engineering proceedings

Proceeding Paper

Optimizing Waste Collection and Transportation in Islamabad: Efficient Vehicle Routing for Sustainable Waste Management †

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† Presented at the Third International Conference on Advances in Mechanical Engineering 2023 (ICAME-23), Islamabad, Pakistan, 24 August 2023.

Abstract: The municipal solid waste management is key for preserving the environment, protecting public health, and maintaining public cleanliness. Apart from these benefits, developing countries are more attracted to such systems as they offer an economical solution for waste management. This article intends to present a cost-effective and optimized waste management solution for Islamabad, Pakistan. The key steps of this research include; 1. acquisition of data; 2. transformation of data into coordinate form; 3. modeling of optimized waste collection routes and transportation; 4. modification of the capacitated vehicle routing algorithm to yield the optimized vehicle routes. The simulations are performed in MATLAB 2017B. Trial results show the efficacy of the recommended method.

Keywords: capacitated vehicle routing problem (CVRP); Islamabad waste management; vehicle routing problem (VRP)

Citation: Rashid, T.; Ullah, S.; Habib, U.; Rehman, N.; Qureshi, U.R.; Jafar, F. Optimizing Waste Collection and Transportation in Islamabad: Efficient Vehicle Routing for Sustainable Waste Management. *Eng. Proc.* **2023**, *45*, 41. https://doi.org/10.3390/engproc2023045041

Academic Editors: Mohammad Javed Hyder, Muhammad Mahabat Khan, Muhammad Irfan and Manzar Masud

Published: 14 September 2023

1. Introduction

The collection, transportation, and disposal of solid waste (SW) produced by houses is a process known as municipal solid waste management. Waste collection and transportation are accomplished using a fleet of trucks. This conventional waste collection is based on speculation as to whether the filling levels of waste bins could vary from overflowing, partial filling, to completely emptying, which would result in unnecessary resource consumption. Improvements will reduce municipal spending as the cost of waste collection/transportation accounts for 60–80% of overall waste management system (WMS) expenses.

VRP research was conducted in 1959, and its goal was to model the distribution process and map out the most efficient pathways to deliver products to consumers [1]. In addition to the VRP's constraints, the CVRP adds the constraint of the vehicle's capacity.

A significant amount of garbage is produced due to the development in product diversity and consumption, endangering the ecosystem [2]. E-waste seriously harms the ecosystem when combine with the air and soil [3]. Burning/burying plastic garbage could endanger the land and air due to the hazardous chemical gases released [4]. Some 4 to 12 million metric tons of plastic trash are dumped into the oceans annually, leading to water contamination [5]. When medical waste is disposed of, it might cause major environmental issues [6].

It is estimated that the global daily production of medical waste due to the pandemic was over 1.5 million tons [7]. It is now necessary to collect this waste in a systematic manner [8], in order to lessen its harmful impact [9], along with other forms of e-trash [10]. One Indian city's annual e-waste contained valuable materials worth $65,000 [11], showing the economic advantages of employing demolition waste, which is between 50 and 70% of the world's total SW [12].

In this study the method of optimizing routes is used not the waste. The remainder of this article is outlined as follows: Section 2 includes the acquisition of a dataset and an overview of the research methodology; Section 3 contains the model design; the simulation results are presented in Section 4; finally, the article is concluded in Section 5.

The MATLAB 2017B algorithm CVRP is used for simulation.

2. Data Acquisition and Research Methodology

In this section a brief overview of steps to acquire data and the employed research method are provided. The following steps were taken to acquire the waste bin and vehicle data from the concerned authorities: 1. visit MCI; 2. enlist their challenges and collect data; 3. locate the bins on Google Maps according to the acquired dataset; 4. import data to the web plot digitizer, draw axes, locate bins, and find coordinates; 5. create CSV and TXT files so the data becomes ready for the mathematical computing and analysis tools.

The dataset is ready, the only problem left was to employ the research method for obtaining the optimized route. Amongst the available resources, CVRP is widely used as discussed in Section 1. The following steps were taken to obtain an optimized route: 1. import geographic data into MATLAB 2017B; 2. transform data, i.e., the number of vehicles, capacities of vehicles, distances between the bins, expected expenditure, etc. into the MATLAB 2017B format; 3. locate bins and input the amount of waste in each bin into MATLAB 2017B; 4. run the CVRP simulation in MATLAB 2017B; 5. find optimal results; 6. based on these results, we plan to submit the proposal to MCI.

