SCHEDULING OF SOLID WASTE COLLECTION ROUTES

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ABSTRACT

Routing of solid waste collection vehicles in Nigeria poses a challenging task because of attitudinal and haphazard infrastructure problems to contend with. The objective is to minimize the overall cost, which was essentially based on the distance travelled by collection vehicles. The study proposes heuristic methods to generate feasible solution to an extended capacitated Chinese Postman Problem (CCPP) in undirected network. The heuristic procedure consist of "route first, cluster second" and "cluster first, route second" and was applied to scheduling solid waste collection problems in two cities – Abuja and Onitsha. The two techniques were compared and with the existing schedule with respect to cost, efficiency, and distance travelled. A cost model was developed to compare the quality of solution derived. The adoption of the proposed heuristics in Onitsha resulted in reduction of the number of existing vehicles by three, $325.90 (or 7.65%) in refuse collection cost and 28.17km (or 6.03%) in vehicle distance travelled per day. In Abuja, the heuristics produced routes which could save about 19.08km travel per day and $31.10 (or 21.09%) of collection cost per day. Efficiency in refuse collection was increased from 86% to 98% in Abuja and 75% to 95% in Onitsha. The results revealed a good performance of the proposed heuristic methods which will find useful applications in other areas of vehicle scheduling.

Keywords: Scheduling, collection, heuristics, solid waste.

Introduction

Solid waste collection is one of the most difficult operational problems faced by most cities in Nigeria, solid waste collection are done in an adhoc manner, which contributes to high solid waste collection cost. Solid waste collection vehicles are assigned to zones without any serious demand analysis and route construction is left to the drivers. Every time the vehicle is filled up, it heads to the disposal site, to unload and then return to the zones [1, 2]. This method contributes to high solid waste collection cost. Some methods have already been advanced for improving solid waste management system. Prominent among these methods include fleet and truck size selection [3], selection and assignment of generating sources to sanitary landfill sites and transfer stations [4], vehicle route and optimization of solid waste collection routes [5, 6], and so on. Nevertheless, the number of papers that have reported studies on scheduling and routing of solid waste collection vehicles as a method of minimizing solid waste collection cost is surprisingly low. Examples of such papers are Pinnoi and Tung [7] and Moura [8].

Wang et al [9] proposed a model where waste collection, recycling and disposal are explicitly considered, but route design problem is solved only considering the districts as the sources of demand, without analysis of collection routes inside each of the zones. Pinnoi and Tung [7] formulated a heuristic procedure consisting of construction and improvement phases. The route construction routine is a modification of Solomon's [10] heuristics while the improvement phase is the mixture of the exchange procedures (power of Or-opt and 2-opt* together) introduced by Potvin and Rousseau [11]. The route procedure starts an initial solution obtained from the route construction phase and attempts to find a better neighbouring solution in terms of the number of vehicles and total time spent, while maintaining solution feasibility.

Agunwamba et al [12], chose to associate the demand to a set of point representing a set of streets, instead of considering in details the arcs of the network. Solid waste is collected from different sanitation zones, transported to some transition stations, and finally to a landfill. Most of these works have considered waste collection problem at a district level. None of the above literature took into account the road network detail in finding solution to waste collection problem. This work proposed algorithm for determining solution for real case studies concerning solid waste collection in urban areas, represented in full detail as regards the road network.

The vehicle routing problem has been studied extensively for the past thirty or so years. It is a hard combinatorial optimization problems. As such only relatively small vehicles routing problems can be solved to optimality. Current researchers are concentrating on the development of approximation algorithm, heuristic and mataheuristics. Gendreu et al [13] developed a tabu search heuristic for the vehicle routing problem with capacity and route length restrictions [14 – 16].

Residential refuse collection requires services at a large number of discrete points. These points are close together and distributed along the links. Algorithm for solid waste route is considered to belong to Capacitated Arc Routing Problems (CARP). Special cases of the CARP are Chinese Postman Problem (CPP) and Capacitated Chinese Postman Problem (CCPP). CPP is an extension of famous "Konigsberg bridges" of Leonhard Euler.

