

GIS Routing and Modelling of Residential Waste Collection for Operational Management and Cost Optimization

Billa, L.^{1,2}, Pradhan, B.^{2*} and Yakuup, A.³

¹University of Nottingham Malaysia Campus, School of Geography, 43500 Semenyih, Selangor, Malaysia

²Geospatial Information Science Research Center (GISRC), Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

³Unit for GIS in Spatial Planning (UGiSP), Bureau of Innovation and Consultancy, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

ABSTRACT

In this paper, optimum routing was developed based on the travel salesman method and integrated in ArcInfo GIS using linear programming. The results of the optimized travel distances and times for residential waste collection and routing to disposal site were used to calculate the number and type of required track collection, labour requirement, costing of waste collection and to determine the overall solid waste management efficiency through waste management operation research methods. The objective of the study was to optimize residential collection and hauling to disposal site through operation cost minimization for Petaling Jaya Municipality in the state of Selangor, Malaysia. The study determined that with optimized routes and recycling possibilities, the total cost of waste collections could be reduced from RM90,372 to RM20,967, with a reduction of 76.8%. It was also revealed that optimum routes might not necessarily be the shortest distance from point A to point B as travel time maybe high on short distances due to traffic congestion and the presence of many traffic lights. Techniques and methods developed using general GIS have proven effective in route optimization and allowed management of data to suit local conditions and limitations of waste management for the studied area. Thus, scenarios of travel distances, time and waste quantity value generated from the GIS enabled appropriate determination of the number of waste trucks and labour requirements for the operation and the overall calculation of costs of waste management based on the operation research methods used in the study.

Keywords: Route optimization, GIS, Waste collection, Operational cost, Malaysia

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E-mail addresses:

Lawal.Billa@nottingham.edu.my (Billa, L.),

biswajeet24@gmail.com (Pradhan, B.)

*Corresponding Author

INTRODUCTION

Studies on waste management increasingly show that solid waste collection and transportation absorb almost 80% of municipal waste management budgets (Ogwueleka,

2009; Vijay *et al.*, 2008; Meulen, 1996). This problem is experienced in Malaysia, where waste collection routes are left at the discretion of drivers, consequently impacting on costs, effectiveness and efficiency of waste management in municipal council areas such as Petaling Jaya. These financial and socio-environmental considerations such as smell and public nuisance in waste transportation have prompted waste collection planners to consider geographical information system (GIS) solutions for route selection and optimization in the collection operation. The objective of this study is to apply the travelling salesman's method, together with other heuristic routing techniques and GIS, in optimizing routing trucks and collection of residential waste so as to minimize the travel distance, time and financial costs during the collection process. Many of the waste management agencies involved in municipal waste in Malaysia incur high costs in the collection and transportation of wastes to disposal sites. Studies of their operations revealed the limited application of routing optimization and spatial information techniques.

Waste collecting routing in Malaysia is left at the discretion of drivers, resulting in abnormal time and distances travelled and thus higher operation costs. The process of residential waste collection involves door-to-door travels by collection vehicles. Studies by several researchers (see Lopez *et al.*, 2008; Kim *et al.*, 2006; Triantafyllou & Cherrett, 2009; Massie, 1997; Tchobanoglous *et al.*, 1993; Hagget & Chorley, 1969; Mills, 1967) show that routes taken based on drivers' experiences do not necessarily mean optimum routes are followed. Although waste management software is available, it is rather expensive, while its functions and features cannot be easily customized to suite local conditions where they are being used. These problems have some limitations in their usage. In this study, data were developed in ArcView and Arc/Info GIS. Techniques and processes that had been developed for optimum routing were applied to the GIS for street network processing and analysis. Data were also assessed for separation and estimation of recyclable materials, and the results obtained were used to calculate the overall financial cost for the waste collection operation.

Network optimization techniques are used in many transport-planning cases; a typical route network optimization can be performed for waste collection, post delivery, street cleaning, snow removal, school bus routing and delivery of goods to customers (Chalkias & Lasaridi, 2009; Li *et al.*, 2009; Tavares *et al.*, 2008; Triantafyllou & Cherrett, 2009; Ghose *et al.*, 2008; Vijay, 2008). Although according to Wallace (2011), route optimization could eliminate hours spent on manual routing, maximize productivity, optimize equipment and staff allocations for better control of routing operations, a review of the routing algorithms showed that different problems required different routing models. A summary of the general routing problems and path finding algorithms revealed that the Floyd's and Short Path (SP) algorithms are suitable for identifying in a simple network from point A to point B. The Chinese Postman (CP) algorithm, on the other hand, identifies the shortest path in a network to link a series of points by passing through all the points at least once. The Travelling Salesman (TS) algorithm is similar to CP, but it has added features that allow travels through all given points and arcs in a network and arrivals at the starting point, and thus forming a circuit. These short path and routing problems have been extensively discussed in Tavares *et al.* (2008), Karadimis, *et al.* (2008), Karadimis, *et al.* (2007), Belenguer *et al.* (2006), Johnson *et al.* (2002), Clarke and Wright (1964) and Mandl (1979).

Over the years, planners have established that the TS algorithm is useful for optimizing travels for street cleaning, waste collections, snow clearance and newspaper/ postal delivery that require an arc-routing solution with side constraints (Shih *et al.* 1997). In a GIS, street/ road networks are represented by arcs, intersections by nodes and directions can be assigned as one- or two-way lanes. Findings of the optimum TS routes require travels through all arcs of a given network such that the route is a circuit, where the initial and final nodes of the route are the same. A route circuit that passes through all arcs at least once guarantees that service can be carried out in the minimum time so as to minimize both travel and cost. Travares *et al.* (2008) and Belenguer *et al.* (2006) explained that municipal waste collection activities can be handled in the same way as street cleaning and the problem to be considered is how to route waste trucks to minimize the total travel time of the vehicles and determine the minimum number of trucks needed each day so that certain nodes are serviced on at least one route. The challenge of the study was to resolve the TS problem in a situation of unlimited route length, in such a way the optimum required tracks, travel distance and time can be estimated in waste collection from normal households.

