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Modeling municipal solid waste collection: A generalized vehicle routing model with multiple transfer stations, gather sites and inhomogeneous vehicles in time windows

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ABSTRACT

Municipal Solid Waste (MSW) collection is a necessary process in any municipality resulting in the quality-of-life, economic aspects and urban structuralization. The intrinsic nature of MSW collection relates to the development of effective vehicle routing models that optimize the total traveling distances of vehicles, the environmental emission and the investment costs. In this article, we propose a generalized vehicle routing model including multiple transfer stations, gather sites and inhomogeneous vehicles in time windows for MSW collection. It takes into account traveling in one-way routes, the number of vehicles per m^2 and waiting time at traffic stops for reduction of operational time. The proposed model could be used for scenarios having similar node structures and vehicles' characteristics. A case study at Danang city, Vietnam is given to illustrate the applicability of this model. The experimental results have clearly shown that the new model reduces both total traveling distances and operational hours of vehicles in comparison with those of practical scenarios. Optimal routes of vehicles on streets and markets at Danang are given. Those results are significant to practitioners and local policy makers.

1. Introduction

The world has witnessed over 10,000 natural and industrial disasters, killing millions and affecting many more, because of climate change (Technology, 2013). Municipal solid waste (MSW) is one of the primary factors that contribute greatly to the rising of climate change and global warming (Consonni et al., 2005). In 2011, 1.3 billion metric tons of municipal solid waste (MSW) were generated, and this is expected to grow to 2.2 billion metric tons by 2025 (Levis et al., 2013). In the U.S., MSW systems processed approximately 250 million tons of waste and produced 118 Tg of CO2e emissions, which represents over 8% of non-energy related greenhouse gas (GHG) emissions, and 2% of total net GHG emissions (Levis et al., 2013). Technological advancements, environmental regulations, and emphasis on resource conservation and recovery have greatly reduced the environmental impacts of MSW management, including emissions of greenhouse gases (Weitz et al., 2002). More effective, technically viable, environmentally effective and economically sustainable collection schemes are the target of waste managers (Teixeira et al., 2014). They make feasible CO_2 reduction (Cioca et al., 2015) and affect maintenance strategies of MSW incinerators (Ragazzi et al., 2013). It was shown that developing countries are currently in the progress of urbanization and industrialization, resulting in the augmentation of various types of wastes that leaves a burden to both the municipality's infrastructure and the community (Dyson, 2011). Urbanization and demographic transition are key factors of economic development that lead to a significant concentration of human resources, economic activities, and resource consumption in cities (Madlener and Sunak, 2011). It is undoubted that optimizing MSW collection brings much meaning in terms of environmental, landscape developments and economic savings (Mora et al., 2014).

The intrinsic nature of MSW collection relates to the development of effective *vehicle routing* (VR) models that optimize the total traveling distances of vehicles, the environmental emission and the investment costs (Apaydin and Gonullu, 2011). VR is a scheduled process that allows vehicles to load waste at gather sites (a.k.a. sites) and dump it at a landfill with the target being oriented by a single or multiple objectives (Tung and Pinnoi, 2000). Waste generation and collection cannot be measured on a detailed basis, which would allow further evaluation of disposal habits, changes and trends so that modeling

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MSW collection is of particular importance (Beigl et al., 2008). Several VR models were presented in the literature with various objectives such as the minimum fuel consumption, minimum traveling distances and environmental emissions. Now, we herein summarize the relevant researches as follows.