3. Model Design

3.1. Description of the Problem

The aim of this research is to minimize the overall distance traveled and the total comprehensive cost, including vehicle costs. The vehicles are located at a depot, and its routes begin there. When a waste truck is full, or the assigned task is completed, it returns to the depot.

Assumptions: In addition to the above, we assume the following: 1. one vehicle collects each bin once; 2. there is a single depot; 3. the vehicles leave the depot and return when the job is completed; 4. the vehicles are of various capacities; 5. the location of the depot and each bin is known.

3.2. Model Construction

In this subsection, the complete mathematical model for the optimized waste collection problem is provided. The main objectives are to minimize the vehicle distance as well as the cost of waste collection. Therefore, the objective function are as follows:

$$\min TD = \sum_{m\in(B\cup D)} \sum_{n\in(B\cup D)} x_{mn}^k d_{mn} \tag{1}$$

$$\min TC = \sum_{k\in V} \sum_{n\in(B\cup D)} x_{0n}^k P_{fixed} + \sum_{m\in(B\cup D)} \sum_{n\in(B\cup D)} x_{mn}^k d_{mn} r_{mn} P_{fuel} \tag{2}$$

These objective functions are constrained by following conditions:

$$\sum_{k\in V} \sum_{m\in(B\cup D)} x_{mn}^k = 1; \quad \forall\, n \in (B\cup D) \tag{3}$$

$$\sum_{k\in V} \sum_{n\in(B\cup D)} x_{mn}^k = 1; \quad \forall\, m \in (B\cup D) \tag{4}$$

$$\sum_{m\in(B\cup D)} x_{mn}^k = \sum_{n\in(B\cup D)} x_{mn}^k = 1; \quad \forall\, m \in (B\cup D), k\in V \tag{5}$$

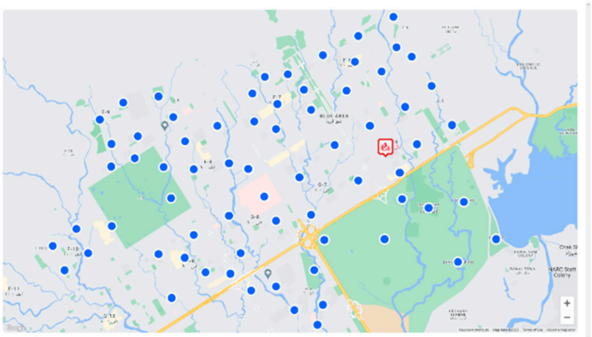
$$\sum_{m\in(B\cup D)} \sum_{n\in(B\cup D)} x^k_{mn} q_n \leq C_p; \quad \forall\, k \in V \tag{6}$$

$$x^k_{mn} \in \{0,\ 1\}; \quad \forall\, m,\ n \in (B \cup D), k \in V \tag{7}$$

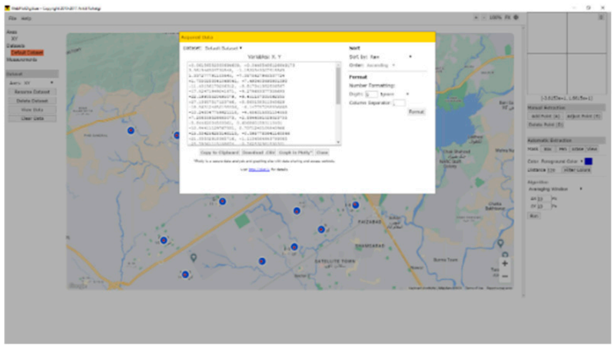
To begin, we have two objective functions, Equation (1) and Equation (2), their respective goals are the minimum total distance and minimum total cost. Constraint Equation (3) ensures that each waste bin is collected by a single vehicle. All routes will respect the maximum capacity by Equation (4) to Equation (6). Equation (7), defines the variable types, where B represents bins, D is depot, V is a set of vehicles, P_{fixed} is the expenses attached to each vehicle, d_{mn} is the distance between bins 'm' and 'n', r_{mn} is fuel consumption rate per unit kilometer, P_{fuel} is fuel consumption cost, x^k_{mn} checks whether a vehicle 'k' moves from waste bin 'm' to waste bin 'n'. q_n shows Waste collected at waste bin 'n'. C_p is a vehicle's maximum carrying capacity.

