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GIS ORIENTED SERVICE OPTIMIZATION TOOL FOR FECAL SLUDGE COLLECTION

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ABSTRACT

In developing countries most of the urban dwellers don’t have access to sewer system. People are mostly using “on-site” systems such as septic tanks or pit latrines that need to be emptied periodically, as the densely built urban environment won’t allow new pits to be dug every time they fill up. In the conventional fecal sludge collection systems, authorities are collecting the sludge from house to house and dump on the plant. Fecal sludge collection system is different from traditional vehicle routing and even from solid waste collection system in terms of dynamic collection points, urgency of getting the service and diversity of demand. Due to those vibrant factors authorities are facing proper networking and management problems. This research describes algorithms that can accommodate constraints and prioritized customers who need immediate service. The GPS log data of the fecal sludge collection truck that maintained by Nonthaburi Municipality, Thailand has been considered as the base data during the development of this application. Spatial analysis has been done using Geographic Information Systems (GIS). Tabu Search has been implemented in order to optimize. Basically two algorithms were produced for assisting fecal sludge collection systems. First algorithm was able to produce multiple trip for each vehicle if required considering all the customers having equal priority, time window. The second one was able to perform optimization that can accommodate priority along with the first one. Input for the algorithms were very simple; distance matrix having distance between each customers and plant, customer order with latitude, longitude, order unit, time window, priority and vehicles with capacity. Algorithms were able to produce better result than the actual operation or even from shortest path algorithm in term of distance. After optimization, efficiency of the algorithms were tested with the actual travelling distance. Travelling distance were reduced to half compare to actual cost and it ensured maximum utilization of vehicle capacity by allocating maximum number of customers in each route.
1. INTRODUCTION

Mostly in urban areas of developing countries, onsite sanitation systems (OSS) are used for the collection of the black water and (or) grey water where the separation of the solid and liquid fraction occurs. Examples of OSS include septic tanks, pit latrines, dry toilets, and aqua privies, (Strande et al., 2014). The liquid contained in the septic tanks are drained into the sewer system and the solid parts are accumulated at the bottom. The solid parts that has been digested due to microbial activities and are settled at the bottom of the septic tanks is known as fecal sludge. In urban and rural areas of the developing countries OSS are widely used for collection and pretreatment of excreta. Usually, the untreated fecal sludge collected from these systems are disposed haphazardly into the urban and semi-urban environment which causes a serious threat to the environment and to the public health (Ingallinella et al., 2002). Surface and groundwater pollution, transmission of excreta related infections, unpleasant smell are some of the effects in the environment and public health. OSS is cost effective but on the other hand there are several problems. One of the major problem is emptying (Furlong et al., 2014). It cost handsome amount of money for emptying (ICEA, 2007), in addition to that it is hazardous. Different small scale emptying process have been developed but due to high cost couldn’t sustain for long run. Another problem arises after emptying, where to dump and practice is simply dumped into the immediate environment (Furlong et al., 2014). This makes high risk of contamination of pathogens to the environment and to the human. In larger cities, fecal sludge collection and haulage are faced with great challenges: emptying vehicles often have no access to pits; traffic congestion prevents efficient emptying and haulage; emptying services are poorly managed (Ingallinella et al., 2002).

Fecal Sludge Management (FSM) service chain consists of household level users, private collection and transport (C&T) businesses that empty the fecal sludge with trucks from onsite septic tanks and transport it to the treatment facility. This process is complicated considering the facts regarding the distance between the customer and the service provider. Further, service provider also needs to offload the sludge to the plant (Dodane et al., 2012). Serving as many customers as possible in the shortest possible time using available vehicles but optimizing travel cost is the major concern of C&T businesses. FSM collection and transportation system is different from traditional logistics and solid waste collection system. In FSM, collection points are dynamic e.g. everyday customers are different, demand is diverse and need the services immediately.