The problem of finding a route of minimum distance, which covers all arcs in a network, is known as the Chinese Postman Problem (CPP). Because of the capacity constraints on collection vehicles, more than one tour is usually required to collect refuse in an urban area. Therefore, a solution of the Chinese Postman Problem cannot solve urban refuse collection problem. In this situation, a number of tours must be determined. This network theory problem is called capacitated Chinese Postman Problem, that of determining a minimum cost of m tours, which collect all the streets. A constrained version of the CPP is called the Capacitated Chinese Postman Problem (CCPP). The Capacitated Chinese postman problem (CCPP) arises when arc has associated with it a positive demand and the vehicles to be routed have a finite capacity [17]. In CCPP, $q_{ij} > 0$ for all (V_i, V_j) according to Christofides [18]. One truck may not be able to service all the roads in a district due to its limited capacity. The CCPP is to find a set of routes single depot that service all edges in the graph at minimal cost and subject to the constraint that the total demand on each route does not exceed the capacity of the vehicle. The cost of a trip comprises the cost of its serviced edges and of its intermediate paths. Demands are usually amounts collected along the streets (urban waste). Costs are often distances or travel times.

The CCP belongs to a class of a network optimization problem, which have high practical relevance in the areas of routing and scheduling [19]. CCPP remains difficulty to solve to optimality. CCPP problem is NP – hard [20]. This means that it is one of a set of many combinational optimisation problems for which no algorithm has yet been devised which will guarantee an optimal solution in a number of steps which is a polynominal function of the size of the problem. As this problem cannot be solved by optimal (exact) method in practice, heuristic are used for this purpose, the study resorts to heuristic procedure to obtain bear optimal solution [21, 22].

Therefore, this research paper develops heuristic method that provides good feasible solutions for an undirected capacitated arc routing problem, inspired by the refuse collection problems in Onitsha and Abuja both in Nigeria. The heuristic is limited to residential collection and collection along the streets instead of intersections (nodes). The network is undirected network, where collection occurs on both sides of the street at the same time and the streets are not one-way streets, hence a street is represented by a single undirected arc.

The refuse is located in containers along the streets and they must all be collected by a fleet of vehicles whose capacity cannot be exceeded. However, large institutions such as school, hospitals etc. have the refuse stored in large metal/rubber containers. Each vehicle can service several streets before going to the sanitary landfill to unload. The vehicle leaves the depot at the start of the day and must return there empty at the end of the day. The first trip begins when the vehicle starts collection of refuse along the streets and when it gets filled up, the vehicle drives to a sanitary landfill, located well away from the city, to unload the refuse. The vehicle then goes back to the city and begins its second trip. Every time (except for the last) the vehicle's residual capacity so demands it must head to the sanitary landfill, to unload and then returns to the city. After completing its final trip, the vehicle proceeds to the landfill to unload, for the last time and finally returns to the depot.

The Proposed Heuristic Method

In this paper, efficient constructive heuristic method for arc routing problem of collection of refuse is developed. The heuristic method is "route first, cluster second" approach. The algorithm minimizes the total cost (time or distance) of the operation.

A single route over all edges with positive demands in the network was constructed. This single route is called the "giant tours". Since one vehicle will not generally be able to cover all the required streets in the giant tour in a reasonable time or due to limited vehicle capacity, it is necessary to decompose the giant tour into a collection of m sub tours, each of which can be handled by one vehicle. The cost of a trip comprises the cost of its serviced edges and of its immediate connecting path. Demands are usually amounts to be collected along the streets (urban waste). Costs are often distance or travel times. Network $G = (V, E)$, is the set of vertex (node) and E, is the set of (undirected) edges.

The first step is to develop the network representation of the collection district and then to inspect the map of the district to determine most of the required information. The method of collection and whether both sides of a street may be collected simultaneously must be taken into consideration. This algorithm is for undirected network.

Algorithm for Route First, Cluster Second

The Chinese postman problem involves replication of some of its edges or arcs to make it Eulerian. If a route covering all of the streets in G once can be found, then this route is called Euler tour [23]. If an Euler tour does not exist in G, this amounts to determining a least cost augmentation of a graph (streets have to be added to G to create a new network $G_2 = (V^1, E^1)$ in which an Euler tour will exist, if the network G is connected). This method is based on heuristic reasoning. The odd degree vertices are edges first identified (there is always an even number of such vertices) and the cost C_{ij} of a shortest chain is computed for each pair of odd degree vertices V_i and V_j. Heuristics can be used for augmentation of the graph. These heuristics often embed matching algorithm or shortest spanning tree algorithm or shortest spanning tree algorithm to generate an augmented graph that satisfy the unicursality conditions. Exact algorithm for the generation of Eulerian graphs uses two of the techniques commonly employed for travelling salesman problem (TSP). In the case of undirected graphs, the problem is formulated as an integer linear programming typically containing a large constraint set.

