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AN ANALYSIS OF THE UTILISATION OF LANDFILL FACILITIES IN A WASTE COLLECTION VEHICLE ROUTING PROBLEM

FAZLINI HASHIM*, AIDA MAUZIAH BENJAMIN AND SYARIZA ABDUL-RAHMAN

Decision Science Department, School of Quantitative Sciences, Universiti Utara Malaysia, UUM Sintok, 06010, Kedah, Malaysia.

**Corresponding author: fazlini.hashim@uum.edu.my*
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Abstract: Recent studies have addressed several constraints to ensure the effective applicability of numerous models. However, an exclusive model meant for landfill utilisation for landfill facilities is still untapped. As such, this paper proposes a new constraint faced by landfill facilities to ensure a more comprehensive model and its applicability to real-life issues. This idea is influenced by three main reasons. First, the lifespan of selected landfills is bound to decrease due to the increasing density of waste transported to landfills daily. The second reason is abandoning the available landfill sites due to inappropriate locations. Lastly, the government would need to bear high costs in establishing more landfills to accommodate the annually increasing waste. Hence, the Nearest Greedy method was applied to a benchmark problem of waste collection vehicle routing problem (WCVRP) to construct feasible initial routes by considering the following three scenarios of landfills: (1) without capacity priority, (2) balance capacity priority, and (3) imbalance capacity priority. This study highlights the importance of using all available landfills to unload waste for the WCVRP. Weighing in this additional constraint may increase the life expectancy of the available landfill sites. However, the computational findings revealed that utilising all available landfill facilities (scenarios 2 and 3) can significantly increase the total distance travelled and the number of vehicles used compared to Scenario 1.

Keywords: waste collection, vehicle routing problem, heuristic, landfill utilisation.

Introduction

Waste collection problem (WCP) is a vehicle routing problem (VRP) variant highlighted by Dantzig & Ramser (1959). Practically, WCP is one of the real-life applications of VRP with Pickup and Delivery (VRPPD) that have been widely discussed (Abraham *et al.,* 2012; Ai & Kachitvichyanukul, 2009; Montane & Galvao, 2006). According to Sitek *et al*. (2021), VRPPD can be described as transporting several goods from certain pickup points to other delivery points by the same vehicles. Thus, the problem objective is designed to optimise the vehicle route to visit the pickup and delivery points. Other real-life applications of VRPPD are in distributing dairy products, agriculture items, pharmaceuticals goods, dry cleaning supplies, electronic appliances, hardware items (Min *et al.*, 1992) and daily routing and scheduling demands in industrial applications (Hosny, 2012).

Initially, WCP was introduced by Beltrami & Bodin (1974) to collect 25,000 tons of waste in New York City. Gruler *et al.* (2017) stated that WCP is an optimisation problem widely discussed in the scientific literature. The waste collection vehicle routing problem (WCVRP) has extended greatly and garnered attention from researchers across various fields. The WCVRP comprises three main components; a depot, a set of customers (pickup customers where wastes need to be collected), and a set of landfill facilities (delivery customers where the collected wastes need to be unloaded).

The complexity of WCVRP depends on several constraints, including time interval between customers, landfill facilities, depots, and different types of vehicles used to serve the customers (Beliën *et al.,* 2012), different types of customers involved (i.e., regular or priority customers), availability of more than a depot (most probably the vehicle starts and ends at different depots), and the break time for the drivers during collection time (Benjamin & Beasley, 2013; 2010; Benjamin, 2011; Kim *et al.,* 2006). Table 1 lists the constraints in WCVRP reported in prior studies.

Recent studies have explored other additional constraints, such as the workload of drivers/vehicles, to ensure the effective applicability of the models in addressing real-life problems (Benjamin & Abdul-Rahman, 2016; Benjamin *et al.,* 2015; Kim *et al.,* 2006; Lee & Ueng, 1999). However, the aspect of landfill utilisation is largely untapped. As depicted in Table 1, most researchers focused on minimising travelled distance, travelled cost, and the number of vehicles while constructing the proposed solutions. Their solutions have disregarded landfill criteria, contributing to the underuse of some landfill facilities.

The proposed solutions also showed that the drivers unloaded waste only at the nearest