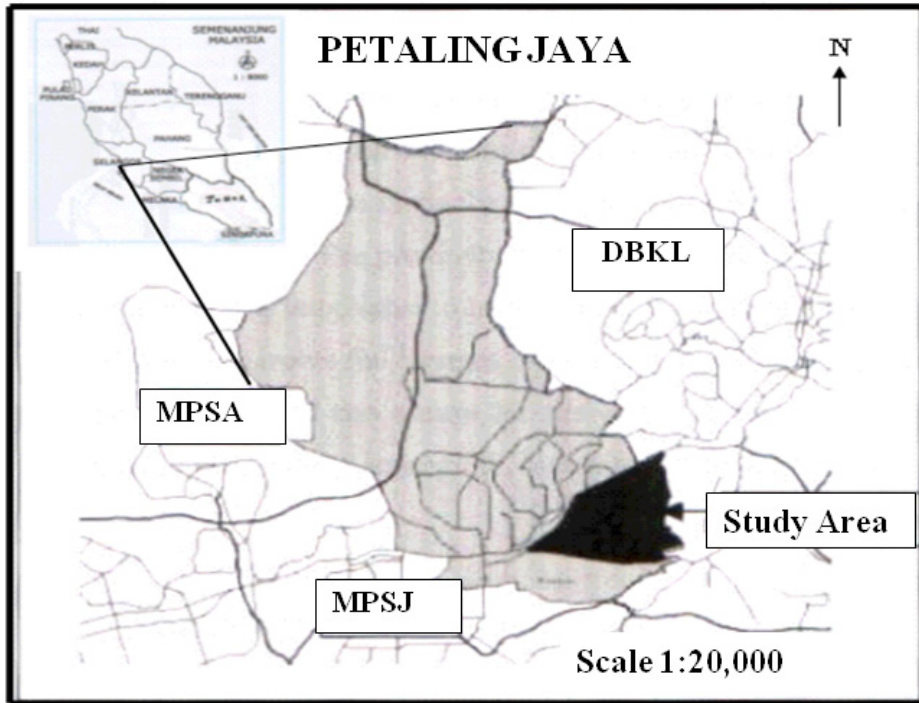
MATERIALS AND METHODS

The waste collection route optimization study was conducted in zones eight and nine of the municipal area of Petaling Jaya, a residential suburb of Greater Kuala Lumpur in Malaysia (Fig.1). In this paper, the findings of the collection route S18 zone eight are presented and discussed. Without any effective monitoring system, there have been dissatisfactions with untimely waste collections, and the collection process in the area has also shown abnormally high travelling time for some routing areas. These abnormalities were found to be attributed to unofficial recycling activities conducted by waste collection personnel. Generally, the area has an extensive residential road network, and the limited waste management resources available make it difficult to institute a timely waste collection process and also monitor the time travel of waste collection trucks. This study was thus conducted to optimize the use of garbage trucks and improve the routing of these trucks.

There are five collection sectors/ routes for the zone with a total population of about 16,365 people. Incomplete data for the study area were collected from the municipal council (MPPJ, 1998; 1997) and the waste management authority (AFSB, 2000; 1996). Firstly, a primary survey was conducted to update information on the number and type of houses on each residential street. Housing type was categorized as semi detached, flats or others, while the income type of housing was classified as high, medium and low, based on the national classification. The extent of each residential collection sector was also confirmed using the sector map given by AFSB. Other information regarding the average waste storage container size, waste collection vehicle capacity, truck type (compaction and non-compaction), the average speed of truck during collections in residential areas and the speed of truck during travels to the landfill location was supplied by the management company (AFSB).

A thematic map was generated for the study area to show the type and quantity of wastes by collection sector. The average waste generation rate for zone 8 was calculated as 0.55 kg/capita with the population density of 62/ha. The total daily waste production was 8,875.2 kg

and after effective recovery, the expected waste for daily disposal in the zone was 4,118.14 kg. On average, waste emanating from the medium income households accounted for over 85% of the total waste collection. Details of the waste generation rate by sectors in zone 9 are presented in Table 1. Breakdown of the number of houses by income level, the total waste collected and the type of wastes are shown in Table 2.



MPSA: Majlis Perbandaran Shah Alam
 MPSJ: Majlis Perbandaran Subang Jaya
 DBKL: Dewan Bandaraya Board Kuala Lumpur

Fig.1: Study area (Petaling Jaya)

TABLE 1
 Waste arising for zone 8

Col. sector	No. of Houses	Gen. Rate	Qty/day (kg)	Qty 3/week Col. (kg)	Qty after Rec. (kg)
S 2	556	0.88	2446.40	4892.80	1135.24
S 13	606	0.56	1677.20	3354.40	778.10
S 1	858	0.47	2004.55	4009.10	929.98
S 5	838	0.43	1863.50	3727.00	864.84
S 7	415	0.41	883.55	1767.10	409.98
Total	3273	0.55	8875.20	17750.40	4118.14

Col: collection; Gen: generation; Qty: quantity; kg: kilogram; Rec: recycling

TABLE 2
Waste arising in collection sector S -2

Housing Type	NH	Qty/d (kg)	Rc. (kg)	Oc. (kg)	W. LF (kg)
High income	0	0	0	0	0
Medium	342	1504.80	380.71	774.89	349.18
Med/flats	204	897.60	227.08	462.25	208.23
Low	10	44	11.13	20.66	10.21
Low/flats	0	0	0	0	0

NH: Number of houses, Qty/d: Quantity daily, Rc: Reusable content, Oc: Organic content, W.LF: Waste for landfill, kg: kilogram

The Existing Collection Routes

The travel time of waste collections generally varies for each route/ sector. The influencing factors were identified as the distance of the operation depot to each routing area, the number of premises, the type of waste storage containers, and the mileage of roads to be covered within the collection area and the distance from the collection areas to the landfill site. Although travel time for the residential collection routing sector was not available, the management highly observed the collection times for the routes, particularly in S-2. Table 3 presents the travel time from the depot to collection area, the collection area to landfill, and the landfill to the depot which is located 17.5 km away.