In Edmonds and Johnson [23], let $x_{ij}(i < j)$ be an integer variable equal to the number of copies of edge (V_i, V_j) that must be added to G in order to make it Eulerian. A non-empty subject of V is called odd, if it contains an odd number of odd degree vertices.

Let $\delta(s) = \{(V_i, V_j) \in E;\ V_i \in S,\ V_j \in V/S \text{ or } V_i \in V/S,\ V_j \in S\}$

The problem is then

Minimize (1)

Subject to $(S \subset V, S \text{ is odd})$ (2)

$$x_{ij} \geq 0[(V_i, V_j) \in E] \quad (3)$$

$$x_{ij} \text{ integer } (V_i, V_j) \in E] \quad (4)$$

This integer programming model is solved in a branch and cut fashion. Equations (1) – (3) can be solved as a matching problem on the odd degree vertices of V with matching costs C_{ij}. A new graph G_2 (V, E^*) that contains $F(i, j) + 1$ copies of each edge (i, j) in graph is constructed. Clearly, an Euler tour of G_2 corresponding to a postman route in graph. Original network is converted to a unicursal network by matching algorithm.

Condition for Unicursal or Eulerian

1. The network must be connected.
2. All the vertex of the network must be an even degree.

The resulting network is subdivided into a set of cycles to facilitate the formulation of collection districts. The algorithm proposed by Edmonds and Johnson determined random cycles to form a tour. The algorithm starts at the depot and randomly selects any edge (or street) not included in the tour until sequence of streets returns to the depot. This study proposes the use of predetermined set of cycles as building block instead of generating cycles as proposed by Edmond and Johnson [23].

In this algorithm, pair of nodes are connected by block face. Cycles are joined together to form bigger sub cycles. This bigger sub cycles traverse the route on the first sub cycle until it hits this common node. Each cycle is indicated by a letter.

Each cycle formed in step 2 is represented by a cycle node. Join adjacent and connected cycle nodes by edges of zero length to obtain the cycle node and representation for the unicursal network for each sub area. These edges have zero cost. A node is added to represent the depot. This artificial node is connected to each cycle node by dashed lines. An edge is included from the depot to each cycle node whose length is twice that of the shortest distance from the depot to the closest node in corresponding cycle. Cycle nodes are assigned loads equal to the sum of total solid waste of the streets in the cycle. Each cycle nodes is indicated by a letter.

Formation of minimum cost capacitated spanning tree

The algorithm determines the district by constructing sub trees on the network of cycle nodes. The collection district is identified on collection vehicle capacities. At the stage, *M* trees of cycle nodes are found, each rooted at the depot by an edge representing the shortest path to and from the depot. This edge is called an arm. *M* arms represent the only non-zero cost edges in the tree. Each of the M trees corresponds to a route and must not violate the vehicle capacity. The *M* trees representing the m tours form the minimum cost capacitated spanning tree for each sub network.

The cycle nodes are added to form *M* sub trees, once all cycle nodes have been included, the feasibility of the sub tree load is checked. If one or more of the district load exceed the truck capacity, some edges are switched from the sub-tree to an adjacent sub-tree to balance the loads. In developing countries, collection vehicles can make two or more trips.

The final step of this algorithm is decoding the spanning tree into the corresponding tours. Cycles are joined whenever their corresponding cycle nodes are paired in the spanning tree. The cycle nodes in one sub-tree are combined into one tour,. connected to the depot by a path represented by arm. This path represents travel both to and from the district. The final tours are decoded. The dashed lines represent retracing of streets. The total streets length in each route gives the optimal length of streets. The *M* tours equal the total number of vehicles.

Data

Data for the case studies were obtained from the various municipal authorities responsible for solid waste management in Abuja and Onitsha, both in Nigeria. The data include existing route maps, characteristics of operational solid waste collection vehicles, existing routes distances with street sequence, the number of tours and vehicles and the general mode of operation. Additional data on costing items, types of vehicles, collection routes and distances were also obtained from literature [2]. The maps showing districts in Abuja and zones in Onitsha are shown in figs l and 2 respectively. The summary of street lengths and waste volumes for each district and zones (Onitsha) are presented in Table 1. In Abuja, the data were obtained and analysis performed for the central Area Districts one and two only.

