Integrated Planning of IoT-Based Smart Bin Allocation and Vehicle Routing in Solid Waste Management

Arindam Roy[1,3], Apurba Manna[2], Jungmin Kim[3], and Ilkyeong Moon[3,4](✉)

[1] Department of Computer Science and Application, Prabhat Kumar College, Contai 721404, India

[2] Research Centre in Natural Sciences, Raja N L Khan Women's College, Medinipur 721102, India

[3] Department of Industrial Engineering, Seoul National University, Seoul 08826, Korea

ikmoon@snu.ac.kr

[4] Institute of Industrial Systems Innovation, Seoul National University, Seoul 08826, Korea

Abstract. The internet of things (IoT) is a prominent modern technology that offers robust solutions to modernizing consecutive systems. It accords controlled and calibrated outcomes to streamline smart cities, smart homes, smart industries, and smart environments. In this study, an ultrasonic sensor-based waste filling level is considered on IoT-based waste bins to optimize dynamic routes instead of fixed routes, such that the efficiency of waste collection and transportation can be improved. This article illustrates the time-dependent penalty concept to waste management authorities if these smart bins are not emptied in time after becoming full. This article presents a smart waste management model for smart cities that takes into account both bin allocation costs and routing costs. An innovative meta-heuristic neighborhood search technique is developed to solve the above model. The proposed model is illustrated with some numerical data, and a sensitivity analysis is performed with some parameters. After the waste from smart waste bins is collected, some waste products are recycled and reused through application of the game-theoretic concept involving the South Korean aspect of waste management.

Keywords: Smart bin · Neighbourhood search · Vehicle routing

1 Introduction

Due to rapid urbanization, waste management is becoming a vital issue in today's developed and developing countries. In South Korea, a rapid transition to urbanization and industrialization has changed both solid waste characteristics and management techniques. The generation of municipal solid waste (MSW) has

Published by Springer Nature Switzerland AG 2021
A. Dolgui et al. (Eds.): APMS 2021, IFIP AICT 632, pp. 499–509, 2021.
https://doi.org/10.1007/978-3-030-85906-0_55

increased many times over the past few years in urban areas. Hence, the collection and treatment of waste are twin headaches that present vital problems to waste management authorities. Traditionally, waste bins are cleaned at certain intervals by cleaners. But, this process has plenty of drawbacks. Continuous monitoring is required to control the overflow of waste bins for a healthy and clean environment. Sometimes in specific areas, waste bins are filled up faster, due to various factors like festive seasons and unexpected overloads. The situation gets worse in the monsoon season, when rainwater enters waste bins, leading to the decomposition of waste by bacteria and insects that in turn increase the release of bad odors.

Nowadays, both municipal and private authorities are giving serious consideration to the use of advanced technologies, such as computerized vehicles, that make decisions on optimal route planning and scheduling for collecting waste, as described by Huang and Lin [8]. The mathematical model most often used for vehicle routing to collect municipal solid waste was presented by Beltrami and Bodin [4]. Angelelli and Speranza [2] considered a model in which collection vehicles use immediate facilities for unloading along their routes. In another research paper, Angelelli and Speranza [3] considered an algorithm that was used to measure the operating costs of three different waste-collection systems. Hemmelmayr et al. [7] presented one research paper on integrated waste bin allocation and vehicle routing in solid waste management. In that paper, however, they considered bin allocation cost and routing cost separately and did not consider smart waste bins. Nuortio et al. [9] and Vicentini et al. [11] developed sensitized waste collection containers for content estimation and collection optimization, but have not considered any other new advanced web-based information systems. Today, advanced IoT algorithms can boost information technology to a large extent. Sinha, Kumar, and Saisharan [10] proposed a smart waste bin that can contribute to a clean and hygienic environment to build a smart city. In our proposed model, we consider the smart waste bin system, which therefore has the potential for detecting the overflow of waste through an ultrasonic sensor. A smart waste bin can send a message to a central monitoring system (CMS) to clean the waste bin. Using our Vehicle Routing technique, we can clean the bin as early and efficiently as possible. A time-dependent penalty is considered if the filled (100%) bins are not emptied in time. Our study also highlights the game-theoretic approach of private and public waste collection and the ways in which waste is properly utilized for different purposes in South Korean society.