Table 1: Constraints in WCVRP

Item	Constraints	Reference
Depot	1. Time window	Wy *et al.* (2013, 2010); Benjamin (2011); Benjamin & Beasley (2010, 2013); Buhrkal *et al.* (2012); Islam & Rahman (2012); Ombuki-berman *et al.* (2007); Kim *et al.* (2006)
	2. Vehicle leaving and returning to the depot	Gruler *et al.* (2017); Vecchi *et al.* (2016); Markov *et al.* (2014); Otoo *et al.* (2014); Fooladi *et al.* (2013); Islam & Rahman (2012)
	3. Single depot	Vecchi *et al.* (2016); Otoo *et al.* (2014); Fooladi *et al.* (2013); Buhrkal *et al.* (2012); Islam & Rahman (2012)
	4. Multiple depots	Gruler *et al.* (2017); Markov *et al.* (2016); Ramos *et al.* (2014); Hemmelmayr *et al.* (2013)
Landfill	1. Multiple landfill facilities	Wy *et al.* (2013, 2010); Benjamin (2011); Benjamin & Beasley (2010, 2013)
	2. Time window	Buhrkal *et al.* (2012); Islam & Rahman (2012); Benjamin (2011); Wy *et al.* (2010); Ombuki-berman *et al.* (2007)
Customer	1. Single visit	Vecchi *et al.* (2016); Otoo *et al.* (2014); Markov *et al.* (2014); Fooladi *et al.* (2013); Hemmelmayr *et al.* (2013); Buhrkal *et al.* (2012); Benjamin (2011); Ismail & Ramli (2011); Ombuki-berman *et al.* (2007)
	2. Time window	Wy *et al.* (2013); Buhrkal *et al.* (2012); Islam & Rahman (2012); Benjamin (2011); Ombuki-berman *et al.* (2007)
Vehicle/ driver	1. Capacity of collected waste per day	Vecchi *et al.* (2016); Alshraideh & Qdais (2016); Markov *et al.* (2016, 2014); Ferreira *et al.* (2015); Otoo *et al.* (2014); Hemmelmayr *et al.* (2013); Fooladi *et al.* (2013); Benjamin (2011); Benjamin & Beasley (2010); Ismail & Loh (2009)
	2. Rest period/break hours	Markov *et al.* (2016); Wy *et al.* (2013, 2010); Buhrkal *et al.* (2012); Islam & Rahman (2012); Benjamin (2011); Benjamin & Beasley (2010); Kim *et al.* (2006)
	3. Multiple landfill trips	Wy *et al.* (2013); Kim *et al.* (2006)
	4. Different working time	Wy *et al.* (2013)
	5. Balance workload among vehicles/ drivers	Benjamin & Abdul-Rahman (2016); Benjamin *et al.* (2015); Lee & Ueng (1999), Kim *et al.* (2006

landfills to attain the minimum distance travelled, causing the abandonment of the farthest landfills. Thus, the models proposed in the past studies have drawbacks and do not reflect real-world applications; despite the ability to generate viable solutions in terms of total distance travelled, total cost, and the number of vehicles used. This gap has motivated this study to address a new constraint on utilising landfill facilities and to build a more comprehensive model with better applicability to overcome real-life issues. The additional constraint has never been discussed in any previous studies. Hence, the main objective of this study is to analyse the impacts of the new constraint in solving WCVRP using the Nearest Greedy method. The impacts are discussed regarding the total travelled distance and the number of vehicles used.

This paper is organised as follows. Sections 2 and 3 discuss WCVRP and the issues related to the utilisation of landfill facilities. Next, Section 4 depicts the methodology employed in this study, including the heuristics method used to minimise travelled distance and the number of vehicles used. Section 5 presents the computational results obtained from the proposed method. Lastly, this study is concluded in Section 6.

Waste Collection Vehicle Routing Problem (WCVRP)

Waste collection is a part of the waste management process. Waste collection can be divided into two general categories; residential and commercial. The waste management company serves along the streets or quarters for residential routes but certain locations for commercial routes. Residential waste collection is often considered an arc routing problem because the exact location of every customer is unnecessary. Residential wastes can be found in residential areas.

On the other hand, commercial waste collection is typically considered a node routing problem because it involves point-to-point collection, and the exact location of every customer must be known. Commercial waste can be found in restaurants, retail outlets, factories, apartments, and other WCVRP applies the same concept as VRPPD. Both problems consider three types of nodes; a depot, a set of customers (considered pickup nodes in the VRPPD), and a set of landfill sites (considered delivery nodes in the VRPPD). However, the flow of the problems is slightly different. In a basic VRPPD, only a single trip is allowed to visit pickup and delivery nodes. Whereas, in WCVRP multi-trip to landfill sites (i.e., delivery nodes) is an important constraint that must be considered in solving the problem. Thus, fully utilising the available landfill sites for unloading the collected waste is highlighted in this study.

Issues Related to the Utilisation of Landfill Facilities in WCVRP

According to Fauziah & Agamuthu (2010), 111 landfills in Malaysia had been closed upon reaching their maximum capacity, apart from being located in unsuitable areas. In 2020, the National Solid Waste Management Department of Malaysia reported that out of the 296 existing landfills in Malaysia, only 165 were functional and the remaining 131 were either abandoned or not fully utilised. Previous studies on WCP have assumed that the parameters involved are deterministic, yet their uncertainty renders this model inapplicable in real life (Yazdani *et al.,* 2021). This study proposes a new landfill constraint to solve the issue related to WCVRP.

The idea is influenced by three main reasons. First, the lifespan of selected landfills will reduce due to the increasing density of wastes transported to the landfill daily. In Malaysia, Ismail & Dzulkifli (2021) stated that 30,000 tons of solid waste are produced daily, and only 5% is recycled. Second, available landfill sites are abandoned due to inappropriate locations (far away from residential areas and the depot). In Malaysia, the landfill location is under the supervision of the government of each state. Thus, a new landfill selection needs to undergo several site suitability assessment assessments by considering the environmental, physical, and socio-economic impact (Amkieh, 2021). In socio-economics, Ahamad & Ahmad (2020) proposed the standard parameters (1000 m) for a residential area in the landfill site selection. In addition, neglecting the available landfills will cause abandoned landfills and wastage of valuable resources, such as money, time, and effort, to build a new landfill. Third, the government will have to spend high costs to build more landfills to accommodate the increasing waste annually. The average capital cost to construct a new landfill can exceed RM 30 million (Pariatamby, 2014). This cost includes facility development, construction, operation, closure, and post-closure (Eilrich *et al.,* 2003; Cointreau, 2008). The life expectancy of landfills has been discussed previously by MacGregor (2017), Fauziah & Agamuthu (2010), and Ustohalova *et al*. (2006). Several factors related to the life expectancy of a landfill are weight limits and waste compacting (MacGregor, 2017; Cointreau, 2008). The rising amount of waste to dispose of daily tends to increase the density of waste in landfill facilities, thus reducing the lifespan of those landfill sites. Moreover, compacting landfill sites leads to closure and a new site must be built.

