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Vehicle routing–scheduling for municipal waste collection system under the "Keep Trash off the Ground" policy☆

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ABSTRACT

This paper investigates the waste collection problem and characterizes the problem as a set-covering and vehicle routing problem (VRP) complicated by inter-arrival time constraints. The study proposes a bi-level optimization formulation to model the split delivery VRP with multiple trips to determine the minimum-distance route. The first stage optimally plans the collection points that cover all residential blocks. The second stage applies a heuristics method to solve the minimum vehicles used and minimum distance traveled for collecting residential waste. This research contributes to model this period VRP and to introduce the heuristics method to solve the problem efficiently. The study is important in laying the groundwork for understanding the possibility of improving the service level of municipal solid waste collection.

1. Introduction

Solid waste management is among the mandatory and essential services provided by municipal authorities in most countries to keep urban centers clean [1]. However, it is often among the most poorly rendered services—the systems applied are unscientific, outdated and inefficient [2]. Most developing countries have to wrestle with the problem of efficient solid waste management in the face of increasing waste-generation rates, high collection costs and dwindling financial resources [3]. In some cities, waste is dumped randomly and litters the streets [4]. Public waste collection points are usually extremely smelly and create a sight that largely affects the hygiene and image of a modern society. This once was the situation in Taiwan, the second most densely populated country in the world, where 23 million people crowd 35,800 km^2 of which two-thirds area is rugged mountains. The central government, therefore, decided to change the waste collection system and employ several policies. Among these policies, those having the most direct influence on residents' lifestyle are the mandatory garbage-sorting policy and the "Keep Trash off the Ground" policy, which requires residents to personally bring their waste from their house to dump it into collection vehicles. One advantage of changing the collection system from designated dumping locations to block collection is the elimination of permanent containers and storage sites. However, if family members are out when collectors pass by, the waste must be left at home for the next scheduled collection day, causing a considerable nuisance.

This paper examines the problem of efficiently routing and scheduling collectors for municipal solid waste collection in Taiwan. Municipal solid waste management includes a heterogeneous collection of waste produced in urban areas, the nature of which varies from region to region [5]. In the United States and most European countries, residents place trash and household waste in garbage cans for curbside collection once-a-week. The resulting problem of collecting municipal waste involves visiting each street in a residential network, and studies have typically modeled the problem as a capacitated arc routing problem (CARP), and sought to solve it accordingly [6–13]. Under Taiwan's "Keep Trash off the Ground" policy, the waste collection problem is modeled as a vehicle routing problem (VRP), involving point-to-point collection with stop points for collection trucks scattered throughout the area.

Due to the hot climate of Taiwan, most residential blocks require four visits per week (e.g. Monday–Tuesday–Thursday–Saturday) and the same collection schedule is repeated weekly. To allow residents with daytime jobs to dump their refuse, collection trucks must visit neighborhoods at different times on each collection day, particularly in the evening. Therefore, establishing vehicle routes requires that each collection point is first scheduled [14]. Russel and Igo [15] examined a refuse collection routing problem in which the objective was to assign customer demand points to days of the week and to solve the resulting node routing problems for the entire week.

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Because residential refuse collection involves regularly scheduled collection [16,17], several researchers have modeled the problem of collecting waste as a periodic VRP [15,18–21].

This paper applies management science to the collection of waste in Taiwan, to minimize collection costs while providing adequate service for the entire residential network with fixed charge [22]. The current study characterizes this real-world vehicle routing–scheduling problem as a set-covering and routing problem [23,24] complicated by inter-arrival time constraints at each collection point. To solve a set covering problem [25], we must first determine the collection points at which trucks temporarily stop to collect waste. This problem is a very rich and challenging VRP [7]. Several heuristic algorithms with stochastic techniques were employed to solve complex VRPs and were found to be powerful form the viewpoints of management science [26–29]. We referred to the urban waste collection problem solving with ants heuristics presented by Bautista et al. [6], in which the objective was to minimize the total traveling cost. However, our problem differed from that of Bautista et al. [6] in two respects. First, under Taiwan's "Keep Trash off the Ground" policy, the waste collection problem is directly modeled as a VRP that involves point-to-point collection with stop points. In comparison; Bautista et al. [6] considered the problem of collecting municipal waste as involving visiting each street in a network, and modeled the problem as a CARP, then they transformed the problem into a node routing one. Second, we dealt with scheduling collectors and the number of stops along a route. In contrast, Bautista et al. [6] considered forbidden turns, which implied important constraints for defining feasible routes and specified the routing plan while minimizing collection costs. This study introduces a heuristic based on ant colony optimization (ACO) to overcome the routing–scheduling problem of municipal solid waste collection. Dorigo et al. [30] was the first to propose the ACO based on the food-foraging behavior of ant colonies and researchers have advocated the ACO algorithm for solving VRPs [32,33].