The furthest routing sector from the landfill is about 26.2 km. At an average speed of 50 km/hr and a minimum speed of 40 km/hr, the travel time to the landfill should be between 39 and 31 min, respectively. The factors influencing collection and disposal time depend on the route size, the capacity of the collection vehicle and the travel time. Meanwhile, the routing areas vary in size and location, which are relative to the operation depot and landfill site. Open dump trucks have less waste capacity compared to compaction vehicles, which are considered to be inefficient in waste collection process. The travel time is influenced by the average speed of the vehicle, distance travelled, and accessibility.

TABLE 3
Distance and travel time for routes in km

Adm Cd	Rte Cd	Total-time Rte-Lf-Dpt (hr)	Rte-Lf (hr)	Lf-Dpt (min)	Dist.Rte-Dpt (km)	Dist.Lf-Dpt (km)
Zone						
PJ 8 - 1	S -2	2:09	1:48	0:21	23.1	17.5
PJ 8 - 2	S -5	2:01	1:40	0:21	23.8	17.5
PJ 8 - 3	S -7	1:57	1:36	0:21	22.5	17.5
PJ 8 - 4	S -13	1:17	0:56	0:21	21.4	17.5
PJ 8 - 5	S -1	1:38	1:17	0:21	23	17.5

Adm: Administration, Cd: Code, Rte: Route, Lf: Landfill, Dpt: Depot, hr: hours, min: minute, km: kilometer
Source: MPPJ (1996) and AFSB (1997)

Development of Waste Collection Data

Various data were collected for the development of GIS, and these included land use (location of disposal sites), details of the roadway network of the study area, details of the residential layout and boundaries of the residential collection sectors, as demarcated by the waste management authority. Data were digitized into digital form; a total of five layers were developed in ArcView for database development. The network layer was then converted into Arc/Info coverage for cleaning and editing and prepared for network processing and analysis. Since the processing of extensive network data took up more time and computer memory, each collection sector area was dealt separately to facilitate proper routing and coordination of the road system and thus ensured an easy and quick data processing. Where an area was not clearly defined, the residential streets were demarcated as the collection area. Data were managed in such a way that enough computer space would be available to facilitate fair processing speed and analysis. Some network attributes were presented through an organized coding system. Dynamic segmentation was applied for road classification to provide an alternative to using pseudo nodes and record other attributes. The features of the route system and the event handling commands within the Arc/Info provide this dynamic segmentation capability. Then, the entire optimized routes are linked to the GIS network file using a linear programming in Arc/Info. Analysis of the database for the waste collection optimization process was carried out in Arc/Info where separate node attribute table (NAT) and an arc attribute table (AAT) were created. Using dynamic segmentation function points, line attributes were entered in one arc; the route function was then used to explore and generate various routing scenarios.

Road Network Data Development

The road network was the most important data needed for the study. After a detailed road network had been developed and topologized, a turntable was developed. The turntable is an ARC level command that builds or updates a coverage turntable for every possible “arc” – to - “arc” turns in the coverage by calculating the azimuth and angle for each arc to turn. A weed tolerance level is set, and this option is the distance in map units used to weed the vertices from the calculated turn angles. The road network attribute has 36 fields of attributes ranging from road name, class and traffic capacity. Others are the distances and travels where the field items are distance in kilometres and miles. Travel time is calculated at 30, 40, and 50 km/hr. Travel time which includes pick-up time for garbage is calculated at 5 to 7 km/hr plus pick-up time of 30 seconds for house to house containers, and 90 to 120 sec for 1100 kg containers located at flats, apartments and community dumps. The other category is demographic and waste quantity which comprises of the number of residences, houses, the income type of house and the quantity of waste for one to three times of collection frequency.

The waste collection truck is to follow a certain route, which should have a minimum length. This optimum route is calculated together with all the related information stored in the road segment such as waste offered, pick-up points, each pick-up time and expected delay time at traffic congestion. Using the existing routing sectors, the travelling salesman’s problem was solved for each routing sector. The route enters the collection sector and follows an optimized

path while passing through all streets at least once and then back to the entry point. This ensures that the services are provided along all the streets based on the minimum distance and time, thus resulting in cost minimization.

It is crucial to note that the routes from residential or collection areas to disposal site (landfill) were not based on the travelling salesman's method. Rather, the detailed major road network was encoded with the attributes of road intersections, length, classification and traffic congestion. The choice of route was mainly on the primary roads, thus limiting the options of routing and simplifying the routing process. The route begins from the exit of the collection areas and the best possible arc link is selected on a primary road to the direction of the waste disposal site. The "near"-function was used to link the costs, directions and speed to the arcs and nodes. Together with the "near"-function, the modules calculate the shortest path between two or more points and optimize the sequence of stops making the route. The major objective is to minimize travel time and distance. Once there is a reduction in time and distance, there will be a corresponding reduction in cost of waste management. Roads are classified according to the national road classification scheme, and these include highways, primary, district, local distributors and minor roads (AFSB, 2000; Arshad, 1992). Using these attributes, it is easy to determine the road characteristics in terms of its width, size and capacity. Highways are identified separately because waste transportation on such roads makes distances shorter but imposes higher costs.