2 Smart Bin

Our proposed model of an IoT-based smart bin system has the potential for remotely detecting overflow of waste bins. Given this potential, it also has the potential to alert waste management authorities regarding the cleaning of waste bins in case of overflows above a set threshold fill level (TFL).

Detail Configuration

Ultrasonic Sensors (USs): Ultrasonic sensors sense the distance between the closing lid of the smart bin and the level of waste within it. The continuously recorded data by USs is sent to a Wi-Fi module through the ARDUINO UNO system in real-time data from the smart bin's US sensor and is transmitted through the wireless module to a smart waste management application platform. The ARDUINO UNO system is an automation system derived from the use of an ARDUINO UNO board; automation refers to the entire self-functioning system. The board itself acts as the "brain" or the central processing unit (CPU) for the entire apparatus. It controls the various interactions and synchronizations of the sensors.

Wi-Fi Module: Internet access, through Wi-Fi, will be allocated to our system by ESP8266, which is known as a Wi-Fi module. The Wi-Fi module can communicate with any kind of micro-controller and can help in making the system wireless for remote access. The Arduino technology is among the leading transmitting devices in the IoT platform.

Working Principle: Through the use of an Arduino board and the sensors, we can automate the function of a normal bin, thereby turning it into a smart bin. By using the US, the smart bin can measure the amount of waste, and detailed information on it can be sent to the Arduino board. As soon as the waste reaches a particular level set by the waste management authorities, the smart bin sends a notification to the municipal corporation for immediate cleaning of the bin. The Wi-Fi module is triggered from the Arduino board and sends the real-time data to the central monitoring system to analyze the amount of waste that is within the bin.

3 Problem Description and Mathematical Formulation

We present the smart waste collection problem occurring in a smart city where some IoT-based smart bins are placed in different places around the city. Our problem consists of integrating the IoT-based smart bin allocation with vehicle routing for waste collection. This problem is called the waste bin allocation and routing problem (WBARP) and requires a balance between bin allocation costs and vehicle routing costs in an optimum measure. In our proposed model IoT-based smart bins are sending alerts to cleaning authorities when smart bins are filled to a predefined threshold fill level, say, 90%. A time-dependent penalty cost to the waste management authorities is considered if smart bins are not emptied in time after filling full (100%). We developed a virgin neighborhood searching technique, which will search the filled (90%) bins and nearest neighbor bin's status at the time of cleaning of the last filled bin. The nearest neighbor bin will be cleaned when its waste filling status is less than TFL and sufficient space is available to hold the waste.

In our proposed model, a vehicle starts its journey from a depot and collects waste from a set of bins, and then unloads the waste into the nearest disposal center. Finally, the vehicle returns to the depot. To achieve the objective of this waste management model, some assumptions, notations are considered to make the model more realistic. These are given below:

Assumptions

- All the empty vehicles start from the depot and collect waste from all filled (≥90%) waste bins and their neighbor waste bins and carry the collected accumulated waste to the nearest disposal center and return to the depot.
- The CMS sends a vehicle from the depot when some waste bins are filled (≥90%).
- The cumulative waste of all the filled waste bins of a route must not exceed the maximum vehicle capacity of that vehicle assigned for that route.
- The capacities of waste bins are homogeneous.
- The capacities of vehicles are homogeneous.
- The average uniform speed of all vehicles is considered throughout the routing to avoid traffic congestion.