4. Results and Discussion

The major results of this research are presented in this section. The map of the waste collection points and depot at G-6/1 is presented in Figure 1a. Seventy bins are located throughout the territory. The red truck represents the MCI and the blue dots indicate the waste bins.



(a)



(b)

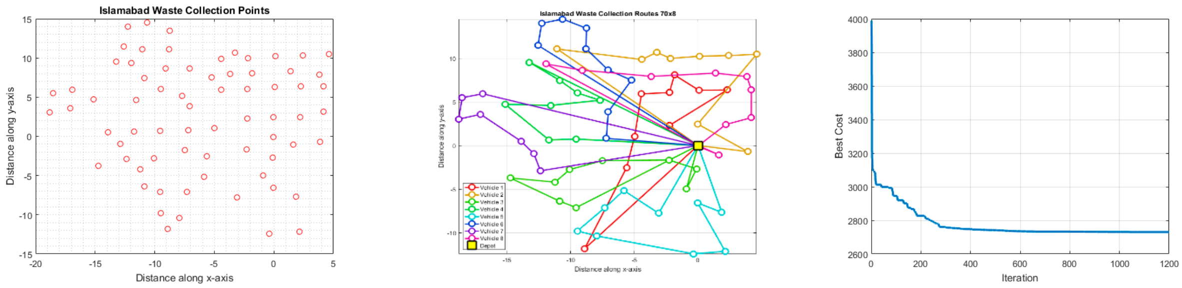
Figure 1. (**a**) Locating the collection points on Google Maps; (**b**) importing to WebPlotDigitizer 4.1, drawing axes, locating collection points, and finding coordinates.

The CVRP algorithm is used for analysis to determine the exact method of solving.

In Figure 1b, the Google Maps points were transferred into the WebPlotDigitizer 4.1 to transform the location of bins into a Cartesian plane dataset. The depot was defined at $(0, 0)$, the $x - axis$ parallel to the Kashmir Highway and the $y - axis$ perpendicular to it. The geographic coordinates were retrieved and saved in both CSV and TXT file formats.

In Figure 2a, bins are displayed graphically within MATLAB 2017B, after the geographical coordinates were imported. The red circles are the location of the bins and the depot at $(0, 0)$.

In Figure 2b, the yellow square shows the depot and rest of the colors show the optimized routes. Figure 2c shows a monotonic reduction, illustrating a steady decline in cost.



(**a**) (**b**) (**c**)

Figure 2. (**a**) Islamabad waste collection points in MATLAB 2017B; (**b**) Islamabad waste collection routes (70 × 8); (**c**) Islamabad waste collection optimized cost (70 × 8).

5. Conclusions

A case study in which the environmental problem of SWM was optimized by employing CVRP. The case involved SWM in the Islamabad Capital Territory (ICT) administered by MCI supervised by Capital Development Authority (CDA). The algorithm implemented for optimizing the routes shows a consistent and gradual decrease in cost with each iteration. It is crucial to emphasize that the algorithm ensures no further cost reduction is possible. After 1200 iterations, the algorithm identified the optimum paths, and no additional route optimization was achievable. This finding highlights the algorithm's effectiveness in enhancing SWM efficiency.

Author Contributions: Conceptualization, T.R., S.U. and U.R.Q.; methodology, T.R. and U.H.; software, T.R. and F.J.; validation, U.H. and N.R.; formal analysis, T.R. and U.H.; investigation, S.U.; resources, T.R. and U.R.Q.; writing—original draft preparation, T.R., N.R. and F.J.; writing—review and editing, U.H. and U.R.Q.; visualization, F.J.; supervision, S.U.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Dataset is available upon request.

Acknowledgments: The authors are thankful to the Sanitation Directorate (MCI), CDA, Islamabad for their continuous support during the course of this research.

Conflicts of Interest: The authors declare no conflict of interest.

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