Table 1: Existing routes length of 16m^3 capacity vehicle for Onitsha

Zones Distance km	Route
Okpoko	37.37
Housing Estate	48.08
GRA	55.76
Upper Iweka	99.12
Inland	122.8
Fegge	104.39

Results and Discussions

Heuristic Verification

All preliminary test result showed that the proposed heuristic algorithm performed very well and were consistent. Encouraged by the results, the heuristic algorithm was applied to solve real waste collection problems.

The results of "route first, cluster second" applied in Okpoko, Housing Estate, GRA, Upper Iweka, Inland and Fegge zones are shown in Table 2 and are comparable to the actual existing route lengths in Table 1.

Table 2: Best result of 16m^3 capacity vehicle for Onitsha

Zones Distance km	Route
Okpoko	36.03
Housing Estate	47.02
GRA	45.87
Upper Iweka	94.30
Inland	116.74
Fegge	99.39

The flow chart for the main program of refuse collection vehicle routing system is shown in Appendix A1.

Comparison of Results with Existing Schedules

Comparison between existing situations and result in Onitsha and Abuja were done with respect to cost, efficiency and distance travelled.

In Onitsha situation, adoption of "route first, cluster second" procedure reduced the deadheading distance by 28.17km (about 6.03%) and collection cost by US $280.00 (5.56%) and 2 vehicles (see Table 3). Cutting down the work of two vehicles not only reduced labour and maintenance cost, but also greatly reduced total travelling distance and fuel consumption.

Inspection of overtime, incentive time, vehicle capacity utilization, distance travelled, productive time and quality of refuse handled yields data from which cost and efficiency analyses may be made.

(5)

i.e. (6)

where w_0 is the allowable off route factor

(7)

If the sum $P_t + s + h$ is eliminated using equation 7,

$$\Rightarrow \ E = (1 - w) + W_{\mathbf{0}} \tag{8}$$

P_t = pickup
S = time spent at the disposal waiting to load and offload (on site time)
h = time spent after loading to reach disposal site and back to the collection route
w = time spent per activities that are non-productive.
T_t = time required per trip for the hauled container system

Comparing Solutions for a Homogeneous Fleet

Comparing solutions for a homogeneous fleet can become a more complex situation. The decision as to the preferred solution can be based on the capital and operating costs of both solutions as well as other factors such as the amount of overtime. A feasible solution with more vehicles and less dead heading is preferable if its capital cost is significantly smaller. In most arc routing problems, the following holds:

1. The total travel distance in any solution is the sum of the service distance on the streets and the total dead head distance.
2. The total service distance on the street is assumed to be a constant and is generally much larger than the total deadhead distance in the solution, which is a variable.
3. A vehicle class is defined to be a set of vehicles with identical characteristics. In Arc routing problem with a non-homogeneous fleet, the fleet of vehicles used in a solution can come from more than one vehicle class; a homogeneous fleet Arc routing problem has one vehicle class.

Principal Cost Factors

a. Capital cost of the vehicles

Associated with each vehicle is an amortized daily capital cost that can be determined from the purchase cost of the vehicle, maintenance cost, insurance cost etc. along with the expected lifetime of the vehicle. This daily capital cost is vehicle class dependent because larger vehicles generally have a larger daily capital cost than small vehicles. Let CAP_K represents the daily capital cost of a vehicle from vehicle class *k*.

b. Salary cost of the crew operating the vehicle

Association with each district is crew that operates the vehicle. A fixed daily salary including benefits and overhead can be established for a crew. Let $\$\text{SAL}_{\mathbf{K}}$ represent the daily salary of a crew associated with vehicle class *k*.

c. Overtime

The salary cost paid to a crew is for a specified workday (generally 8 hours). Let $\text{TARGET}_{\mathbf{K}}$ represent the target length of the workday of a crew from a vehicle class *k*. If a district requires a crew longer than TARGET_K, overtime must be paid to the crew operating the vehicle. Let $\$\text{HOUR}_{\mathbf{K}}$ represent the hourly cost of overtime for a crew from vehicle class *k*.