Notations

B Set of waste bins $B = \{b_1, b_2, b_3, \cdots, b_n\}$
V Set of vehicles $V = \{v_1, v_2, v_3, \cdots, v_m\}$
d_0 Depot of vehicles.
B_f Set of all bins filled $\geq TFL$, $B_f \subseteq B$
$N[b_i]$ Neighbor of b_i $\{b_x : b_x \in B,\ b_i \in B_f$ and $d(b_x, b_i) \leq K,\ K$ is a fixed positive number, d denotes the euclidean distance; where filling level of $b_x <$ TFL$\}$ including b_i.
B_p Set of all bins initiated for a penalty, $B_p \subseteq B_f$.
D Set of disposal center.
B^+ $(\{d_0\} \cup B \cup D)$; consider $G^+ = (B^+\ ,\ E^+)$ to be the undirected graph. where B^+ is the vertex set and $E^+ = \{(i, j) : i, j \in B^+, i \neq j\}$ is the edge set.
B_f^+ $(\{d_0\} \cup B_f \cup D)$; consider $G_f^+ = (B_f^+\ ,\ E_f^+)$ to be the undirected graph where B_f^+ is the vertex set and $E_f^+ = \{(i, j) : i, j \in B_f^+, i \neq j\}$ is the edge set.
$N^+[b_i]$ $(\{d_0\} \cup N[b_i] \cup D)$ consider $G_N^+ = (N^+[b_i],\ E_N^+)$ to be the undirected graph where $N^+[b_i]$ is the vertex set and $E_N^+ = \{(i, j) : i, j \in N^+[b_i], i \neq j\}$ is the edge set.
r_h Unit traveling cost of the vehicle type h per unit distance.
C_b Unit bin allocation cost.
$x_{ijh} = 1$, if a route visited between the i^{th} node to j^{th} node in the undirected graph using the vehicle h; 0, otherwise.
d_{ij} Distance between the i^{th} node to j^{th} node in the undirected graph, for simplicity, $d_{ij} = d_{ji}\ \forall\ i, j$
$\beta_1 = 1$ if $N[b_i] \neq \phi$ else $\beta_1 = 0, \quad \forall\ b_i \in B$
$\beta_2 = 1$ if $B_f \neq \phi$ else $\beta_2 = 0$
$\beta_3 = 1$ if $B_p \neq \phi$ else $\beta_3 = 0$
$P_i(t)$ Penalty cost of waste bin b_i, after filling 100% waste at time t, $b_i \in B_p$.

lb_i Amount of waste at bin b_i at the time of visit.
L_h Maximum load capacity of the vehicle h.
l_{ijh} Load of vehicle h; when visited between node i to node j in the undirected graph G^+.

In our proposed waste bin allocation and routing problem (WBARP), a vehicle starts its journey from the depot after receiving the signal from the CMS to clean the filled bins, neighbor bins, and unload the waste to the nearest disposal center, while maintaining a minimum travel distance. Here, vehicles follow the shortest path using our developed neighborhood search technique. The mathematical formulation of the above-proposed model is given below.

Routing cost for collecting waste from filled bins

$$Z_2 = \beta_2 * \sum_{i=1}^{|B_f^+|} \sum_{j=1}^{|B_f^+|} \sum_{h=1}^{|V|} x_{ijh} * d_{ij} * r_h \tag{1}$$

Routing cost for collecting waste from neighboring bins

$$Z_1 = \beta_1 * \sum_{i=1}^{|N^+[b_i]|} \sum_{j=1}^{|N^+[b_j]|} \sum_{h=1}^{|V|} x_{ijh} * d_{ij} * r_h \tag{2}$$

Penalty cost of waste bin b_i, after filling 100% waste at time t

$$P_i(t) = a + bt, \qquad a, b, t > 0, \;\; \forall\, i = 1, 2, ..., |B_p| \tag{3}$$