Geographic Information Systems (GIS) is one of the most advanced technology to capture, store, manipulate, analyze and display spatial data. GIS has been successfully used in a wide variety of applications, such as urban planning, transportation, natural resources management, health sciences, forestry, geology, natural disasters prevention and relief, and various aspects of environmental modelling and engineering (Brimicombe, 2003). GIS can be used in order to calculate route in real scenario. One way, turn restriction, tollway should be considered in this case as metaphor. GIS application in waste management is mostly focus on solid waste only. GIS has been applied on routing through selecting appropriate transfer station (Esmaili, 1972), suitable landfill sites (Despotakis et al., 2007) and location of treatment sites (Adamides et al., 2009; Zsigraiova et al., 2009) for solid waste management. GIS may provide significant economic and environmental savings through the reduction of travel time, distance, fuel consumption and pollutants emissions (Johansson, 2006; Kim et al., 2006; Sahoo et al., 2005; Tavares et al., 2008).
Vehicle Routing Problem (VRP) refers to a problem that can be defined as a set of spatially distributed customers with associated demands that need to be served with a number of vehicles having defined capacity. In that, the starting and the ending point of the routes are predefined and generally each vehicle starts from depot and ends at depot. The main objective of VRP is to minimize the travelling distance and number of vehicles used (Brandão, 2004). Similar to VRP, while managing fecal sludge collection there are a number of considerations to be made like; multiple customers, capacity of septic tank to be served, multiple vehicles, vehicle capacity limit, serving time window for customer etc. Also, the vehicles might have to go for multiple trips if necessary. Among the VRP algorithms Travelling Salesman Problem (TSP) is a classic combinatorial optimization problem. In this problem, a travelling salesman is expected to visit a set of cities. The objective of this problem is to find the shortest tour in which the travelling salesman visits each city once and returns to the starting city without considering vehicle capacity. To overcome shortcoming of TSP, Pham and Karaboga (2012) were applied Genetic Algorithms (GA), Tabu Search (TS), Simulated Annealing (SA), and Neural Networks (NN) to a TSP consisting of 50 cities to evaluate their performances. Among these, GA was able to generate best solution in terms of travelling distance (5.58) followed by TS (5.68), NN (6.61) and SA (6.80). On that particular test Tabu Search was close to best results but they hadn’t evaluate the calculation time. Bajeh and Abolarinwa (2011) compared the calculation time between Genetic Algorithm and Tabu Search in solving scheduling problem. They found that Tabu Search can produce better timetables than Genetic Algorithm even at greater speed.

Hence, the requirement of effective application/tool that can generate viable routes that optimizes the cost but without compromising with the service time is always in demand. This research is focused on development of Tabu search based algorithm to generate optimal route for fecal sludge collection. The overall objective is geospatial route optimization for fecal sludge collection in complex urban environment considering multi-path, time windows, cost (distance) and vehicle capacity.

2. STUDY AREA AND DATA

Nonthaburi is over 400 year’s old city, it was from the time when Ayutthaya was the capital. It is located in northwest of Bangkok on the Chao Phraya river. It has six district (Figure 1) and it’s a part of the greater Bangkok Metropolitan Area. The province has an area of 622.30 square kilometers and total population of the province is 1,334,083 as of 2010 (National Statistics Office, Thailand). Per annum almost 9,000 cubic meter of the sludge is treated in the fecal sludge treatment plant. The liquid fertilizers produced from sludge was tested by Kasetsart University, Thailand and it was found safe to be used in the agriculture especially for the edible crops (USAID, 2010).

The study was based on fecal sludge collection vehicle GPS log data obtained from the company operated in Nonthaburi Municipality. Specifically, data between September 2013 and February 2014 of Nonthaburi Municipality was processed for the purpose. It has been found that four vehicles each with the capacity of six (6) cubic meters has been used for the fecal sludge collection. Nonthaburi province was suitable due to the availability of the data and testing of algorithm in real scenario. Cost were calculated in terms of distance only. Traffic conditions have not be considered due to unavailability of data. Beside the GPS log data, road network plays an
important role for the vehicle routing. Actual road network data was purchased from NOSTRA (business unit of ESRI (Thailand) Company Limited). GSP log data were stored in PostgreSQL with PostGIS and pgRouting extension. PostGIS extension is required for spatial query whereas pgRouting is used for finding the distance that has been travelled by the vehicles during fecal sludge collection. Python scripting was used for calculating the actual cost, shortest path for the whole six months. Basic Tabu Search algorithm with time window was downloaded from github (https://github.com/pgRouting/pgrouting/tree/gsoc-vrppdtw/src/vrp_basic/src).