d. Mileage cost of operating the vehicle

The operating cost associated with the vehicle covering the streets on its route can be vehicle class dependent. Let $\$MILE_K$ represents this cost per kilometre travelled by a vehicle from vehicle k. $\$MILE_K$ is assumed the same whether the vehicle is performing a service or deadhead.

e. Tipping cost of refuse collection vehicle at the disposal facility

The tipping cost of a vehicle at the disposal facility is a cost that is specific to sanitation vehicle problem. Because a vehicle has a fixed capacity (let M_K be the capacity of a vehicle from class *k*), when the vehicle capacity is reached, the vehicle must be emptied at a disposal facility. A vehicle can make several trips to disposal site. The tipping cost is typically measured as a fixed cost plus a variable cost measured in \$/unit of weight. Because the total weight collected over an entire solution is constant regardless of the fleet mix, the weight component of the tipping cost is a constant for any fleet mix. Let $\$TIP_K$ be the fixed cost district of the tipping cost for a vehicle from vehicle class *k*. In addition, every trip to the disposal facility adds both time and distance to the statistics for a district.

Statistics for a District

Assume that there are arcs assigned to district *p* and that a vehicle from vehicle class *k* is assigned to district *p*. Assume that a travel path has been formed through the streets assigned to district *p*. Then, the following statistics can be computed for district *p*.

a. Total Distance ($DIST_p$)

$DIST_p$ is the total distance that the vehicle travels in the travel path associated in covering all the arcs and edges in district *p*. This distance includes deadhead distance and the distance to/from the disposal facility and the distance to/from the depot.

b. Total time ($TIME_p$)

$TIME_p$ is the total time, including deadhead time that the vehicle that services district p requires to traverse the travel path that covers all of the arcs and edges in district *p*. This time includes the time to/from the disposal facility and the time to/from the depot.

c. Overtime (OT_p)

$OT_p = MAX[(TIME_p - RATGET_K), 0]$ is the overtime associated with district *p*. Because a vehicle from vehicle class *k* is assigned to district *p*, $TARGET_K$ is known.

d. Total trips (Z_p)

Z_p is the total number of trips to the disposal facility needed to service all arcs in district *p*.

e. Total cost of a district

The total cost of this district is the sum of the fixed costs (FC_p), variable labour costs (VLC_p) and variable routing costs (VRC_p) for the district where:

$$FC_p = \$CAP_p + \$SAL_K \quad (9)$$

$$VLC_P = \$HOUR_P \times MAX\ (TIME_P - TARGET_K), 0] \quad (10)$$

$$VRC_P = \$MILE_K \times DIST_P + \$TIP_K \times Z_P \quad (11)$$

f. Total cost of a solution

The total cost of a solution is the sum of the costs of each individual district.

i.e. total solution cost = $\sum_p (FC_p + VLC_p +$

VRC_p) (12)

Assume there is only one vehicle class in overtime and one trip per route, then for any district p. $\$CAP_k$, $\$SAL_k$. $\$MILE_k$ and $\$TIP_k$ do not depend upon vehicle class k, $\$HOUR_k = 0$ and $Z_p = 1$. Thus, the only variable in the cost of any district p is $DIST_p$ and the total variable cost of a solution is the total travel time over all of the routes.

Minimizing $\sum_p DIST_p$ is the objective of most Arc Routing Problems (ARP).

The total costs associated with a district include fixed costs (capital costs + crew salary costs), variable labour costs (overtime cost) and variable routing costs (mileage costs + disposal costs). The total cost comparison among vehicle classes was determined for each of the zones in Onitsha for instance, for Okpoko, the total cost (daily vehicle cost multiply by number of vehicles) for using a 5m^3 capacity vehicle was US\$315.40 and for a 7.5m^3 vehicle was \$251.90. For a 16m^3 vehicle, it was \$280.40. In this scheduling, the use of a 7.5m^3 vehicle was found to be optimal. In Central Area District one, the total cost of using a 5m^3 capacity vehicle was \$63.70 and for a 7.5m^3 capacity vehicle was \$53.30. A 5m^3 capacity vehicle is preferred to a 7.5m^3 vehicle.

Comparison of Solution from the Two Proposed Algorithms

The two algorithms "route first, cluster second" and "cluster first, route second" approach were compared (Table 3). The total deadheading distance covered by the fleet is somewhat less (4%) using the "route first" procedure. Much of the deadheading time occurs while attempting to service streets on the boundary of the zones. By districting the network before the routing is carried out, more streets on the boundary are created and hence more deadheading time results. "Route first" procedure should be superior. "Cluster first" procedure is likely to be more expensive to operate and should be utilised when non-overlapping routes are desired.