In Eq. (3), a penalty cost of a waste bin means if a waste bin is filled above 100%, waste management authority should pay a penalty for that. The formula for penalty is a plus bt, and both a and b are two positive constants. A is the fixed part, i.e., the minimum cost of the penalty, and the penalty cost is linearly increasing with time (t). The objective function is to minimize the bin allocation cost, transportation cost, and penalty cost as follows:

$$Z = C_b * |B| + Z_1 + Z_2 + \beta_3 * \sum_{i=1}^{|B_p|} P_i \tag{4}$$

subject to:

$$\sum_{i(b_i \in B_f)} x_{d_0ih} = 1, \quad \forall\, h \in V \tag{5}$$

$$\sum_{i(b_i \in B_f)} l_{d_0ih} = 0, \quad \forall\, h \in V \tag{6}$$

$$\sum_{i(b_i \in B_f \cup N[b_l])} lb_i \leq L_h, \;\; b_l \in B_f, \;\; \forall\, h \in V \tag{7}$$

$$x_{ijh} \in \{0, 1\}, \;\; i \neq j, \;\; (\forall\, i, j : \;\; b_i, b_j \in B_f \cup N[b_l]), \;\; b_l \in B_f, \;\; \forall\, h \in V \tag{8}$$

In Eq. (7) and in Eq. (8), b_l indicates the last filled bin being visited. Equation (5) confirms that each vehicle starts its journey from a depot. Equation (6) ensures that h^{th} vehicle will start its journey from the depot without any load. Equation (7) states that the total collected waste from a set of filled waste bins and its neighbor waste bins must not exceed the maximum load capacity of a vehicle. Equation (8) represents some binary variables.

4 Neighborhood Search Algorithm (NSA)

The vehicle routing problem (VRP) is a well-known optimization problem. Akhtar et al. [1] used the backtracking search algorithm (BSA) to solve the capacitated VRP. Our proposed algorithm finds the nearest set of bins from the current bin being visited. The nearest set of bins will be visited if they fulfill the pre-specified TFL. The proposed neighborhood search algorithm (NSA) is as follows.

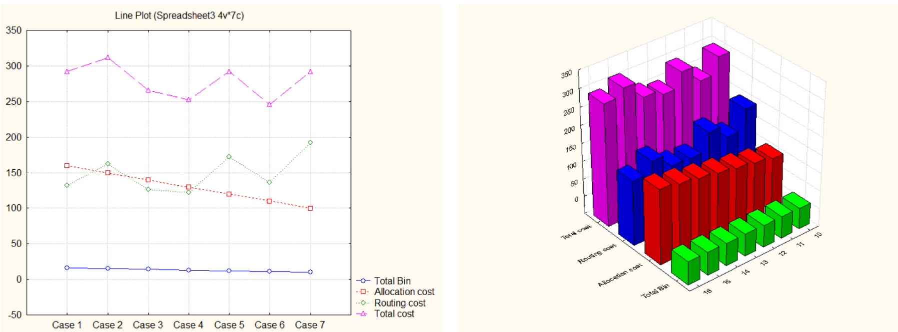
Algorithm 1 Neighborhood search algorithm

Require: A set of given waste bins, B, with their current status.
Ensure: An optimum path for waste collection and transportation.

Begin
initialize the set of bins, (B_f), that have to be visited based on the report from CMS;
a vehicle h starts its journey from the depot, (d_0);
find the nearest bin, b_i, from the depot and visit b_i, $b_i \in B_f$;
while($|B_f| > 1$)
find the nearest neighboring bin from b_i with pre-specified TFL;
visit the nearest neighboring bin, b_j, from b_i, if vehicle waste load $\leq L_h$, $b_j \in B_f$;
randomly select a bin, b_k, $b_k \in B_f$;
create an alternate route, starting from b_k;
find the nearest neighboring bin from b_k with pre-specified TFL;
visit the nearest neighboring bin, b_m, from b_k, if vehicle waste load $\leq L_h$, $b_m \in B_f$;
$b_i = b_m$;
end while
if $|B_f| = 1$
repeat the above searching technique from the current position for a set of neighbour bins $N[b_i]$; visit the neighboring bins $\in N[b_i]$, if vehicle waste load $\leq L_h$;
end if
finally, find the shortest path to collect waste from bins and unload the collected waste into the nearest disposal center;
vehicle returns to it's depot (d_0);
End