This study introduces the utilisation of landfill facilities constraint to solve WCVRP. This additional constraint is incorporated into the vehicle routes. Therefore, all collected customer waste will be unloaded at all available landfill facilities with a certain priority. Solving WCVRP by embedding this additional constraint yields a more comprehensive solution and better applicability to real-life problems. This is because; the consideration of this additional constraint may increase the life expectancy of the existing landfills, ensure balanced utilisation of all available landfill sites, hinder the closure of existing landfill sites, and avoid the construction of new landfill sites. The complexity of this issue demands a viable solution.

For instance, Figure 1 illustrates the location of the depot, customers, and landfill facilities for test problem 335 by Kim *et al.* (2006). Based on Figure 1, the locations of all customers are quite close to Disposal 1 and the depot. This scenario leads to the sole use of one landfill facility (Disposal 1) despite four available landfill facilities. Therefore, one of the main objectives of the study is to minimise the total distance of vehicle routing and the number of vehicles used by taking into account the utilisation of all available landfill facilities. Based on Figure 1, to minimise the total distance of vehicle routing, only one landfill (Disposal 1) is most probably used due to its location, which is the closest to all customers compared to the other three landfill facilities (Disposals 2, 3, and 4). Therefore, this study addressed the utilisation of all available landfill facilities in WCVRP.

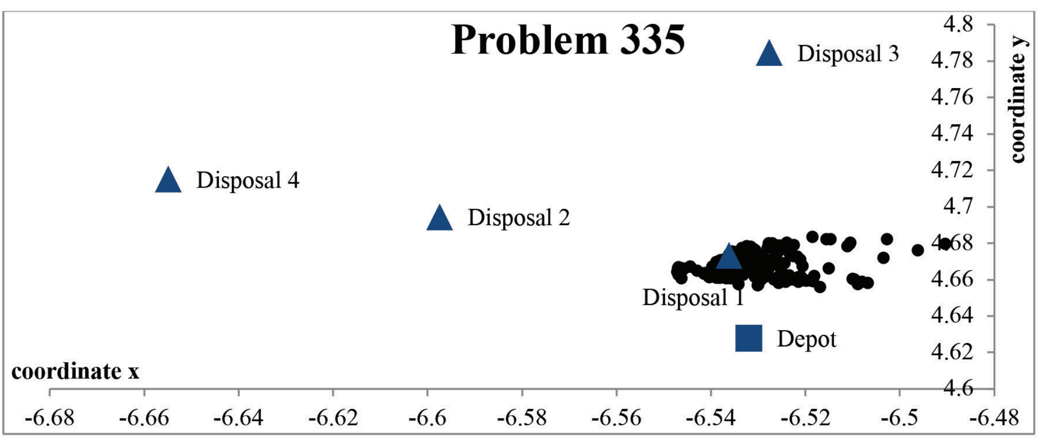

Figure 1: Location of Depot, Customers, and Landfill Facilities for Problem 335

Methodology

The modern VRP variants are more relevant to real-life applications due to the complex objectives and operational constraints (Lin *et al.,* 2014). Therefore, efforts have been made to develop more practical mathematical models and high-performance algorithms to solve waste collection optimisation problems. For example, linear and mixed integer programming have been applied to solve these nondeterministic polynomial time (NP) hard combinatorial problems. However, in recent studies, heuristics and metaheuristics methods are often applied to solve modern VRP issues compared to other methods, such as exact, simulation, and real-time solution methods (Braekers *et al.,* 2016). In addition, heuristics and metaheuristics methods such as the Nearest Neighbourhood Search algorithm and Greedy algorithm (Sahoo *et al.*, 2005; Bautista & Pereira, 2006) have become popular and effective approaches because these algorithms can overcome the problem of huge computational time (Akhtar *et al.,* 2017; Yazdani *et al.,* 2021).

In this paper, a heuristics method called Nearest Greedy was applied to construct feasible initial routes of WCVRP. This Greedy method is an example of the constructive heuristic technique widely used to construct a feasible solution. This method is typically adopted as it is one of the most suitable techniques to produce an arbitrary group of initial solutions (Buch & Trivedi, 2021) within reasonable times, a locally optimal solution, and global optimum solutions. In addition, this Greedy algorithm has been widely used to solve WCVRP (Buhrkal *et al.,* 2012; Mat *et al.,* 2017; 2018;).