Table 3: Computational results using "Route first, Cluster second" and "Cluster first, Route second" procedures.

	Nodes	Link	Arc Edge	Route first, cluster second	Cluster first, route second
Central area district one	61	99	5.45	29.47	30.90
Central area district one	85	149	37.18	41.93	43.77
Okpoko	72	115	22.33	36.02	38.10
Housing Estate	96	165	32.41	47.02	49.67
GRA	60	92	26.53	45.87	48.38
Upper Iweka	85	119	56.16	94.30	98.60
Inland	149	240	50.61	116.74	120.54
Fegge	170	252	33.55	99.39	103.77

Comparison of Results with Existing Schedules

Comparison of the existing situations in the Central Area District one and two Abuja and Onitsha with the heuristic solution were done with respect to cost, efficiency and distance travelled. Application of "route first, cluster second" procedure resulted in reduction in refuse collection cost of $31.10 (21.09%), deadheading distance of 19.02km (21.09%) and increase in efficiency from 75% to 95% (Table 4).

Table 4: Comparison between existing and optimal system for Central Area Districts One and Two.

	Particulars	Existing system	Optimal system
a.	Total number of collection vehicles required per day		
	Central area District one	1	1
	Central area District one	1	1
b.	Total vehicle distance travelled for collection of refuse per day	km	km
	Central area District one	38.16	29.47
	Central area District one	52.32	41.93
	Total	90.48	71.40
c.	Cost of hiring of collection vehicles, fuel and labour costs Cost per km $1.63 per km per day	$147.45	$116.35
d.	Saving in hiring and labour charges per day		$31.10
e.	Total saving per day	75%	$31.10
f.	Efficiency		95%
g.	Percentages saving		
	In route length		21.09%
	In collection cost		21.09%

The efficiency of "route first, cluster second" procedure for Onitsha, is 87%, while the efficiency of existing system for Onitsha is 74%.

Table 5: Comparison between existing and optimal system for Onitsha

	Particulars	Existing system	Optimal system
a.	Total number of collection vehicle required per day		
	Okpoko	3	3
	Housing Estate	5	5

	GRA	4	4
	Upper Iweka	7	7
	Inland	9	8
	Fegge	8	8
	Total	36	33
b.	Total distance travelled for collection of km refuse per day	km	km
	Okpoko	37.37	36.03
	Housing Estate	48.08	47.02
	GRA	55.76	45.87
	Upper Iweka	99.12	94.30
	Inland	122.80	116.74
	Fegge	104.39	99.39
	Total	467.52	439.35
c.	Cost of hiring of collection vehicles, and labour costs per day	US $5093.30	US $4810.40
d.	Savings in hiring per day		US $283.00
e.	Total saving per day		$283.00
f.	Efficiency	74%	87%
g.	Percentages saving		
	In route length		6.03%
	In collection cost		5.569%

Conclusion and Recommendations

The study proposed two-phase constructive algorithm ("route first, cluster second" and "cluster first, route second") for solving routing and scheduling of solid waste collection trucks problem. The heuristic determined the optimum refuse collection routes for servicing a defined collection area. The algorithms worked with objective functions: the minimisation of the total cost (distance) of the operation. Minimising the total deadheading distance acts as a surrogate for minimising the number of vehicle used.

Edmond and Johnson [21] algorithm for Chinese postman problem was modified to incorporate capacity and length of workday constraints. The study which combined heuristic approaches with computer solution was implemented in Visual Basic language and applied to one of the largest districts of the city of Abuja, named Central Area Districts one and two and Onitsha, Nigeria. The proposed heuristics produced reasonably good results when compared to the 'chain-based insertion' and 'look ahead strategy approaches'.

"Route first, cluster second" approach gave routes which severely overlapped when the heuristic were compared with current practice. The proposed heuristic showed good performance in terms of the solution quality and its application increased the efficiency of solid waste collection and decreased the number of vehicles required from 36 to 34. Because of the shorter operation time and lesser runs of trucks, reduction in operational and labour costs were achieved.