5 Computational Experiments and Discussion

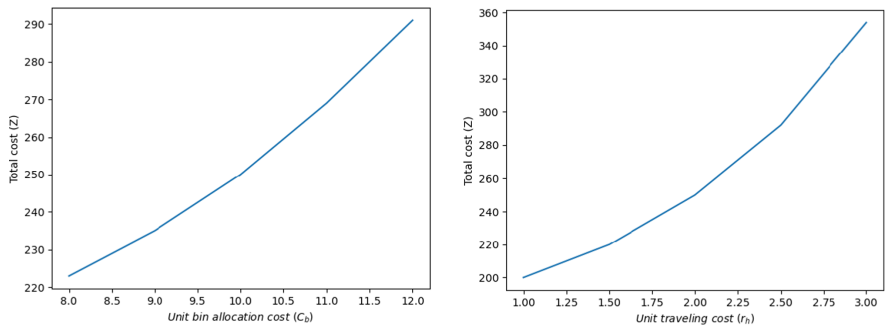
Our proposed algorithm was created in Python on a PC with an Intel Core i3 processor running at 3.0 GHz and 8 GB of RAM. In this study, the proposed NSA algorithm is our developed search algorithm. This algorithm depends on only one parameter. The routing of a vehicle always depends on the current report from the CMS. The goal of our present study is to fulfill the main objective of optimizing the waste collection and transportation route by allocating the ideal number of smart waste bins. In Fig. 1(a), we consider seven cases according to the number of bins considered. In Case 1, the number of bins is 16; in Case 2, the number of bins is 15; and in this way in Case 7, the number of bins is 10. Here, Case 6 presents with low cost and Case 4 is near about Case 6. In Case 4, the number of bins allocated and the corresponding cost is higher than it is in Case 6, but the vehicle routing cost is lower than in Case 6. Figure 1(b) presents a comparative study of total costs along with routing costs and allocation costs. A sensitivity analysis is performed on Case 6 for the minimum total cost (Z) concerning different values of the parameters, results are graphically presented in Fig. 2(a) and Fig. 2(b) respectively. It is observed that unit traveling cost slightly more cost-effective than unit bin allocation cost. Figure 3 shows the performance of our proposed NSA algorithm against the traditional genetic algorithm (GA) and it is clearly shown that the performance of NSA is better than GA.



(a) Optimum number of bins to minimize the total cost.

(b) Routing cost vs allocation cost.

Fig. 1. Different costs vs optimum number of bins.



(a) Unit bin alloc. cost (C_b) vs Total cost (Z) for Case 6.

(b) Unit traveling cost ($r_h, h = 1$) vs Total cost (Z) for Case 6.

Fig. 2. Unit bin allocation & traveling cost vs total cost for case 6.