The pseudocode of the Nearest Greedy algorithm with the utilisation of all available landfill facilities is presented in Figure 2. The list of WCVRP constraints considered in the algorithm is as follows:

a) Time windows of the depot, landfill facilities, and all customers

b) Waste capacity does not exceed the vehicle capacity for a trip

c) Capacity of the vehicle from the depot and back to the depot must be emptied

d) Vehicle capacity does not exceed the maximum capacity and number of stops allowed per day

e) Each customer is served once

f) Multi-trip of the vehicle to landfill facilities

g) One-hour driver's rest time from 11:00 am to 12:00 pm

h) Disposal trips (when a vehicle is full, it must go to a landfill facility)

i) Utilisation of all available landfill facilities with certain priority (new constraint)

The algorithm shown in Figure 2 assumes that each vehicle departs from the depot with zero capacity, visits the nearest customer to serve each customer once and goes to the landfill facility after meeting the vehicle capacity constraint and returns to the depot. Each route must meet the constraints involved, such as the time window of the depot, customers, landfill facilities, and lunch break.

First, depot/start is marked as node 1, all nodes/customers (*n*) denote *Unused*, landfill facilities are equal to *setdiff* (*n*-1: *n*, start), and the vehicle is 0. An empty route for a vehicle is created and set as *Tour* = *start*. To update the next customer (*Next*) in a route, the minimum distance was determined by checking the Unused(i) row and column. Before *Unused(i)* is updated as *Next*, *Tour* = [*Tour Next*] must fulfil all constraints, including rest time [i.e., 11:00 am to 12:00 pm].

The next step is to check the condition of accumulated waste (total waste collected) if it exceeds the vehicle capacity. If accumulated waste exceeds vehicle capacity, it must go to the landfill facility after satisfying the time window of that landfill facility and meeting the utilisation of landfill facility constraint. In this step, utilisation of all available landfill facilities is involved by considering three scenarios: (1) without capacity priority, (2) balance capacity, and (3) imbalance capacity.

Initialise: Set *start* = 1, marked all customers as *Unused*, *vehicle* = 0, *capacity* = 0, *current_time* = 0, *distance* = 0, Next = start

while length (*Unused*) ≠ 0

for *i*=1: length (*Unused*)

Step 1: Find the nearest customer (*Unused(i)*) from *Next* and check time window of *Unused(i)*

If *Unused(i)* has the nearest *distance = mindist*, and fulfils time window, then update *Unused(i) = Temp_Next*

Step 2: Check *rest time* [11:00 – 12:00] based on *arrival_time* of *Temp_Next*

If *current_time* is included in the *rest period*, the vehicle must rest for one hour

else continue to visit *Temp_Next*

end if

end if

Step 3: Check whether *Temp_Next* is updated as *Next* or go to the landfill facility

If (accumulated waste capacity < vehicle capacity) and (number of stops < maximum allowed per day), then update *Temp_Next* = *Next*, update current *distance*, update current *capacity*

else, *Temp_Next* = *disposal(j)*

for *j*=1:length (*disposal)*

Check the time window of *disposal(j)* before selecting a landfill facility

If *disposal(j)* has the nearest distance and fulfils the time window, then update *disposal(j) =Temp_disposal*. Then check whether *Temp_disposal* follows Scenario 1, Scenario 2 or Scenario 3.

For Scenario 1, *disposal(j)* is selected based on the minimum distance of *disposal(j)* from the previous *Temp_Next* and without considering any capacity priority.

For Scenario 2, *disposal(j)* is selected based on the minimum distance and considering the balance capacity of the total waste collected.

For Scenario 3, *disposal(j)* is selected based on the minimum distance and considering the imbalance capacity of the total waste collected that is randomly generated. For scenarios 2 and 3, if *disposal(j)* has already achieved its maximum capacity, the vehicle must go to another *disposal(j)*. Then, after *selecting disposal (j)*, updated *Next = Temp_disposal*.

end if

end for

end if

end for

Step 4: Updated *Tour = [Tour Next]*. Repeat insertion of *Unused(i)* and *disposal(j)* to *Tour*. Then, update the total distance and vehicle capacity. A trip is completed after a route starts with a new vehicle. Then, update *Tour = [Tour Next]* and *vehicle = vehicle + 1*.

Step 5: Continue the steps until *Unused(i)* becomes *empty*. Next, update the total travelled distance and number of vehicles used.

end while

Figure 2: Nearest Greedy Algorithm with the Utilisation of All Available Landfill Facilities Constraint

(1) **Scenario 1: Without capacity priority**

This scenario is similar to the basic Nearest Greedy algorithm. It denotes that a vehicle can go to the landfill facility for waste disposal based on its minimum distance without considering any capacity priority, whether a balance or unbalanced waste capacity for each landfill.

(2) **Scenario 2: Balance capacity priority**

Balance capacity of waste refers to all landfill facilities having the same total waste capacity to be unloaded. However, it is difficult and impossible to reach the same amount of waste due to hard constraints, such as maximum vehicle capacity and capacity of vehicles allowed per day. Thus, the amount of waste (percentage) approximated to the same amount (percentage) is assumed as the balance capacity of waste.

(3) **Scenario 3: Imbalance capacity priority**

The imbalance capacity of waste reflects that all available landfill facilities are allocated with a random total waste capacity. This capacity is generated randomly by the computer based on the algorithm.

After a vehicle goes to the selected landfill facility, the arrival time is updated. Then, the looping checks the other constraints if the vehicle continues serving customers or returns to the depot. If vehicle capacity has hit the maximum capacity or number of stops allowed daily, the vehicle must return to the depot and a trip is restarted with a new vehicle. Hence, the accumulated waste capacity is updated as zero and the vehicle becomes *vehicle* + 1.