In this study, the road network of the collection sectors comprises 881 arc segments. However, when the roads from the waste management depot and the roads disposal site location are included, the total arc segments considered in the study were 3843. In the application of network analysis in Arc/Info, all the attributes of the network are calculated and included in individual arc segments. Primary, district and local distributor roads provide high vehicle capacity and allow rapid travel, and are therefore classified as mass transit roads. The travel times on these roads are low because a waste collection truck may travel at a speed between 30 to 50 km/h from the collection sectors to waste disposal site. Meanwhile, road intersections and junctions with incidence of traffic at certain time periods are identified and excluded from the mass transit. A thematic map was generated in GIS to show the road network from the waste management operation depot to the residential collection areas and to the landfill. In GIS, the roads for collection and hauling of wastes from collection sites to disposal landfill are presented separately to allow for an easy processing of data.

Waste production and distribution were analyzed for the housing file and optimum collection routes on the network file. Residential houses along the route were classified according to the national classification scheme, as follows: low, middle and high income housing type; the national average household size of five was then used to compute the population and the expected quantity of waste for collection for each house using the per capital waste generation figures collected in earlier studies for Petaling Jaya. The waste generation was calculated for different income housing levels such as low income (0.65 kg/c/d), medium income (1.28 kg/c/d) and high income (1.37 kg/c/d).

Optimum Route Based on the Travelling Salesman (TS) Method

The TS algorithm was used for the residential waste collection route optimization. The process of route optimization involves establishing the sequence of streets/roads to be followed in the entire road network of the selected collection area. Meanwhile, a TS cost matrix was worked out using the nodes and the distance of the roads between each two intersections. The problem considered the routing of the service trucks so as to minimize the total distance, travel time and also to determine the number of trucks and personnel needed so that the cost of waste collection in the selected area could be minimized.

According to Karadimis *et al.* (2008), solving the TS problem can be mathematically explained as a problem of combinatorial optimization. The variants of the combinatorial optimization appeared in the recent studies of Gutfraind and Hagberg (2011) and Wallace (2011). The problem is stated as follows: let X_{ij} be a variable, so that $X_{ij} = 1$, if node i is assigned to j and $X_{ij} = 0$, and the coefficients C_{ij} is the cost of assigning node i to j (Mandl, 1979). The governing equations presented are to find 0 - 1 variable X_{ij} so as to minimize:

$$\text{Min} : z = \sum_{j=1}^n \sum_{i=1}^n C_{ij} X_{ij} \quad \text{Eq.(1)}$$

subject to

$$\sum_{i=1}^n x_{ij} = \sum_{j=1}^n x_{ij} = 1 \text{ (for all } i \text{ and } j = 1, 2, \dots, n) \quad \text{Eq.(2)}$$

and

$$x_{ij} = 0 \text{ or } 1 \quad \text{Eq.(3)}$$

In solving the problem, a similar scheme was used, where $X_{ij} = 1$, indicating that a truck travels directly from node i to j , and $X_{ij} = 0$ indicating that it does not travel at all. By assuming that an assignment cost is $C_{ij} = 8$. C_{ij} is the shortest distance from node i to j . Equation 2 in the (TS) problem involves a truck entering a node by an arc, which is also leaving this particular node. The minimum value of z , calculated from equations (1) - (3), is the valid lower bound for the solution to the TS problem for a network with a cost matrix $(c_{ij}) = C$. The construction of a cost matrix among the nodes requires the extraction of distance values from the network. A series of matrix iteration was constructed in Microsoft Excel based on the method of Chou (1997). The route was computed by assigning the numbers to all the intersecting nodes of the sector street network. The lengths of each arc/street between the nodes were identified and used to develop a series of cost matrixes to determine the order and sequence of node to be included in the route. The cost values for the optimum TS route were extracted from the matrix and linked to the street network coverage in the Arc/Info by linear programming.

Various waste management operation research methods were used to calculate the waste hauling time and motion, as explained by Chalkias and Lasaridi (2009), Vijay *et al.* (2008), Oliveira and Borenstein (2007), and Tchobanoglous *et al.* (1977). Collection time is an important factor that can be used to quantify collection efficiency. Optimum waste collection

