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Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using PSO algorithm

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ABSTRACT

Waste collection widely depends on the route optimization problem that involves a large amount of expenditure in terms of capital, labor, and variable operational costs. Thus, the more waste collection route is optimized, the more reduction in different costs and environmental effect will be. This study proposes a modified particle swarm optimization (PSO) algorithm in a capacitated vehicle-routing problem (CVRP) model to determine the best waste collection and route optimization solutions. In this study, threshold waste level (TWL) and scheduling concepts are applied in the PSO-based CVRP model under different datasets. The obtained results from different datasets show that the proposed algorithmic CVRP model provides the best waste collection and route optimization in terms of travel distance, total waste, waste collection efficiency, and tightness at 70–75% of TWL. The obtained results for 1 week scheduling show that 70% of TWL performs better than all node consideration in terms of collected waste, distance, tightness, efficiency, fuel consumption, and cost. The proposed optimized model can serve as a valuable tool for waste collection and route optimization toward reducing socioeconomic and environmental impacts.

1. Introduction

Managing waste is a major concern across the world due to its direct effect on the environment. Rapid urbanization and every day human activities produce a large amount of waste from residential, commercial, or industrial areas all over the world. These activities impact climate by increasing the emission of different greenhouse gases (GHGs). The environment quality is rapidly deteriorating with the concerns of solid waste issues (Manaf et al., 2009; Moh and Manaf, 2014). Accumulation of CO_2 in the atmosphere is showing an increasing pattern of approximately 2 ppm per year (Budzianowski, 2012). Currently, CO_2 in the atmosphere is reaching approximately 390 ppm, which leads to global warming (Budzianowski, 2016). The rapid growth of urbanization and population along with the environmental concern have created a critical situation for waste management (Poser and Awad, 2006; Zhang and Huang, 2014; Cioca et al., 2015; Pérez-López et al., 2019; Hua et al., 2017). Every step of waste management should be performed effectively to solve the solid waste problems.

Among all steps of waste management, waste collection from waste generation center to waste management center, i.e., waste collection route, is an important issue (Kanchanabhan et al., 2010). If waste is not collected properly, then nuisance may occur in the waste generation area (Hua et al., 2017). The typical process of waste collection involves vehicles starting from the depot and traveling in fixed routes to collect waste by visiting all locations, which cost a large amount of budget. This process causes wastage of resources because of traveling to empty a bin that is not full yet. Moreover, given a fixed schedule and route of collection and no real-time information of bin status, a bin is not emptied sometimes, although it is full before the scheduled day. This scenario eventually creates a problem (Johansson, 2006). For an efficient waste collection, the collection route needs to be optimized in such a way that considers all the mentioned scenarios. Waste-collecting cost can be reduced if the bin waste level status is known prior to collection. An algorithm is needed for the decision on an optimized waste collection route instead of collecting garbage in a predefined route (Kuo et al., 2012). This route optimization method can save travel distance and minimize the number of vehicles, which in turn

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reduce labor cost, fuel cost, operation time, and GHG emission (Son and Louati, 2016; Gilardino et al., 2017; Mahmuda et al., 2017; Nowakowski, 2017). The route optimization cannot be effective with the conventional waste collection process given no any real-time information about bin status. A waste collection route needs to be designed on the basis of the waste status of smart bin data to ensure efficiency of waste collection.

In considerable research, the waste collection problem of an area has been designed on the basis of the vehicle-routing problem (VRP), which finds an effective collection route (Bautista et al., 2008). However, vehicle capacity has been disregarded. To solve this problem, Dantzig and Ramser (1959) considered vehicle capacity constraint in the VRP, which was named as capacitated VRP (CVRP). Waste collection has been modeled in CVRP approach with different algorithms and software (Kuo et al., 2012; Liu and He, 2012a; McLeod and Cherrett, 2008). Nevertheless, limited experiments have been conducted with smart bin technologies for waste collection and route optimization (Rada et al., 2010; Kristanto et al., 2016; Mamun et al. 2016).

This study introduces an efficient waste collection and route optimization process based on the data from smart waste bins. Smart bin is assembled with different sensors described in the paper of Mamun et al. (2015), which gives the real-time waste condition of the bin. In the current study, particle swarm optimization (PSO) is applied in a CVRP model to solve the routing problem. A number of local improvement algorithms are also applied to improve the PSO performance. The objective of this study is to verify the feasibility of the proposed method for waste collection and route optimization in terms of collection trucks, distance, efficiency, fuel consumption, and cost.