The proposed Nearest Greedy algorithm was tested using a WCVRP benchmark problem by Kim *et al.* (2006). It consists of 10 test problems with various sizes, starting from 99 until 2092 customers. Assumptions include a single depot, homogeneous types of vehicles, unlimited vehicles, and symmetric routes. Table 2 tabulates the main characteristics of this benchmark problem.

Results and Discussion

This section consists of two parts. The first part analyses the impact of utilising landfill facilities regarding the total waste unloaded at each landfill facility. Then, the second part analyses the impacts in terms of the total travelled

Table 2: Characteristics of a WCVRP Benchmark Problem by Kim *et al.* (2006).

Problem	Total customers	Total landfill facilities	The capacity of a vehicle (yard)	Capacity allowed for vehicle per day (yard)	Route max stop count/day
102	99	2	280	400	500
277	275	1	200	2200	500
335	330	4	243	400	500
444	442	1	200	400	500
804	784	19	280	10000	500
1051	1048	2	200	800	500
1351	1347	3	255	800	500
1599	1596	2	280	800	500
1932	1927	4	462	2000	500
2100	2092	7	462	2000	500

The characteristics of these benchmark problems consist of the total number of customers, the total number of landfill facilities, the capacity of the vehicle (the d), the capacity allowed for vehicle per day (yard), and the maximum number of stops (customers) allowed per day.

distance and the number of vehicles used. Both analyses are presented based on the three scenarios (without capacity priority, balance capacity priority, and imbalance capacity priority) illustrated in this study. The Nearest Greedy algorithm was executed on a Pentium® Dual-Core CPU T4300 @ 2.10GHz with 3.00 GB memory using MATLAB 2017. The algorithm was tested on a WCVRP benchmark problem by Kim *et al*. (2006). Tables 3 and 4 display the computational results retrieved for WCVRP using the Nearest Greedy algorithm. Figures 4 to 6 illustrate the proposed additional constraint based on Problem 335 as an example.

Analysis of utilising landfill facilities

This section presents the analysis of utilising landfill facilities based on the total waste capacity at each landfill facility tested for three scenarios. In Table 3, D_i is referred to as disposal *i* (landfill facility *i*), where different problems have a different number of landfill facilities, while '-' is a null value as the problem is absent in scenarios 2 and 3 due to the use of a single landfill facility which occurred only for problems 277 and 444.

Based on Table 3, Scenario 1 shows that some landfill facilities were underutilised compared to scenarios 2 and 3, in which all the available landfill facilities were utilised

Table 3: Analysis of the Utilisation of Landfill Facilities

Problem	No. of the disposal facility	The total capacity of waste (yard)	Capacity at each landfill facility/disposal (yard/%)		
			Scenario 1	Scenario 2	Scenario 3
102	2	897	D_1 = 677 (75.47%) D_2 = 220 (24.53%)	D_1 = 497 (55.41%) D_2 = 400 (44.59%)	D_1 = 222 (24.75%) D_2 = 675 (75.25%)
277	1	2132.5	D_1 = 2132.5 (100%)	-	-
335	4	2011	D_1 = 2011 (100%)	D_1 =431 (21.43%) D_2 =636 (31.63%) D_3 =545 (27.10%) D_4 =399 (19.84%)	D_1 = 581 (28.89%) D_2 = 241 (11.98%) D_3 = 242 (12.04%) D_4 = 947 (47.09%)
444	1	3991.3	D_1 = 3991.3 (100%)	-	-
804	19	4620	D_3 = 3354.5 (72.61%) D_4 = 122 (2.64%) D_8 = 869 (18.81%) D_{10} = 274.5 (5.94%)	D_1 = 261 (5.65%) D_2 = 277.5 (6.01%) D_3 = 277 (6.0%) D_4 = 279 (6.04%) D_5= 279.5 (6.05%) D_6= 278 (6.02%) D_7= 276 (5.97%) D_8 = 278 (6.02%) D_9= 278.5 (6.03%) D_{10}= 280 (6.06%) D_{11} =270.5 (5.85%) D_{12}= 200 (4.33%) D_{13}= 269 (5.82%) D_{14}= 200 (4.33%) D_{15}= 280 (6.06%) D_{16}= 266 (5.76%) D_{17}= 154 (3.33%) D_{18}= 108 (2.34%) D_{19}= 108 (2.34%)	D_1 = 261 (5.65%) D_2 = 277.5 (6.01%) D_3 = 277 (6.0%) D_4 = 279 (6.04%) D_5= 279.5 (6.05%) D_6= 278 (6.02%) D_7= 276 (5.97%) D_8 = 278 (6.02%) D_9= 278.5 (6.03%) D_{10}= 280 (6.06%) D_{11} =270.5 (5.85%) D_{12}= 200 (4.33%) D_{13}= 269 (5.82%) D_{14}= 200 (4.33%) D_{15}= 280 (6.06%) D_{16}= 266 (5.76%) D_{17}= 154 (3.33%) D_{18}= 108 (2.34%) D_{19}= 108 (2.34%)