![Nonthaburi Province Map](image)

**Figure 1. Study Area**

### 3. METHODOLOGY

GPS log data was recorded in geographic coordinate system i.e. WGS 1984 datum. In order to calculate the distance in meter, it was necessary to project it into UTM system. QGIS was used to convert into shapefile where the projection system was changed to UTM and later stored in PostgreSQL with PostGIS extension. GPS log data was the combination of the way points and the customers’ location. Hence, it was necessary to extract the customers’ location. According to the expert interview, the distance between two septic tank (for different house) are more than 4 meters.
So, buffer of 2 meters was created around each GPS points. Buffer of nearby points (if within 4 meters) overlapped with each other were merged so that all the points within that buffer can be represented with the centroid for each overlapped buffers. Total time spent on the buffer area was calculated from all the points within it and if the time difference between two successive centroids was found to be ten minutes or more than that point was said to be the possible customer location. To remove the kinematic error of the GPS, time difference between the successive possible customers’ was identified. If the time difference of five minutes or less was found then first points among the two was removed from the possible customers’ list. Finally, all the points that lies within 50 meters from the plant location was excluded from the customer list. After identifying the customers, it was verified with the vehicle log book. Only in 10% cases, the number of customers’ were not matched. Finally, python script was used for generating the customers’ list from the GPS log data for each day for each vehicle.

Given a set of vehicles and the number of customers where the constraint being the vehicle capacity which cannot be exceeded during serving the customers. Initially from list of available vehicles, all were marked as “Untapped Vehicle” as they have never been used on that day. From the “Untapped Vehicles”, a vehicle was assigned to Tabu Search and marked as Single Used Vehicle. From the list of customers, distance matrix was generated in PostgreSQL using pgRouting which indicate distance between each customers and plant. Customers order with priority if any, distance matrix, time window and assigned vehicle was inserted in Tabu Search. Based on distance, customer’s priority and considering time window along with the capacity of the assigned vehicles, Tabu Search was generating optimized order of serving by that vehicle in single tour. After that those customer orders were deleted from the order list. It was checked whether there were some remaining customer or not. If there were, then it was checked whether there were any “Untapped Vehicle” or not. In case there was any Untapped Vehicle, it was assigned to the next tour and marked as Single Used Vehicle. Whenever there was not any, one Single Used Vehicle was assigned for the next tour and marked that as Used Vehicle. The same process was repeated until it serves all the customers or all vehicle became Used Vehicle. In this study it was considered that one vehicle can go for only two trip, one in the morning and another in the afternoon based on the actual timing. After getting the optimal order for each tour, Dijkstra shortest path in pgRouting was used to create routes considering turn restriction, one way etc.

The customer order table should have columns as shown in Table 1. The first column provide the customer ID where the first row is the details about the depot. 99999 was assigned as the plant ID. Xcoord (longitude), Ycoord (latitude) were the geographical coordinates of the customer location in UTM. The Demand column provides the demands that has been requested by the customers and the Ready_time and Due_time were used for the time windows. Ready_time was the starting time for the time window and Due_time was the end time. Service_time was used for the time required to provide the service to the customers and the Priority column described the priority and the equal priority customers. Service time was extracted from the actual data. It varies customer to customer based on septic tank size and time required for opening of septic tank, fixing the suction pipe etc. In Priority column, 1 denoted the customers that has been left on the previous day and need to be served on the following day whereas 0 denotes the customers that needs to be served on the same day. The starting time 0 was set to be 07:30 HRS in the morning and the 540 would be 16:30 HRS. While serving the last customer it was check whether the vehicle was able to reach the depot before closing time (16:30 HRS).
Table 1. Sample customer order table

<table>
<thead>
<tr>
<th>Cust_no</th>
<th>Xcoord</th>
<th>Ycoord</th>
<th>Demand</th>
<th>Ready_time</th>
<th>Due_time</th>
<th>Service_time</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>99999</td>
<td>665126.082</td>
<td>1533589.78</td>
<td>0</td>
<td>0</td>
<td>540</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>124852</td>
<td>662428.1813</td>
<td>1530759.392</td>
<td>1500</td>
<td>0</td>
<td>360</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>124686</td>
<td>662382.3807</td>
<td>1535740.701</td>
<td>1500</td>
<td>0</td>
<td>360</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>124581</td>
<td>664704.7437</td>
<td>1533434.066</td>
<td>1500</td>
<td>0</td>
<td>360</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>124421</td>
<td>660665.2113</td>
<td>1534906.019</td>
<td>1500</td>
<td>0</td>
<td>360</td>
<td>27</td>
<td>0</td>
</tr>
</tbody>
</table>

Distance matrix was consisting of three columns as provided in Table 2. First column was the origin, second column was the destination and third column was the cost in terms of travelling distance. Origin, destination can be plant or customer. Vehicle table was much simple one. It has only two columns as presented in Table 3. First column as vehicle ID and second column was the capacity in liter.