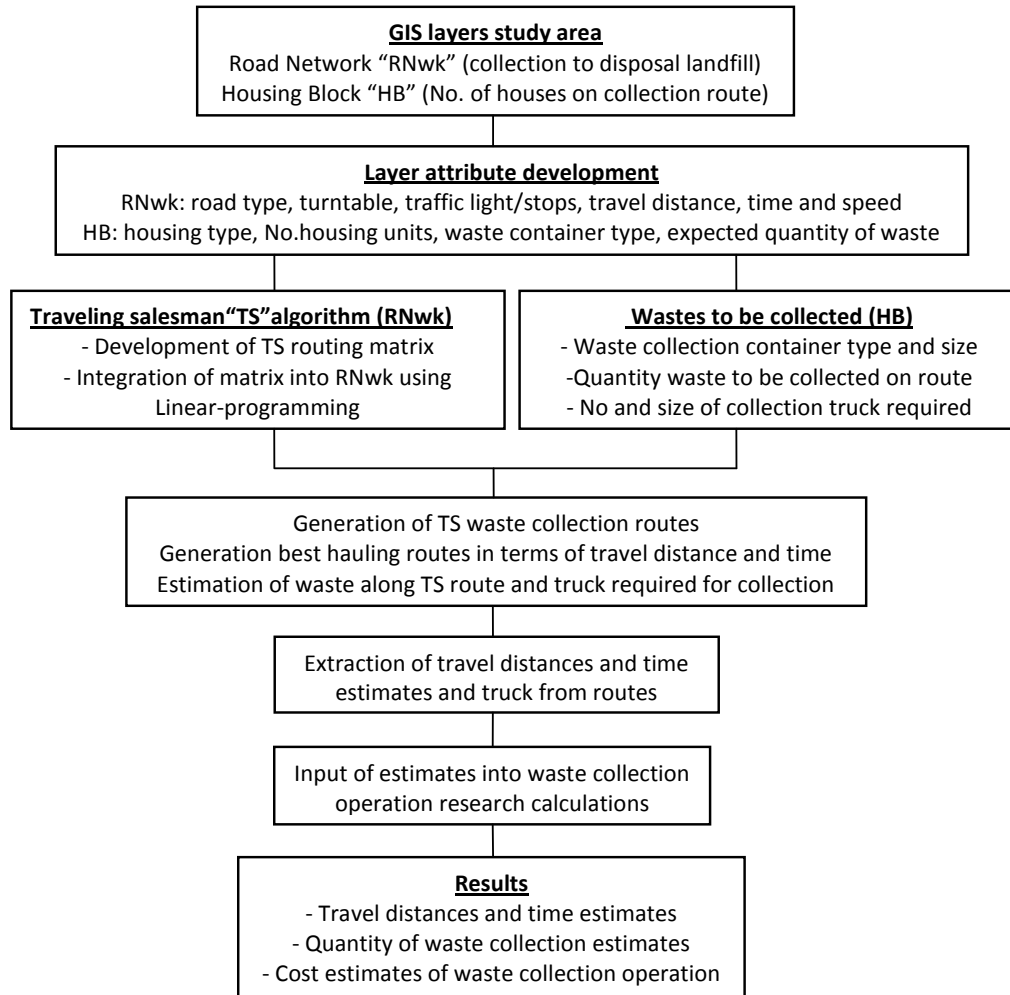


Fig.2: A flow chart of the methodological process adopted in this study

includes the concerns of the optimum filling of collection vehicles at each end of a route and the route to be followed should have travelling characteristics in terms of time and distance. Using time and motion values extracted from the system, the capital expenditure for solid waste management was computed based on Ghose *et al.* (2008) and Holmes (1983).

In this section, a detailed description of the GIS data and detailed methodological processes are given. In more specific, the section explains waste estimation based on housing type and number of units. It also gives elaborated discussions of the travelling salesman method and how it has been integrated into the GIS road network to generate an optimized TS collection route. Fig.2 shows a flow chart of the methodology process adopted in this study.

RESULTS AND DISCUSSION

The TS optimized route means the points of entry and exit at the collection sector are the same. A route is followed from then on without backtracking so as to minimize the distance and time in the collection process. Fig.3 shows the optimum distances and travel time generated using the query function of the Arc/Info GIS. The collection time includes the time spent on picking container and the quantity of garbage to be collected along the route. The pick-up time increases by 20 seconds for every terrace house and 90 seconds for flats and apartment containers. A total of 10 flats are allocated for one container in the flats and apartment blocks.

Although sector S-2 is a large area, the routing process has the same number of housing units with that of other sectors. Hence, the optimum route was computed based on 41 intersection nodes. The travel distance and time from the optimum collection route, the number of housing units and the quantity of waste for collection are presented in Fig.4(a) and Fig.4(b), Fig.5 and Fig.6, respectively. Since the tables are generated by the GIS system as a scroll down, the values presented (in the tables) are the samples values and they do not sum up to the total value as computed by the system. At an average speed of 7 km/hr for residential waste collection, the total distance covered through the course of the collection process is 7.55 km (see Fig.4a). Travel time includes time spent on each residential pickup and the pick-up time for communal containers along the route. The collection time for S-2 is recorded as 2.24 hrs (see Fig.4b). The time recorded in S-2 was less because it has fewer number of houses, and only a few flats and apartments, where the container pick-up time of 90 seconds would have increased the collection time. The total number of residential housing units in the collection route is 524 units (see Fig.5). Fig.6 shows the expected quantity of wastes to be collected as 2199 kg.

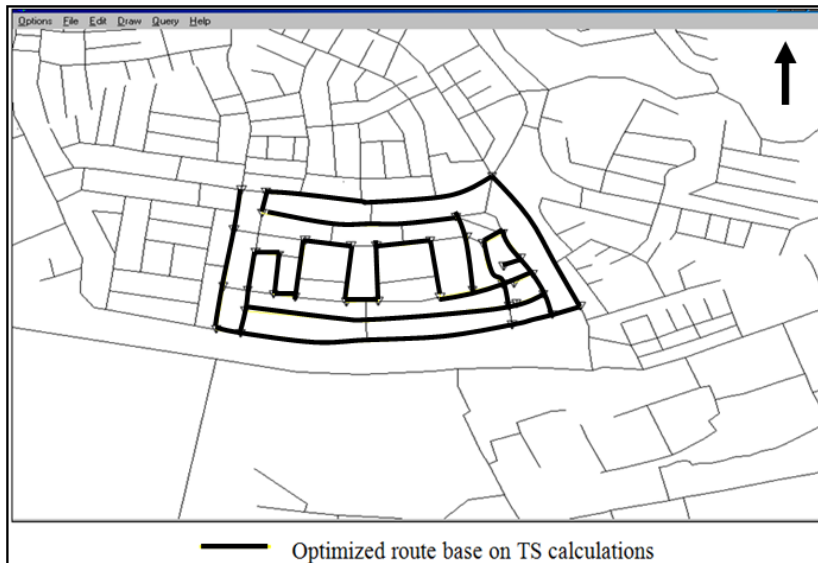


Fig.3: Optimum collection route in S-2 (zone 8)