1051	2	12695.5	D_1=7368 (58.04%) D_2=5327.5 (41.96%)	D_1=6332 (49.88%) D_2=6363.5 (50.12%)	D_1 = 5184 (40.83%) D_2 = 7511.5 (59.17%)
1351	3	5445	D_1 = 1550 (28.47%) D_2 = 294 (12.89%) D_3 = 3601 (66.13%)	D_1 = 1802 (33.09%) D_2 = 1793 (32.93%) D_3 = 1850 (33.98%)	D_1 = 2861 (52.54%) D_2 = 1496 (27.48%) D_3 = 1088 (19.98%)
1599	2	8524	D_1 = 1652 (19.38%) D_2 =6872 (80.62%)	D_1 = 4263 (50.01%) D_2 = 4261 (49.99%)	D_1 = 6003 (70.42%) D_2 = 2521 (29.58%)
1932	4	13205	D_1 = 11473 (86.88%) D_2 = 1732 (13.12%)	D_1 =3290 (24.91%) D_2 =3515 (26.62%) D_3=3386 (25.68%) D_4=3015 (22.83%)	D_1 =7850 (59.45%) D_2 =2785 (21.09%) D_3 = 1739 (13.17%) D_4 = 831 (6.29%)
2100	7	17166	D_1 = 1375 (8.01%) D_2 = 1339 (7.81%) D_3 = 7090 (41.304%) D_4 = 462 (2.69%) D_5 = 1271 (7.40%) D_6 = 3743 (21.80%) D_7 = 1886 (10.99%)	D_1 =2681 (15.62%) D_2 =2614 (15.23%) D_3 =2433 (14.17%) D_4 =2698 (15.72%) D_5 =2071 (12.06%) D_6 =2572 (14.98%) D_7 =2097 (12.22%)	D_1 = 3714 (21.64%) D_2 = 3511 (20.45%) D_3 = 1513 (8.81%) D_4 = 917 (5.34%) D_5 = 2025 (11.80%) D_6 = 3214 (18.72%) D_7 = 2272 (13.24%)

according to their capacity priority. Referring to Problem 335, only one landfill facility (Disposal 1) out of four available landfill facilities was utilised in Scenario 1 (2011 yards, 100%). Meanwhile, in scenarios 2 and 3, all landfills were utilised based on their capacity priority. As for Scenario 2, the total capacity at Disposal 1 was 431 yards (21.43%), followed by Disposal 2 (636 yards, 31.63%), Disposal 3 (545 yards, 27.10%), and Disposal 4 (399 yards, 19.84%). In Scenario 3, which is based on random capacity priority, the total capacity at Disposal 1 was 581 yards (28.89%), followed by Disposal 2 (241 yards, 11.98%), Disposal 3 (242 yards, 12.04%), and Disposal 4 (947 yards, 47.09%), accordingly.

Slightly different from Problem 804, scenarios 2 and 3 have the same waste capacity at each landfill. In this case, the total waste capacity was 4620 yards and distributed to 19 landfill facilities. Since the proposed constraints asserted that all available landfill facilities must be utilised for scenarios 2 and 3, the total capacity at each landfill facility relied on the maximum vehicle capacity (280 yards per trip) and the capacity allowed for a vehicle (10000 yards per day). On the contrary, in Scenario 1, only four out of the nineteen available landfill facilities were utilised, wherein the total capacity at Disposal 3 was 3354.5 yards (72.61%), followed by Disposal 4 (122 yards, 2.64%), Disposal 8 (869 yards, 18.81%), and Disposal

10 (274.5 yards, 5.94%). As for scenarios 2 and 3, all landfill facilities were utilised with the total capacity for Disposal 1 resulting in 261 yards (5.65%), then 277.5 yards (6.01%), 277 yards (6.0%), 279 (6.04%), 279.5 (6.05%), 278 (6.02%), 276 (5.97%), 278 (6.02%), 278.5 (6.03%), 280 yards (6.06%), 270.5 yards (5.85%), 200 yards (4.33%), 269 yards (5.82%), 200 yards (4.33%), 280 yards (6.06%), 266 yards (5.76%), 154 yards (3.33%), 108 yards (2.34%), and 108 yards (2.34%), respectively for Disposals 2 until 19.

Based on the outcomes tabulated in Table 3, this study presents a significant insight into the underutilisation of certain landfills (Scenario 1), which were found to be excessed and could affect future waste management planning. Furthermore, the importance of utilising all available landfills based on certain priorities to unload waste for WCVRP is also highlighted as portrayed in scenarios 2 and 3, which could provide proper planning for the waste management to manage their landfill facilities. The findings in this section also affect the total travelled distance, which is directly related to the number of vehicles used for the three scenarios.

Analysis of Total Travelled Distance and Number of Vehicles Used

The results based on total travel distance and the number of vehicles used tested for the three scenarios are presented in Table 4. For the total travelled distance, Scenario 1 has a lower total travel distance for most problems, except for problem 102, in comparison to scenarios 2 and 3. Based on the number of vehicles used, Scenario 1 exhibited the least number of vehicles used. For example, in problem 335, the total travelled distance for Scenario 1 was 219.287 miles, whereas scenarios 2 and 3 recorded 531.548 miles and 580.243 miles, respectively. This example displays a significant increment in the total travelled distance for scenarios 2 and 3 compared to Scenario 1. Notably, six vehicles were used for the three scenarios.

Meanwhile, problem 2100 revealed a slight increment in the total travelled distance for Scenario 2 (1673.879 miles) and scenario 3 (1606.986 miles) when compared to Scenario 1 (1506.779 miles). However, a significant increase was noted in the number of vehicles used. In Scenario 1, only 18 vehicles were used, in comparison to 21 vehicles in Scenario 2 and 20 vehicles in Scenario 3.