- Tung and Pinnoi (2000) introduced a VR model for Hanoi city, Vietnam whose components are a depot, a landfill and multiple sites. Vehicles are homogeneous and are allowed to travel to sites under time window constraints. The works of handcarts are left manually. The objectives are to minimize the traveling times and distances of vehicles.
- Apaydin and Gonullu (2008) argued that route optimization in a VR model should be taken into account the exhaust emission of vehicles when they are running. Therefore, the environmental emission was attached to the objective function besides the traveling times and distances of vehicles. Based on a standard table about the exhaust emission of a specific type of vehicles per a distance unit, the quantities of some gases such as CO_2, HC, CO and PM could be determined and used in the objective function.
- Tavares et al. (2009) stated that short routes do not guarantee minimum fuel consumption of vehicles, but long routes having negative road gradients may require less fuel since the resistance of vehicles to traction decreases. They proposed the uses of three-dimensional geographic information systems (3D GIS) modeling for the waste collection and transportation. Some factors such as the driving situations, vehicle load and road gradient were integrated to the VR model. This model is capable of finding optimal routes for the minimum fuel consumption of vehicles.
- Fan et al. (2010) proposed a VR model containing a depot, a transfer station, multiple sites and landfills. Waste was classified by the heat value in the transfer station. Waste with high heat value was disposed by incineration while waste with low one was unloaded at the landfill. This research aims to minimize the traveling distance and maximize total heat value.
- Arribas et al. (2010) proposed a methodology for designing an urban solid waste collection system that minimises collection time, and operational and transport costs while enhancing the current solid waste collection system.
- Galante et al. (2010) considered the localization and dimensioning of transfer stations, which constitute a necessary intermediate level in the logistic chain of the solid waste stream, from municipalities to the incinerator. The model examined both initial investment and operative costs related to transportation and transfer stations. Two conflicting objectives are evaluated, the minimization of total cost and the minimization of environmental impact, measured by pollution.
- Larsen et al. (2010) presented five scenarios with alternative collection systems for recyclables were assessed by means of a life cycle assessment and an assessment of the municipality's costs. Enhancing recycling and avoiding incineration was recommendable because the environmental performance was improved in several impact categories.
- Tan et al. (2010a, 2010b) designed a superiority–inferiority-ba sed inexact fuzzy two-stage mixed-integer linear programming model for municipal solid waste management under uncertainty. The developed approach is capable of tackling dual uncertainties presented as fuzzy boundary intervals in both constraints and objective functions.
- Apaydin and Gonullu (2011) suggested appending the parameters "population density per 100 m road distance" and "waiting time at stop signs" to the VR model for the estimation of traveling and collecting time. The objective function is similar to that in (Tung and Pinnoi, 2000).
- Faccio et al. (2011) used real time data to orient the route of a vehicle. They argued that if the real time data of each vehicle and that of replenishment level are known then what bin should be emptied and what should not are totally identified. The data of this research are either deterministic or stochastic. The objective function consists of the number of used vehicles and their traveling times and distances.
- Regarding review notes, Pires et al. (2011b) conducted a thorough literature review of models and tools illuminating possible overlapped boundaries in waste management practices in European countries and encompassing the pros and cons of waste management practices in each member state of the European Union. Tai et al. (2011) provided an overview of different methods of collection, transportation, and treatment of MSW in the eight cities; as well as making a comparative analysis of MSW source-separated collection in China. Beliën et al. (2012) reviewed the available literature on solid waste management problems, with a particular focus on vehicle routing problems.
- Chatzouridis and Komilis (2012) design a VR model whose objective function was a non-linear equation that minimized total collection cost. The cost comprised the capital and operating costs of: (i) the waste transfer stations, (ii) the waste collection vehicles, (iii) the semitrailers and tractors as well as the waste collection within a community, and the cost to haul the wastes to the transfer stations or to the landfills. The decision variables were binary variables that designated whether a path between two nodes is valid or not. Binary variables were also used to designate whether a transfer station should be constructed or not.
- Gunalay et al. (2012) showed how simulation-optimization modeling can be used to efficiently generate multiple policy alternatives that satisfy required system performance criteria in stochastically uncertain environments and yet are maximally different in the decision space. Islam et al. (2012) mentioned an integrated system combined of Radio Frequency Identification (RFID), Global Position System (GPS), General Packet Radio Service (GPRS), Geographic Information System (GIS) and Web camera for MSW collection.
- Hemmelmayr et al. (2013a) and Hemmelmayr et al. (2013b) designed a collection system consisting of the combination of a vehicle routing and a bin allocation problem in which the trade-off between the associated costs has to be considered. The solution approach combines an effective variable neighborhood search metaheuristic for the routing part with a mixed integer linear programming-based exact method for the solution of the bin allocation part.
- Levis et al. (2013) presented the first life cycle-based framework to optimize—over multiple time stages—the collection and treatment of all waste materials from curb to final disposal by minimizing cost or environmental impacts while considering user-defined emissions and waste diversion constraints.
- Mora et al. (2013) showed a planning model for an integrated waste management system based on kerbside collection. A heuristic procedure was also applied in order to obtain some admissible solutions of the real problem in reasonable computational time.

It is clear from the literature that the existing VR models partly examined the components such as the depot, the landfill, multiple transfer stations and multiple gather sites (Galante et al., 2010). Moreover, they worked with homogeneous vehicles only and did not take into account the traveling in one-way routes, the number of vehicles per m^2 and the waiting time at traffic stops for the reduction of operational time, which are essential factors to the real scenario of MSW collection (Apaydin and Gonullu, 2011). Regarding the objective functions in VR models, the most frequent