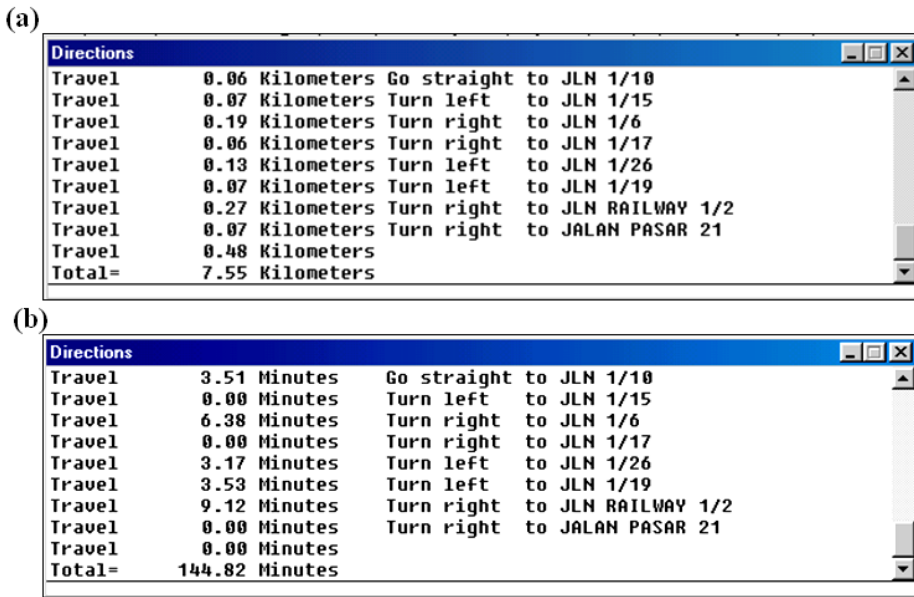


Fig.4: Direction table of distance (a) and time travel (b) at 7km/h

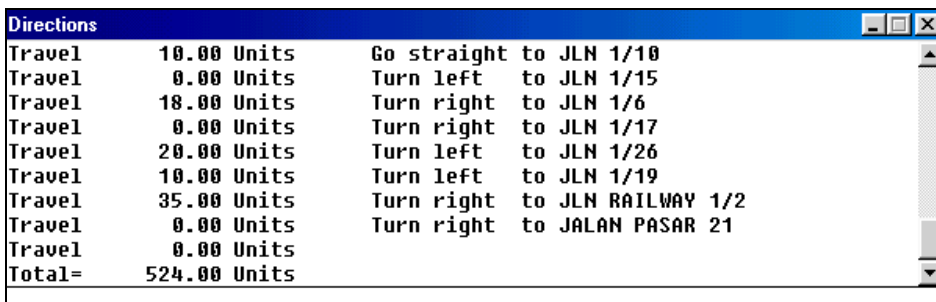


Fig.5: The sample results of the number of housing units

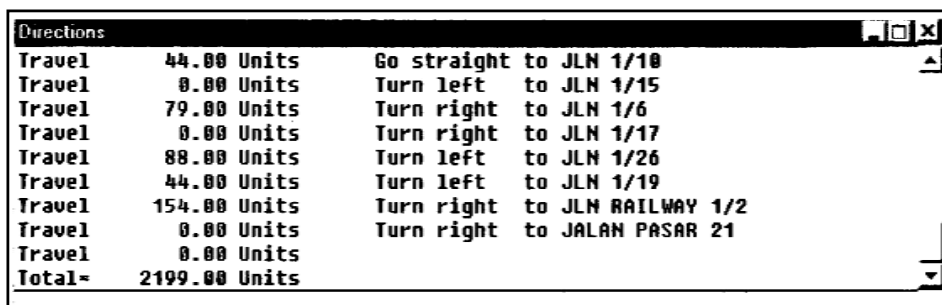


Fig.6: The sample results of the quantity of expected wastes to be collected along optimized route of S-2

Hauling Route from Collection Sector to Disposal Site

The optimum residential waste collection using the travelling salesman algorithm is complicated because it calculates routes from the start node and back to the start node, passing through all streets to form a circuit. However, in the hauling of waste from collection areas to the disposal site, only primary roads and highways are included, making the optimum route development process easy. The options of avoiding the highways due to tolls and also selecting routes that avoid possible traffic congestion are also included in the GIS system.

In the hauling route process, the nearest node from the origin node is located and the process continues to finding the subsequent nearest node in the network until it reaches the destination node (i.e., the nearest to the location of the disposal site). This tree building process ensures that the shortest possible path is taken in terms of distance and time. When the destination node is reached, the algorithm is terminated because the shortest path has been found. The various route scenarios for optimum hauling from sector S-2 collection to the landfill in the GIS application are illustrated in Fig.7. The system is manipulated to generate two optimum route scenarios A and B (details of this hauling route are shown in Fig.8).

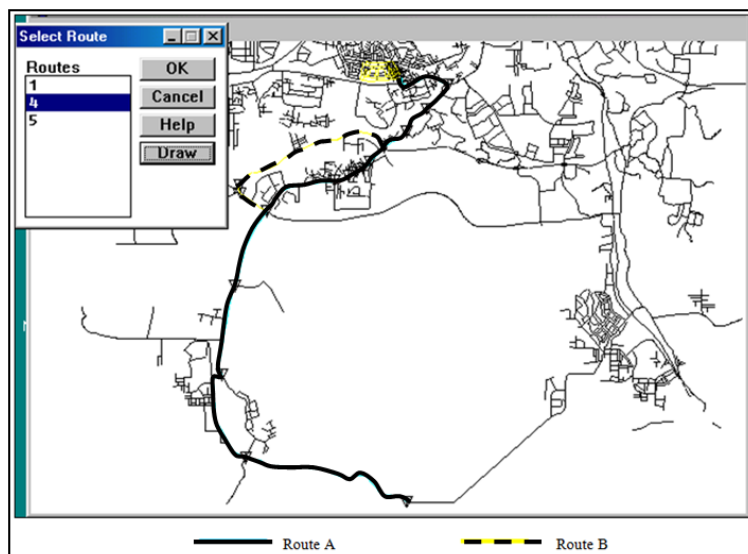


Fig.7: Hauling route A to disposal site from S-2

The travel time and motion values generated from the waste collection GIS show sample directions of two possible hauling route options to the landfill site. The unnamed features in the direction tables are the segments of road names that are not identified when conducting the aerial survey. For this reason, they could not be included in the system. Route A presents a direct route at a travel speed of 50 km/hr through the primary road. The distance to the landfill is 20.42 km, and the recorded travel time of 27.2 min is high due to the road segment being in a commercial and residential area and also the possibilities of traffic congestion along the major road. Route B (see Fig.8) shows a travel distance of 21.30 km in (Fig.9b), with an increase of