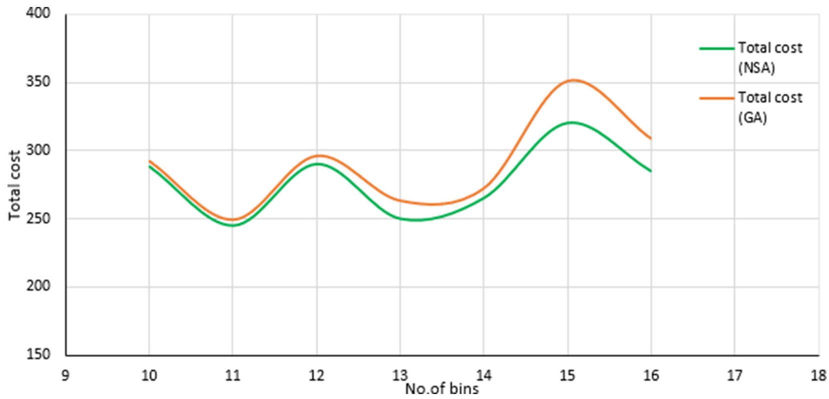


Fig. 3. NSA vs GA

Further extension of this study could be in clarifying the relationship between waste producers in light of the game-theoretic approach [5]. Suppose there exists cooperation between waste producers through communication. To be specific, there is a dominant waste producer, and the other waste producers are dependent on the dominant waste producer. This assumption is quite realistic, because there are two types of waste producers, public waste producers, and private waste producers, and their dominance is interrelated. Moreover, our concept also could be modeled as a Pareto optimization problem. Figure 4 shows that objectives are organized with multiple waste producers, thereby minimizing their total transportation costs, and with multiple wastes to energy(WtE) operators, thereby maximizing their profits. However, some of the waste producer's objectives might not necessarily be cost minimization. Rather, their main concern could be the utilization of waste collection vehicles. In this regard, checking the Pareto optimization in this problem could offer the possibility of improving supply chain value in waste management [6]. Waste could be classified based on its recyclability. Figure 5 shows a possible effective flow of waste management in

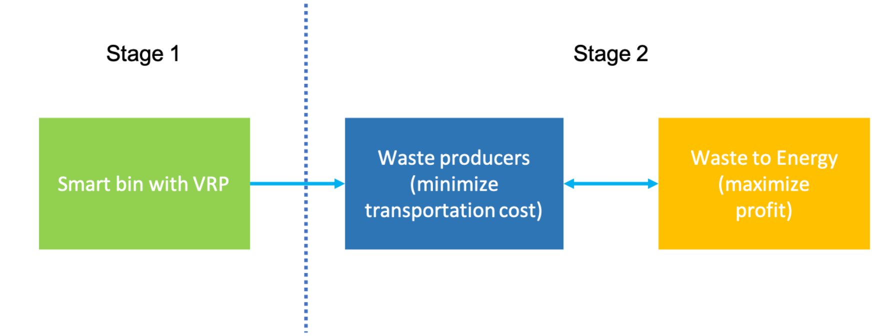


Fig. 4. A two-stage approach in waste management

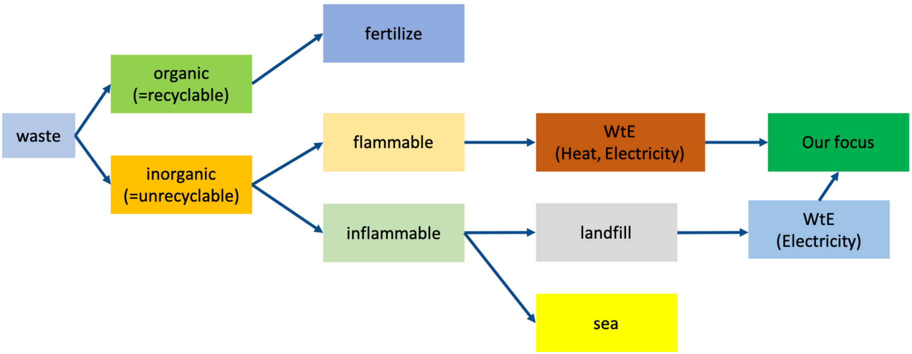


Fig. 5. Waste management in South Korea

Korea. If the waste is recyclable, then this waste could be recycled in several ways, e.g., fermentation to make additional utilization. However, if the waste is not recyclable then we need to decide whether to incinerate the waste. Inflammable waste could be disposed of at landfills or allocated sea areas. At the landfills, we could generate electricity through gas produced from waste, which is called the WtE process. But if the waste is flammable, there is also another WtE process available through the incinerator, which could provide both heat and electricity.