Table 4: The comparison of the total distance and number of vehicles for the three scenarios

Problem	Total landfill facilities	Scenario 1		Scenario 2		Scenario 3	
		Total distance (miles)	Number of vehicles	Total distance (miles)	Number of vehicles	Total distance (miles)	Number of vehicles
102	2	344.237	3	319.417	3	398.963	3
277	1	491.082	4	-	-	-	-
335	4	219.287	6	531.548	6	580.243	6
444	1	93.751	11	-	-	-	-
804	19	629.024	5	1233.730	7	1233.730	7
1051	2	2620.340	17	2679.812	17	2871.233	17
1351	3	1000.078	7	1175.893	7	1214.666	7
1599	2	1493.152	14	1991.141	15	2225.510	15
1932	4	1345.511	16	1364.299	16	1364.968	16
2100	7	1506.779	18	1673.879	21	1606.986	20

Since all the available landfill facilities were utilised (scenarios 2 and 3), the total distance and the number of vehicles were higher. As a result, if a landfill facility has reached its maximum capacity priority, the vehicle will have to be disposed of at another available landfill facility. This directly increases the total travel distance and the number of vehicles used. On the contrary, the selection of each landfill facility in Scenario 1 was based on the minimum distance from customers and without any capacity priority and thus affected the total distance and number of vehicles used. In addition, a difference was noted in the number of vehicles used since the utilisation of all available landfill facilities was influenced by hard constraints, including the time window of the depot, landfill facility, and customers.

It is important to note that the utilisation of landfill facilities has a crucial relationship with the total distance travelled, directly affecting the number of vehicles used. To give a clearer picture of this problem, Figures 3 to 5 describe the proposed routing based on the Nearest Greedy Algorithm for each scenario in Problem 335. Four landfill facilities were utilised in Problem 335.

Figure 3 illustrates the proposed routing based on the Nearest Greedy Algorithm for Scenario 1. Only Disposal 1 was used to unload the waste with a total waste capacity of 2011 yards (100% total waste capacity). Disposal 1 was selected because it was located the closest to all customers and the depot (see Figure 1). Thus, it led to a lower total travel distance (219.287 miles) and six waste transport vehicles.

Figure 4 presents Scenario 2 for the balance capacity of waste disposed at all landfill facilities. In this scenario, all landfill facilities were utilised and the balance capacity of waste denotes the same total waste capacity unloaded at each available landfill facility. However, it was difficult to arrive at the same amount of waste due to the designated maximum vehicle capacity and the capacity of vehicles allowed per day. Hence, the amount of waste (percentage) approximated to the same amount (percentage) was assumed as the balance capacity of waste. In Scenario 2, a landfill facility is selected based on its minimum distance from the previous customer and by considering balance capacity as its capacity priority. If a landfill facility has already achieved its maximum designated capacity priority, the vehicle must visit another available landfill facility.

Based on Figure 4, Disposal 1 recorded 431 yards (21.43%) of waste capacity disposed of, followed by Disposal 2 (636 yards, 31.63%), Disposal 3 (545 yards, 27.10%), and Disposal 4 (399 yards, 19.84%). Six vehicles were used, and the total travel distance was 531.548 miles, a significant increase compared to Scenario