2. Overview of waste collection optimization

Solid waste collection optimization has been studied widely for the last few decades (Swapan and Bidyut, 2015; Khanh et al. 2017; Mahmuda et al. 2017). Every country has to deal with the management of its generated waste. Different optimization approaches have been applied to make the collection system efficient, such as reducing traveling distance, time, cost, and emission. In this section, a brief overview of the related algorithms and solid waste collection technologies is described.

2.1. Optimization algorithms

The algorithms applied in solid waste collection optimization are categorized as conventional, heuristic, and meta-heuristic. In conventional approaches, mathematical programming, such as linear programming (Kulcar, 1996) and mixed-integer programming (Tung and Pinnoi, 2000; Badran and El-Haggar, 2006; Agha, 2006), have been applied for solid waste collection optimization. The limitations of these methods are ineffectiveness for small-scale problems, in which they require numerous components to be considered for optimization; thus, the solution approaches become complicated. These approaches were common at the beginning of solid waste optimization research.

Heuristic approaches have become popular to overcome the complexity of conventional approaches. In case of optimization problems, conventional approaches require considerable computational time. These problems are minimized using heuristic approaches. For example, Faccio et al. (2011) applied nearest neighborhood search algorithm for waste collection optimization. Bautista and Pereira (2006) and Sahoo et al. (2005) used greedy algorithm for collection optimization. However, these techniques lack precision and require a long execution time in collecting solid waste (Viotti et al., 2003). Thus, a new optimization technique is required for efficient collection optimization.

Meta-heuristic approaches, which provide a sufficiently good solution for collection optimization even when incomplete information or limited computation capacity is given, are the most popular approaches in recent years. They incorporate biological evolution, nervous system, and intelligent problem solving. A few popular meta-heuristic approaches are ant colony optimization (Islam and Rahman, 2012; Liu and He, 2012b), genetic algorithm (GA) (Karadimas et al., 2007; Viotti et al., 2003), and PSO (Son, 2014). Recently, agent-based optimization model integrating GIS and backtracking search algorithm (BSA) applied in CVRP model are utilized for solid waste collection and route optimization, respectively (Swapan and Bidyut, 2015; Khanh et al., 2017). Although the performances are promising, however, the obtained results could not achieve optimized value due its continuous optimization problem. The PSO algorithm is a population-based meta-heuristic optimization method that simulates the social behavior of flocks of birds in searching for foods. This method has been used to optimize solutions for difficult problems. The PSO algorithm performs efficiently in route optimization. The basic step of PSO is that it produces a number of particles that are dragged toward the optimized value by a randomly initialized velocity. In every iteration, the algorithm keeps on a track of two best values: the value found by a particular particle (p_{best}) and the best solution found by the entire neighborhood (g_{best}).

ArcGIS is commonly used software for solid waste collection optimization. Real-time road conditions (e.g., traffic and blockage) can be optimized by using this software, and route can be designed accordingly. Considerable research (Malakahmad et al., 2014; Shastri et al., 2014) has applied GIS to determine an optimized route for waste collection. A 3D version of this software was used by Tavares et al. (2009) to determine the most fuel-efficient road. Aremu (2013) used Microsoft Office Excel add-in tool for waste collection optimization. Researchers have also utilized GPS (Arebey et al., 2009) and data mining for solid waste collection optimization (Revetria et al., 2011). However, all software applications are not up to the mark for solid waste collection optimization (Tavares et al., 2009).

2.2. Technologies used for waste collection

Advanced technologies and devices become popular for solid waste collection system. Different technical devices, such as radio-frequency identification for solid waste bin and truck monitoring (Hannan et al., 2011), advanced image processing for bin waste level detection (Arebey et al., 2012), different sensors and systems (Mamun et al., 2015), and vehicular ad hoc network (Narendra et al., 2014), are used to communicate among different collection components to ensure efficiency of waste collection. Kuo et al. (2012) developed a CVRP-modeling concept along with a hybrid algorithm to determine an efficient waste collection route. However, smart bin waste data were not applied and implemented for their collection concept. In the current study, PSO algorithm is used in a CVRP model along with smart bin data from different sensors. These sensors update real-time waste data and bin condition in the server. The modified discrete PSO is modeled and compared its performance with other PSO models as well as BSA meta-heuristic optimization for the validation of the proposed development. The detailed methodology is explained in the next section.

3. PSO algorithm in a CVRP model

A CVRP model is developed on the basis of the present solid waste collection optimization problem. PSO algorithm is incorporated into the CVRP model to solve the route optimization problem. The PSO-based CVRP model uses smart bin data for efficient waste collection. Smart bin is equipped with a number of sensors that