1 km on route A. Due to less traffic, however, the travel time is generated as 25.29 min, i.e. with a decrease of 2 min. The two routes were assessed in terms of time and distance travel and by taking factors such as public nuisance from smell into consideration. Route B presents a better and agreeable travel option as it makes up for the increased distance with a faster travel time that avoids possible public nuisance; thus, the best waste route is not necessarily the shortest distance.

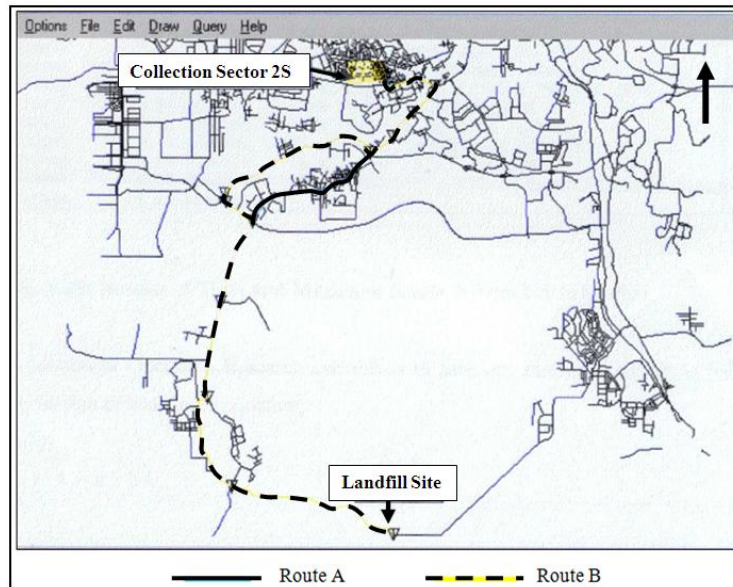


Fig.8: Hauling route B to disposal site from S-2

In this study, the time and distance values that form the optimums were used to evaluate and assess the trip hauling time. Using traditional operation research calculation of time and motion, it is shown as the basic expression of haul speed equation, as follows:

$$\frac{x}{y} = h = a + bx \quad \text{Eq. (4)}$$

Thus, to find the single-trip-haul time for hauling Route A which is located 20.4 km to the disposal site, the values are substituted as:

$$\text{hr} = (0.080 \text{ hr / trip}) + [(0.012 \text{ hr / km})(20.4 \text{ km/ trip})]$$

$$\text{hr} = 0.080 \text{ hr /trip} + 0.245 \text{ h / trip}$$

$$\text{Haul time} = 0.32 \text{ h / trip}$$

Route B

$$\text{hr} = (0.080 \text{ hr / trip}) + [(0.012 \text{ hr / km})(23.2 \text{ km / trip})]$$

$$\text{Haul time} = 0.36 \text{ hr / trip}$$

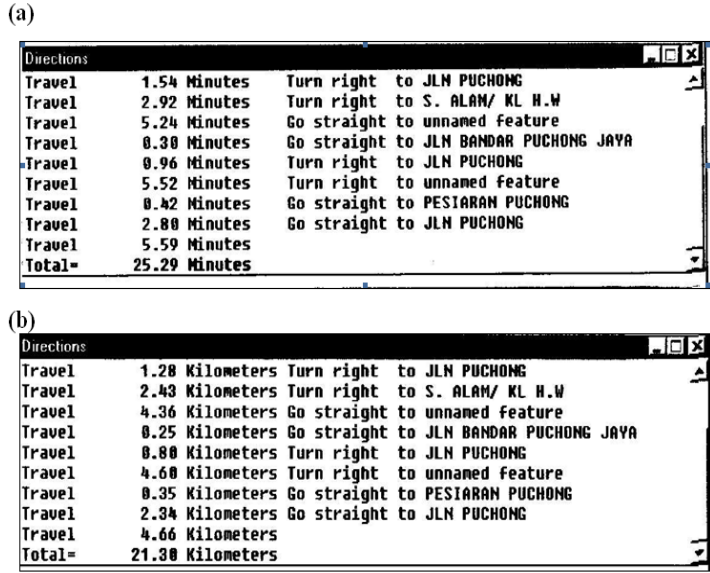


Fig.9: The sample results for the collection time (a) and distance (b) of route B from S-2 to landfill

The greater part of solid waste management expenses is incurred in the waste collection and disposal processes. The possibility of reducing the costs of waste collection involves controlling the factors that influence the cost. The factors specifically include the distance travel and time travel through collection and to disposal and the quantity of waste to be collected for disposal. The development of the optimum routing scenario was difficult but with the use of GIS, the entire procedures have been simplified, and it is beneficial to determine the best route (note that the best route does not necessary be the shortest distance in terms of time). Additionally, using the value from the optimum routing, the hauling time of waste collection trip was calculated.