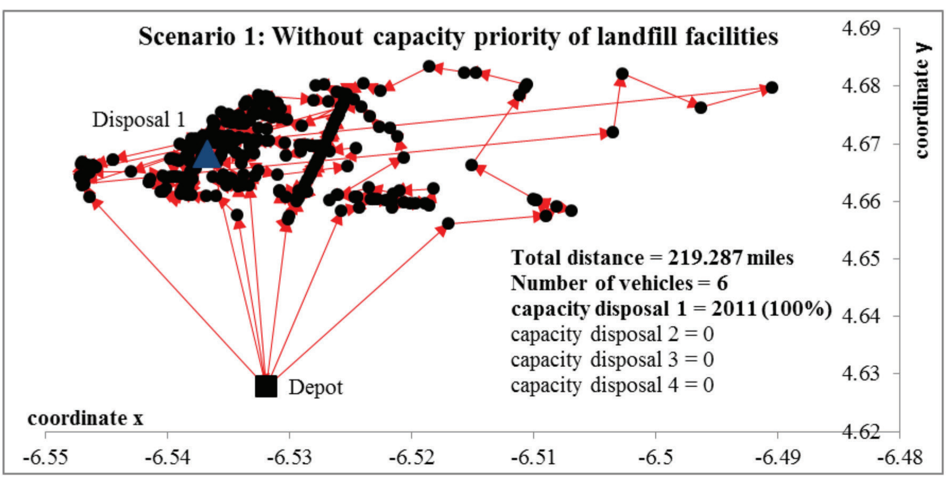

Figure 3: Scenario 1: Without Capacity Priority of Landfill Facilities

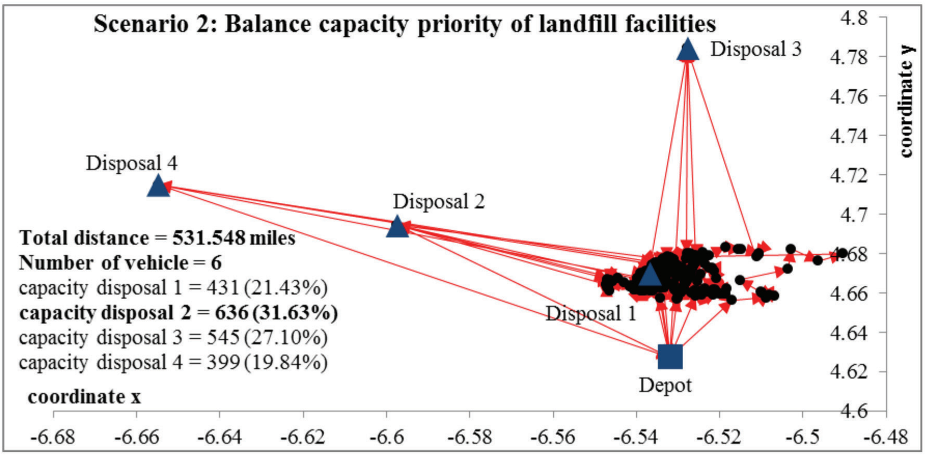

Figure 4: Scenario 2: Balance Capacity Priority of Landfill Facilities

1. The utilisation of all landfill facilities can significantly increase the total travel distance for Scenario 2.

Based on Figure 5, Scenario 3 presents the imbalance capacity of waste disposed at all landfill facilities based on the total random waste capacity. Scenario 3 indicates that all landfill facilities are randomly utilised. For Disposal 1, 581 yards (28.89%) of waste capacity were disposed of, followed by Disposal 2 (241 yards, 11.98%), Disposal 3 (242 yards, 12.04%), and Disposal 4 (947 yards, 47.09%). Six vehicles were used, and the total travel distance was 580.243 miles, which did not differ much from that recorded in Scenario 2. However, this scenario also reveals that utilising all available landfill facilities can significantly increase the total travel distance for Scenario 3.

Conclusion

This study proposed the idea of the utilisation of landfill facilities as an additional constraint in the WCVRP to ensure it applies to the real-life problem in solid waste collection. It was found that some landfills were underutilised, and this issue has led to a decrease in the lifespan of selected landfills, abandonment of the available landfill, and bear the high cost of establishing more landfills. This study highlights the importance of landfills utilisation to unload waste in WCVRP. Overlooking the available landfill sites due to other reasons may lead to unutilised potential landfills and waste of valuable resources, such as money, time, and

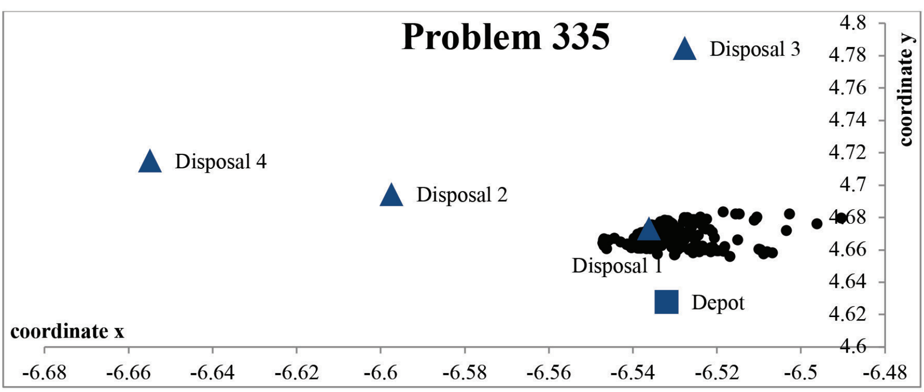

Figure 5: Scenario 3: Imbalance Capacity Priority of Landfill Facilities

effort spent in building new landfills. Weighing in this additional constraint may increase the life expectancy of the available landfill sites.

Thus, this paper introduced a new landfill facility constraint when solving WCVRP. The initial solutions for the WCVRP were constructed using a heuristics technique, namely the Nearest Greedy algorithm. The algorithm was tested on a WCVRP benchmark problem by Kim *et al*. (2006). Three scenarios with different priorities of landfills have been demonstrated to analyse the impacts of the new constraint in the WCVRP. The impacts of the proposed solutions were evaluated in terms of the total waste unloaded at the landfills, the total distance travelled, and the total vehicles used. Computational findings revealed that utilising all landfill facilities (scenarios 2 and 3) can significantly increase the total distance travelled and the number of vehicles used compared to Scenario 1.

Regarding the total travel distance and the number of vehicles used, Scenario 1 generated the lowest total travel distance than Scenario 2 and 3, mainly because the applied algorithm tends to visit the nearest landfill facilities instead of considering all landfill facilities. As for scenarios 2 and 3, if a landfill facility has already achieved its maximum designated capacity priority, the vehicle must visit another available landfill site. This led to an increase in the total travel distance and the number of vehicles used. However, solutions for Scenario 2 and Scenario 3 are more practical in solving real-life WCVRP where all landfills are used to unload collected waste. The analysis presented in this study may assist the waste management team in estimating the total operational cost of providing waste collection services to the community. The new constraint introduced in this paper may also be applied in other VRP variants, such as multiple depots vehicle routing problems and VRP with intermediate facilities. For future works, the WCVRP solutions presented in this study can be improved using metaheuristics algorithms to produce better solutions (i.e., less total distance travelled and fewer total vehicles used).

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