From the study, the following recommendations are made:

1. "Cluster first, route second" approach should be utilised when non-overlapping routes are desired.
2. "Route first, cluster second" approach is recommended due to its superiority over "cluster first, route second" approach in terms of distance, cost and efficiency of solid waste collection.
3. The use of $5m^3$ open loader and $7.5m^3$ open loaders are recommended for Abuja and Onitsha respectively.

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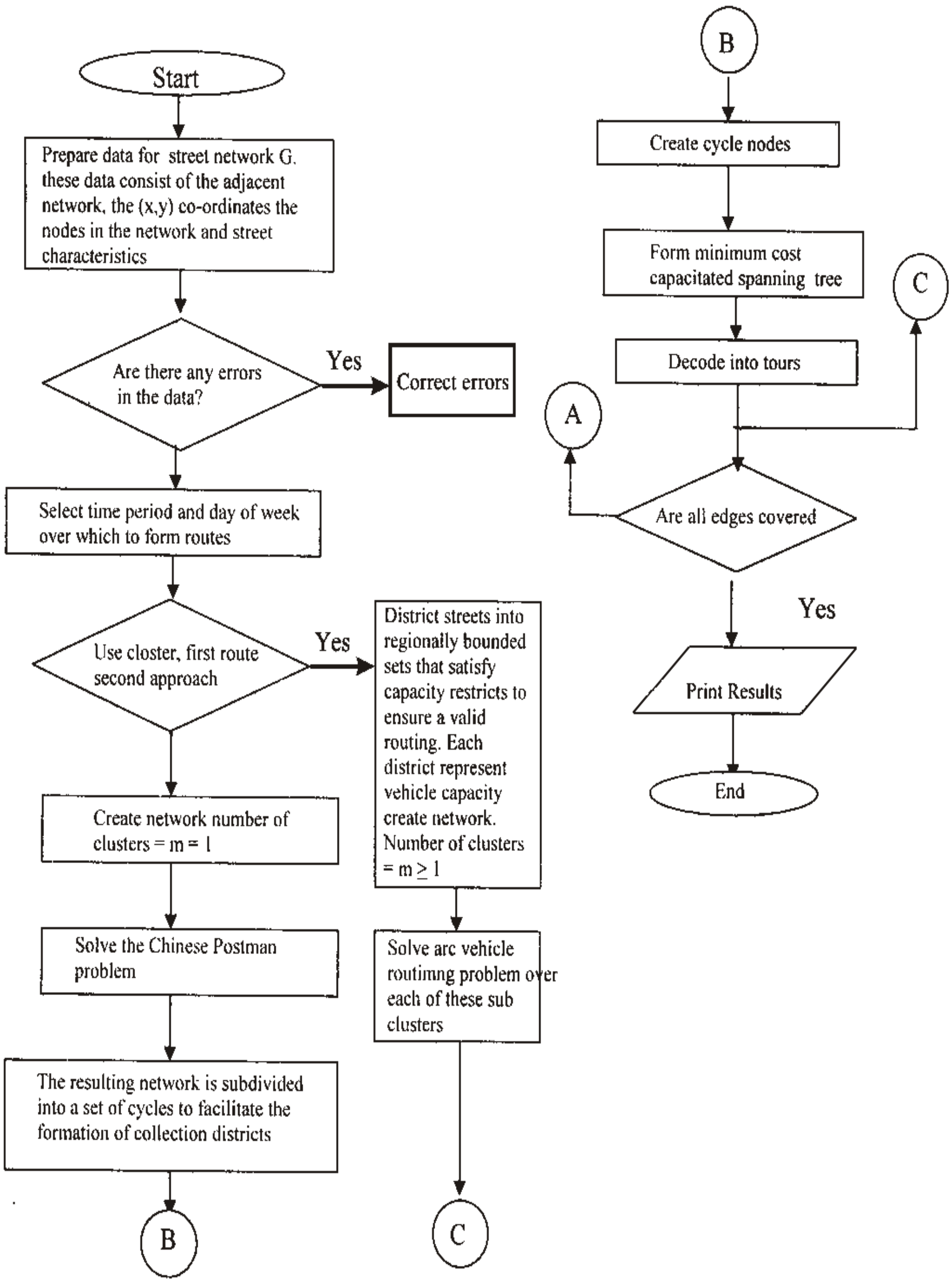

Fig. A1: Flow chart of the main program of refuse collection vehicle routing system