6 Conclusions

The present study represents a dynamic vehicle routing problem for smart bin waste management. The system is configured for IoT-based smart bins. All bins' monitoring processes are controlled through CMS. All vehicles start their journeys from a common depot to serve a set of bins reported by the CMS. The main goal of this paper is to minimize the routing cost for waste collection and transportation using an optimum number of bins because IoT-based bin allocation and maintenance are costly. Waste management authorities always try to minimize their cost using a certain number of bins with a minimum routing cost. To maximize profits, waste management authorities may use the waste of a city for various purposes (for instance, fertilizer, which could be used to fill the land, or WtE strategies could be employed for heat and electricity generation). Different researchers show the efficiency of IoT-based smart bins to keep cities clean. Our study, however, focuses on maintaining an efficient number of bins and on the real-time-based neighborhood search technique to optimize the routing costs and bin allocation costs. Figure 1(a) shows the minimum total cost for a certain number of bins with a minimum routing cost within seven cases. Figure 2(a) and (b) show the cost-effectiveness on traveling cost and bin allocation cost. The results of our study show the efficiency. The best waste management system has two wings. One is quick and efficient waste collection and transportation up to the disposal center with minimum cost. The other focuses on maximizing profits for reusing waste. Proper waste management is necessary to construct a pollution-free smart city. In the future, a large number of smart bins can be considered for a large city. Special types of bins could be considered for different types of critical waste such as medical waste and chemical waste, as well as for regular household and other waste (organic, inorganic, metal, and flammable). Also, different types of vehicles could be considered for separately removing critical and regular waste.

Acknowledgement. This research is supported by the Brain Pool Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT, and Future Planning [Grant No. NRF-2020H1D3A2A01085443].

References

1. Akhtar, M., Hannan, M.A., Begum, R.A., Basri, H., Scavino, E.: Backtracking search algorithm in CVRP models for efficient solid waste collection and route optimization. Waste Manage. **61**, 117–128 (2017)
2. Angelelli, E., Speranza, M.G.: The application of a vehicle routing model to a waste collection problem: two case studies. In: Klose, A., Speranza, M.G., Van Wassenhove, L.N. (eds.) Quantitative Approaches to Distribution Logistics and Supply Chain Management. Lecture Notes in Economics and Mathematical Systems, vol. 519, pp. 269–286. Springer, Heidelberg (2002). https://doi.org/10.1007/978-3-642-56183-2_16
3. Angelelli, E., Speranza, M.G.: The periodic vehicle routing problem with intermediate facilities. Eur. J. Oper. Res. **137**(2), 233–247 (2002)
4. Beltrami, E.J., Bodin, L.D.: Networks and vehicle routing for municipal waste collection. Networks **4**(1), 65–94 (1974)
5. Eryganov, I., Šomplák, R., Nevrlý, V., Smejkalová, V., Hrabec, D., Haugen, K.K.: Application of cooperative game theory in waste management. Chem. Eng. Trans. 887–882 (2020)
6. Govindan, K., Soleimani, H., Kannan, D.: Reverse logistics and closed-loop supply chain: a comprehensive review to explore the future. Eur. J. Oper. Res. **240**(3), 603–626 (2015)

7. Hemmelmayr, V.C., Doerner, K.F., Hartl, R.F., Vigo, D.: Models and algorithms for the integrated planning of bin allocation and vehicle routing in solid waste management. Transp. Sci. **48**(1), 103–120 (2014)
8. Huang, S.H., Lin, P.C.: Vehicle routing-scheduling for municipal waste collection system under the "Keep Trash off the Ground" policy. Omega **55**, 24–37 (2015)
9. Nuortio, T., Kytöjoki, J., Niska, H., Bräysy, O.: Improved route planning and scheduling of waste collection and transport. Expert Syst. Appl. **30**(2), 223–232 (2006)
10. Sinha, T., Kumar, K.M., Saisharan, P.: Smart dustbin. Int. J. Ind. Electron. Electrical Eng. **3**(5), 101–104 (2015)
11. Vicentini, F., et al.: Sensorized waste collection container for content estimation and collection optimization. Waste Manage. **29**(5), 1467–1472 (2009)