the capabilities offered by ICT. In past years, waste collection was treated in a static manner, but nowadays dynamic solutions are enabled by the production of newly developed sensors, actuators and IoT technologies (Carli et al., 2013), where bins can be equipped with various IoT components and sensors such as capacity sensors, weight sensors, temperature sensors, humidity sensors, chemical sensors, pressure sensors and actuators (Li et al., 2013).

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Although recent research in smart cities has proposed some IoT-based strategies for waste collection, transportation, dynamic routing, and dynamic waste collection scheduling, some important issues are still remaining. The objective of value recovery from waste is one of the important issues on which very few studies, if any, has been done. The focus of previous research mainly has been on the on-time waste collection rather than the value recovery.

In this paper, we offer a stochastic optimization model for enhancing the value recovered from collected waste in smart communities. It should be noted that the proposed approach can be employed for any types of waste or mixture of waste. We have developed a waste value recovery function and an allocation model for simultaneous maximization of waste value recovery and minimization of transportation costs. The value embedded in each trash bin is modeled as a random variable with normal distribution. The model has been solved using chance constrained programming method to deal with the uncertainty in the objective function. An example of plastics waste recovery has been provided to show the application of the model, since plastics have a high daily use, high waste rate and high levels of recycling.

The rest of this paper is organized as follows. Section 2 presents the related research and prior studies. Section 3 represents the proposed system architecture for waste management in smart cities. Section 4 describes our allocation models. Section 5 represents the application of the proposed models and several sensitivity analyses on the model parameters. Finally, Section 6 concludes the paper and discusses the future scope.

2. Literature review

Waste management practices can be divided into different categories, ranging from waste collection, and separation to waste recovery and recycling. While an extensive literature exists regarding the optimization of general waste collection and recovery operations, the literature on waste management in smart cities is limited. In this section, first we will provide an overview of research on the scheduling of waste collection and recovery operations, and then we will discuss the most recent studies on waste management practices in smart cities.

In order to identify research gaps in waste collection problems in smart cities, first we will review the literature on vehicle routing problems. Various heuristic and non-heuristic models have been offered in transportation literature for solving routing problems, to name a few studies Reed et al. (2014) have proposed a dynamic model for capacitated vehicle routing problems using Ant Colony System algorithm (Reed et al., 2014). Hemmelmayr et al. (2013) have proposed a heuristic solution for solid waste collection as a periodic truck routing problem (Hemmelmayr et al., 2013), where the collected waste can be delivered into some intermediate facilities and not every collection points need to be covered every day. Banditvilai and Niraso (2017) have proposed a simulation framework for modeling the night shift solid waste collection in Phuket Municipality, Thailand and developed a heuristic approach for assigning waste collection zones and routings (Banditvilai and Niraso, 2017). In order to solve periodic routing problem in the municipal waste collection, Triki (2017) developed a model for defining the routing of collection vehicle with considering the extended planning horizon for some zones, where not all the zones should be served in one planning horizon and the planning horizon can be flexible depending on the needs of different regions (Triki, 2017). To serve multiple disposal facilities with huge amount of waste, Wy et al. (2013) have developed a routing model by integrating several heuristics algorithms to minimize the number of collection vehicles and the total route time considering several factors and constraints such as multiple disposal facilities, different types of client demands (e.g. residential, commercial, industrial), different time periods for demands, and different sizes of containers (Wy et al., 2013).

Moreover, various dynamic models and algorithms have been proposed in the literature to facilitate both waste collection and recovery practices. Gruler et al. (2017) have combined metaheuristics with simulation and proposed a hybrid algorithm for waste management in clustered urban areas (Gruler et al., 2017) considering the impact of cooperation among vehicles departed from different depots and the corresponding savings this cooperation could create. Braier et al. (2017) have proposed an integer programming model to optimize the dynamic routs of collection vehicles for the case of waste collection in Morón, Argentina (Braier et al., 2017). To perform routing enforced with the conflicts context and time windows, Minh et al. (2013a, 2013b) introduced a memetic algorithm to achieve multi-objective optimization for determining the number of vehicles and the trip times considering several constraints such as the time window of waste collection for each regions, the conflicts between waste characteristics, and the availability of multiple landfills (Minh et al., 2013a, 2013b).

Most recently, the concept of waste management in smart communities has been the point of attention in the literature. Overall, the studies that have addressed information technology-based waste collection objectives can be categorized into four main groups: (1) studies that have focused on the development of data acquisition technologies such as sensor-based technology, geographic information systems (GIS), and image processing technologies, (2) studies that have discussed data transformation platforms for transferring data collected through data acquisition technologies to central control platforms used by municipalities, (3) studies that have developed analytical models to demonstrate the application of capabilities of IoT enabled technologies for proper waste collection activities, and finally (4) studies that have shown the capabilities of information technology in real case studies. The main focus of the current study is on the third group of studies, waste collection operations in a smart environment, however, we will briefly review several studies from other categories.

To name a few studies from each category, Vicentini et al. (2009) designed a testing prototype of intelligent containers to measure the actual weight and volume of waste present in each container in Pudong, New Area, Shanghai and transfer the information to a central control system for municipalities. Faccio et al. (2011) defined a framework for integrating real-time data collected from traceability devices into waste collection routing models to determine the number of vehicles, travel time, and areas covered by each vehicle. Chang et al. (1997) also applied a multi-objective optimization model within a GIS environment to optimize the routing and scheduling of waste collection vehicles in Taiwan. Zamorano et al. (2009) also conducted a GIS-based data collection in Churriana de la Vega, Spain to show that the number of location of trash containers can be optimized to reduce the costs resulting from an excessive number of containers. In addition to minimizing operational costs, some studies have adopted multiple objectives. For example, Anghinolfi et al. (2016) have formulated a multi-objective mixed integer linear programing model that aims to not only minimize costs but also environmental impacts. Rada et al. (2013) discussed the application of Web-GIS with RFID in multiple Municipalities in the north of Italy and showed the waste separation efficiency and cost reduction in several aspects.

Most of the IoT-enabled waste management studies have been focused on optimizing routing and scheduling of waste collection vehicles within smart communities. Two types of methods have been developed to facilitate waste collection in smart cities, namely static and dynamic planning models (Anagnostopoulos et al., 2015b). The static models ignore the real-time status of trash