The Costs of Waste Collection Management

A total of RM5,000 per day is spent for the disposal of the entire waste collected in Petaling Jaya, while RM150 is spent on each collection vehicle per day. At three times a week, the 36.149 tons of wastes in the study area are collected at RM100/ton and RM25/ton for disposal. Thus, the total costs of waste collection and disposal was estimated at RM90,372. The potentially high recovery rate means that the quantity of waste could be reduced to 8.387 tons, and this would mean a reduction in the cost of collection and disposal to RM20,967. The evaluation of the capital expenditure for solid waste management was calculated using the mathematical formulas, as expressed by Tchobanglous *et al.* (1993; 1977). The basic expression for man-minute's labour cost per ton is formulated as the total man-minutes per trip:

$$f = b + ade + aT' + aT'' + aT''' \tag{Eq. 5}$$

The terms in Eq. 5 have been defined together with the calculation of the labour cost as follows: distance and time values were used to calculate the labour cost per ton. For a three-time per week collection frequency from curbside location, and with a three-man collection

truck crew in sector 2S, the time and motion information were substituted for the labour cost calculation, as follows:

- a = 3 men per vehicle
- b = 145 man-minutes per trip
- de = 23.5-minute disposal site at a speed of 50 km/h
- T' = 10-minute disposal time, assume time
- T'' = 0 minute of route time
- T''' = 7.3 travel time to first stop
- c = 4.4 tons average refuse per trip
- f = (145) + 3(23.5) + 3(10) + 3(0) + 3(7.3) as the total man-minute per trip;
therefore, $x = f / c = 267.4 / 4.4 = 60.77$ man-min/ton.

Based on the average monthly income the waste workers receive i.e. RM500, the per minute wage was calculated at RM 0.04.

Labour cost per ton will then be: 61 m-m/ton x RM 0.04/m-m = 2.44/ ton.

The operational cost of the waste collection in the sectors was calculated by using the operation research in Eq. 6 to determine the number of containers per trip:

$$C_t = V r / c f \quad \text{Eq. (6)}$$

The values for sector S-2 of the study area were calculated as follows:

- V = 37.5 m³ / trip
- C = 0.78 m³
- f = 0.85
- r = assumed compaction ratio of 2

$$\text{Thus, } C_t = (37.5 \text{ m}^3 / \text{trip}) (2) / (0.78 \text{ m}^3) (0.85) = 75 / 0.663$$

$$C_t = 114 \text{ containers/ trip}$$

The pick-up time per container was then determined by using Eq. 7.

$$P_{scs} = C_t (u c) + (A p - 1) (d b c) \quad \text{Eq. (7)}$$

$$= C_t (u c) + (n p - 1) (a' + b' x')$$

$$P_{scs} = (114 - 1) (0.050 \text{ h / con}) + (114 - 1 \text{ location / trip}) [(0.60 \text{ h / location})$$

$$+ (0.041 \text{ km}) + (0.1 \text{ km / location})]$$

$$= (5.65) + (113) [(0.060 \text{ h/location} + 0.0041)]$$

$$= 5.65 + 113 (0.0641) = 12.89 \text{ h/trip}$$

The number of trips required per week was then determined by using Eq. 8:

$$N_w = V_w / (v r) \quad \text{Eq. (8)}$$

$$N_w = (52.4 \text{ m}^3/\text{wk}) / (37.5 \text{ m}^3/\text{trip}) (2) = 0.69 = 1 \text{ trip/ wk}$$

The operational cost of waste collection in the study area was calculated at RM 300/week, and this cost is relatively high for the short distance to landfill. At three times a week, the 36.149 tons of waste in the area are collected and disposed of at the cost of RM90,372.00. It is also revealed that with effective waste recovery, the quantity and costs of collection and disposal can be reduced to 8.389 tons at a cost of RM20,967.00. Table 4 presents a comparative evaluation of the GIS generated hauling time to disposal site and the traditional method of calculation of time and distance. Moreover, by using GIS, the specific locations of expected traffic congestion can be identified and the delayed time input in the road segments (i.e., time travel) could be better assessed. In the traditional method, however, this factor could not be taken into account. The results of the optimum distances and time obtained from the routing were used to calculate the waste trip hauling time, pick-up time per container, number of trips required per week, basic cost of labour per ton and the overall operational cost of waste collection based on the waste collection operational research methods, as given in Equations 5, 6, 7 and 8.

TABLE 4
GIS generated and traditional time and motion measurement

Route A	GIS generated	Traditional Calculation
Distance	20.4 km	24.4 km
Travel time	27.2 min/trip	0.32 h = 19.2 min/trip
Route B		
Distance	23.2 km	23.2 km
Travel Time	25.2 min/trip	0.36 h = 21.6 min/trip

CONCLUSION

In this study, the optimum routes for residential waste collection were established using the travelling salesman route optimization techniques and network analysis in GIS. A single layer network operation was conducted to determine the optimum route for hauling waste to landfill. Although this route recorded a travel distance of 21.3 km, the travel time was low, i.e. at 25.29 min, because all the possible traffic obstructions were avoided. In the process of this routing application, many benefits of applying GIS were observed. The application did not only bring real-life waste collection routing problems for resolution on a desktop PC but it also simplified the time and means of managing the vast amount of data required. Both the spatial and network data were handled efficiently, while the calculation and estimation of wastes arising were also simplified using statistical and analytical functions in the GIS. This has allowed the evaluation of the expected quantity of waste for collection and the number of expected pick-up stops on each route in the network. Time and motion values within the optimized TS routing area were also assessed and evaluated using the system.

Although the application of GIS in Malaysia is very wide spread, its practical problem-solving application is still in its infancy. The processes and techniques of GIS and the network module in the Arc/Info for resolving the local and practical routing problem in urban residential waste collection are presented in this paper. The various network data structure and routing functions available in the Arc/Info are adequate for the necessary route planning analysis in

the study. The network module in the Arc/Info provided an opportunity to make calculations on road network and link generalized characteristics such as cost, direction and congestion to arcs and nodes of road segments. The extensive route network data of over 500 km of road length in the study was reduced to a PC desktop environment. Meanwhile, the network analysis functions in the Arc/Info were manipulated mainly on a single layer operation method to generate the optimum routing scenarios. Thus, the system allows effective and efficient visual interpretation and display of results.

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