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A novel methodology for designing a household waste collection system for insular zones

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A B S T R A C T

This paper addresses the problem of designing a household waste collection system for rural insular areas using a barge for transportation, based on a novel mixed integer programming model that simultaneously integrates decisions of waste collection sites selection within the islands to be served, visit schedule for each selected collection site, and multi-period vehicle routing. An application to a real-world instance consisting of small rural islands located in the south of Chile shows the effectiveness and complexity of the model, along with the advantages of using a waste compactor instead of transporting the waste using bins onboard a barge.

1. Introduction

In recent decades, researchers and practitioners have shown a significant interest in problems involving the design, planning, and operation of an industrial or household solid waste collection system. This is mainly explained by a growth in the generated waste volume and its environmental impacts, and by an increase of environmental awareness and sustainability requirements in modern societies. Therefore, there has been a strong development of models and tools to support planning and design of urban solid waste management systems (Gottinger, 1988; Kirca and Erkip, 1988; Angelelli and Speranza, 2002a; Viotti et al., 2003; Kim et al., 2006; Karadimas et al., 2007; Sharholy et al., 2007; El-Hamouz, 2008; He et al., 2009; Arribas et al., 2010; Xu et al., 2010; De Figueiredo and Mayerle, 2008; Parker et al., 2010) based mainly on operations research techniques, as presented in this paper. Different modeling structures have been developed to address the Waste Collection System Design (WCSD) depending on the specific features of the problem. The following paragraphs describe some relevant examples of these features along with studies and approaches found in the literature.

When assuming that the waste volume generated between two consecutive visits for each collection site or point is insufficient to fill a vehicle (Less than Truck Load, LTL), the WCSD problem will face the structure of a Vehicle Routing Problem, VRP (i.e., one destination/depot node and multiple origin nodes within a same route/vehicle). See Laporte and Osman (1995), and Ando and Taniguchi (2006) for a review of VRPs.

In the case of hazardous substances and industrial waste, planners and modelers should regard ecological issues such as environmental and community risk minimization jointly with transportation costs by employing multi-objective methodologies. Furthermore, industrial waste collection systems usually are Full Truck Load (FTL), in which the entire load is a single

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consignment. Therefore, instead of a traditional VRP, several studies have considered a network flow-based routing problem between multiple origin–destination pairs for transporting hazardous waste (List et al., 1991; List and Mirchandani, 1991; Revelle et al., 1991; Saccomanno and Shortreed, 1993; Patel and Horowitz, 1994; Erkut, 1995; Sivakumar et al., 1995; Erkut and Verter, 1998; Giannikos, 1998; Zhang et al., 2000; Huang and Cheu, 2004; Meng et al., 2005; Dadkar et al., 2008).

In the household waste case, the waste generated at each collection site is deemed as a LTL case since this volume is too low to be considered a FTL case when compared to vehicle capacities. Therefore, a household WCSD problem can be formulated as a combination of a visit scheduling problem and a VRP for each operation day, which is equivalent to the Periodic VRP, PVRP (Angelelli and Speranza, 2002b; Francis et al., 2008; Hemmelmayr et al., 2013), Inventory Routing Problem, IRP (Bertazzi et al., 2002, 2008; Campbell and Savelsbergh, 2004) or Cyclic Inventory Routing Problem, CIRP (Raa and Aghezzaf, 2007; Raa et al., 2007; Zhong and Aghezzaf, 2009; Zheng et al., 2009; Aksen et al., 2012). In the latter, the visit schedule is defined for a bounded, short period (e.g., one week or one month) that is repeated over time. Notice that the IRP and the CIRP may be defined as extensions of the PVRP, in which inventory management for customers or demand points is part of the optimization problem along with PVRP decisions. Finally, when the planner determines the set of waste collection sites to be served, the household WCSD problem may present a structure similar to the selective VRPs, as in Gendreau et al. (1998), Laporte and Martello (1990), Süral and Bookbinder (2003), Gribkovskaia et al. (2007), Gutierrez-Jarpa et al. (2010), and Aksen et al. (2012).

Several studies have addressed the ship routing and scheduling problem (Ronen, 1993; Desrosiers et al., 1995; Sherali et al., 1999; Christiansen et al., 2003; Bronmo et al., 2007; Agarwal and Ergun, 2008; Gatica and Miranda, 2011) by applying and extending VRP and IRP to the case of maritime transportation. Some specific studies have focused on ship routing problems distributing liquid bulk to nearby islands or archipelagos (Al-Khayyal and Hwang, 2007 and Agra et al., 2013). However, these studies do not address site selection or waste management issues, as in this research.

The main objective and contribution of this paper is to develop a novel Mixed Integer Programming (MIP) model to support the system design for collecting rural insular household waste, and its application to an archipelago located in the south of Chile. In this case study, the waste treatment at the islands is currently performed by the inhabitants without any type of waste collection system. The continuous increase in the waste generation warrants a system for collecting this waste efficiently and environment-friendly. The insular household WCSD problem studied in this paper addresses simultaneously three main set of decisions in an integrated manner: waste disposal and collection site selection among the available sites at each island, site collection frequency, and visit sequence of a barge for each operation period (e.g., day).

The proposed model deals with collection frequency decisions for each site based on a visit pattern selection scheme, simultaneously with daily vehicle routing decisions using a single barge. A visit pattern defines the days of the week that a collection site will be visited (e.g., Wednesday and Saturday, or Monday, Wednesday, and Friday). At the same time, the model optimizes the selection of collection sites among a set of potential sites for each island. Hence, a relevant contribution of this research is the novel integrative modeling approach of these three set of decisions to solve the WCSD problem for a set of islands.

Note that there is a similarity of the household WCSD problem analyzed in this paper with the IRP, and particularly with the case of constant frequency in time such as CIRP found in the revised literature. Thus, the proposed model may be deemed as an extension of the IRP and CIRP, in which visit schedule and daily routes are determined. Unlike PVRP, IRP, and CIRP, the proposed model optimizes the selection of waste collection site at each island, similarly to selective VRPs. In addition, unlike selective VRPs, the demand for each potential collection site is unknown in advance since it depends on the number of sites selected for each island. Accordingly, to the authors' knowledge, the problem studied in this research cannot be resolved directly with the existing models observed in the related literature (i.e. PVRP, IRP and CIRP), which highlights one significant contribution of this research.

The proposed model is used to represent and optimize two operating strategies of the waste collection system by simply modifying parameter values: (i) employing a waste compacting machine on board a barge without the need of transporting full/empty bins, and (ii) transporting waste bins on board a barge.

The paper is organized as follows. Section 2 describes the insular household WCSD problem studied in this paper. Section 3 presents the MIP formulation proposed for solving the problem. Section 4 presents the application of the model on a real-world case study along with the results and discussion. Finally, conclusions and future research are provided in Section 5.

2. Problem description

According to the current household waste situation described previously, the problem addressed in this paper consists of designing a waste collection system to serve a set of nearby, small islands belonging to the same political or administrative district. Waste collection and removal locations among potential available sites at each island (e.g., quays, docks, piers, or ports) are selected. Barges for waste collection and transportation will depart and return to a depot, thus determining waste collection tours. Note that time windows for each collection site are observed based on the real world waste collection problem studied in this paper.

This study focuses on the WCSD problem for a specific year, which is considered as the initial operation period. However, if a route reaches the maximum volume capacity of the barge during one of the following years, then the system should be