Because of the successful application of the ACO, several versions of ant-inspired algorithms have been proposed for routing problems [34–36]. The two most popular ones are ant system (AS) [30] and the ant colony system (ACS) [31]. Ant system (AS) was the first ACO algorithm to be proposed in the literature [30]. Its main characteristic is that the pheromone values are updated by all the ants that have completed the tour. Once all ants have computed their tour (i.e. at the end of each iteration), the AS updates the pheromone trail using all the solutions produced by the ant colony. Each edge belonging to one of the computed solutions is modified by an amount of pheromone proportional to its solution value. At the end of this phase the pheromone of the entire system evaporates and the process of construction and update is iterated. In the ACS only the best solution computed since the beginning of the computation is used to globally update the pheromone. As was the case in AS, global updating is intended to increase the attractiveness of promising route but the ACS mechanism is more effective because it avoids long convergence time by directly concentrate the search in a neighborhood of the best tour found up the current iteration of the algorithm [37]. The main idea of the algorithm developed in this research was inspired by the ACS, which accounts for exploration and exploitation during the transition state. The ants cooperate using an indirect form of communication mediated by pheromone trails of scent and find the best solution to their tasks guided by both information (exploitation) which has been acquired and search (exploration) of the new route.

Scheduling routes for the collection of solid waste involves several factors, including the number of stops along a route, the amount of solid waste accumulated at each refuse-collection point, and road access to the refuse-collection points [38]. The schedule of workers is limited each workday, and full garbage trucks must travel to the nearest available landfill. Therefore, each truck typically delivers the collected waste to a landfill, returning to the depot for a rest several times per workday. Vehicle capacity dictates the number of landfill trips each truck must make. The service demand associated with each collection point is estimated using demographic data to ensure that routing results fulfill the capacity constraints of designated collection trucks. The main objectives of this study are to (1) minimize the total frequency with which collection points are visited, while providing service of a higher level than that currently provided and (2) determine efficient routes in terms of travel distance required to collect waste.

The remainder of this paper is organized as follows. Section 2 provides a detailed description of the set-covering problem used to determine collection points and the routing–scheduling problem of municipal waste collection, as well as formulations for the trucks and distance minimization model. Section 3 discusses the ACO algorithm in detail and describes the procedures involved in applying the ACO to resolve routing–scheduling problems. Section 4 presents the results, which demonstrate the benefits of incorporating the minimum allowable inter-arrival time between two consecutive collections on any block. The final section summarizes the findings and suggests avenues for further research.

2. Model formulation

This study proposes a bi-level optimization model that first plans collection points by solving a set covering problem, followed by route planning based on solving a VRP with pickup and delivery. The first stage reviews the municipality made up of a number of neighborhoods for waste collection trucks to stop temporarily and designates collection points at street intersection of the residential network to collect the waste of any adjacent neighborhood. Fig. 1 illustrates that intersection m is a potential collection point which is adjacent to blocks 5, 8, and 9. If the municipality designates a collection point at intersection m, then the collectors will collect waste produced by the residents of blocks 5, 8, and 9. The objective of the model is to minimize the frequency of collection over the entire residential network, by providing residents with convenient services for the disposal of waste by individuals. However, many residents dislike collection points near their front door, not only because of objectionable odors, but also because of physical obstructions. Although this study permits trucks to stop at any street intersection (node) more than once during a single trip, it avoids the noise of trucks hovering around neighborhoods. Moreover, a reduction in the number of stops facilitates routing and reduces transportation and handling costs. Given a connected graph $G=(V,A,B)$ with V as the set of vertices representing the intersection points in this study, $A=\{(i,j): i,j \in V, i \neq j\}$ is the set of arcs, and $B=\{(i,j,k,\ldots): i,j,k,\ldots \in V, i \neq j \neq k\}$ represents the set of blocks in which the tuple of street intersections $(i,j,k,\ldots)$ defines block b. Referring to Fig. 1, block 5 is characterized by an intersection tuple (i,j,n,m,l,k).

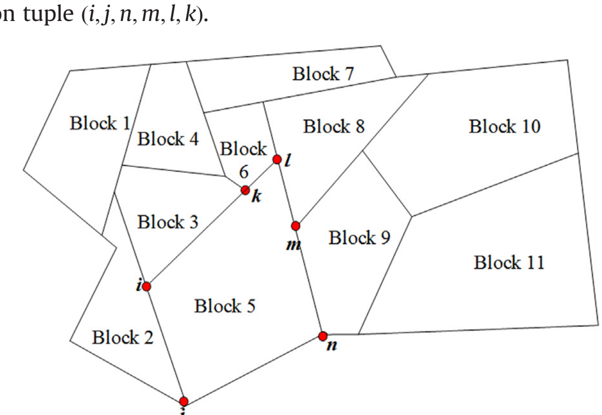

Fig. 1. Adjacency of blocks and intersections.