Table 2. Sample distance matrix

<table>
<thead>
<tr>
<th>To</th>
<th>From</th>
<th>Cost (Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>124375</td>
<td>124686</td>
<td>4.25764331425731</td>
</tr>
<tr>
<td>124375</td>
<td>124421</td>
<td>0.337719708091727</td>
</tr>
<tr>
<td>124375</td>
<td>99999</td>
<td>6.91473205848734</td>
</tr>
<tr>
<td>124375</td>
<td>124852</td>
<td>7.41003837112014</td>
</tr>
<tr>
<td>124375</td>
<td>124581</td>
<td>6.43249171235125</td>
</tr>
<tr>
<td>124421</td>
<td>124581</td>
<td>6.28082480515041</td>
</tr>
</tbody>
</table>

Table 3. Sample vehicle table

<table>
<thead>
<tr>
<th>V_ID</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>126175</td>
<td>6000</td>
</tr>
<tr>
<td>12618</td>
<td>6000</td>
</tr>
</tbody>
</table>

After calculating optimized route it was compared with the actual cost and shortest path cost by keeping the serving order as it did practically. Actual cost was the calculated from the GPS
log data which was the actual distance travelled by each vehicles. For simplicity, all points for each vehicle was filtered to see the route pattern. Due to the GPS error, points recorded were not in a straight line and not also aligned properly with the road network. All the GPS points for each day, for each vehicle was identified to calculated the actual distance that the vehicle has travelled in a particular day.

According to the experts, the average septic tank size for a residential household in Thailand is 1 to 2 cubic meter. Hence, with the capacity of 6 cubic meter a vehicle at a time can serve for at the max four customers (considering the capacity of the septic tank to be 1.5 cubic meters). After serving the customers, vehicle need to go back to the plant for emptying the sludge containing in the tank. And then it had to go again for the next trip for serving the other unserved customers. Shortest path problem is the problem of finding a path between two vertices (or nodes) in a graph so that the sum of the weights of its edges is minimized. The inbuilt Dijkstra algorithm from pgRouting was used for calculating the shortest path.

4. RESULT AND DISCUSSION

A total number of 1978 customers were served during the specified period and four vehicles were used for this purpose. The details of the customers served by each vehicle is shown in Table 4. The available implementation of vehicle routing assumes that the customers will be served within a single trip by each vehicle. However, simulating the available GPS log data with the current implementation, it has been observed that all the customers could not be served with a single trip. Hence, a need to modify the implementation such that it can incorporate multiple trip was generated and hence the existing code has been modified to facilitate the multiple trip.

<table>
<thead>
<tr>
<th>Vehicle No.</th>
<th>Total Customer</th>
<th>Average Customer / day</th>
</tr>
</thead>
<tbody>
<tr>
<td>12617</td>
<td>743</td>
<td>5</td>
</tr>
<tr>
<td>12618</td>
<td>406</td>
<td>6</td>
</tr>
<tr>
<td>12619</td>
<td>342</td>
<td>3</td>
</tr>
<tr>
<td>12829</td>
<td>487</td>
<td>5</td>
</tr>
<tr>
<td>Total Customers</td>
<td>1978</td>
<td></td>
</tr>
</tbody>
</table>

Taking an example of customer distribution as of December 16, 2013, total five customers’ needs to be served. The details of the attribute of the customers is shown in Figure 2 and the distribution of the customers is shown in Figure 3. From the figure, it was clear that five customers’ were being served by one vehicle. After serving first three customers the vehicle had to come back to the plant to make the tank empty. The Actual cost and the shortest path cost for the particular date was 66.08 Km and 31.41 Km respectively whereas the cost was found to be 27.24 Km only for the same day using one vehicle and using the multi-trip.
The optimal route was obtained using the distance matrix calculated from the actual road network and was used in the algorithm. Two routes were generated, which were:

- Plant – 124375 – 124421 – 124686 – 124581 – Plant
- Plant – 124852 – Plant

The modified program was tested and verified again with some random sets of available customer locations for some day and the result shows that even with the multiple trip sometimes it was difficult to serve all the customers in a single day. Here, the term multiple trip would mean that a vehicle can go for at the maximum two trip in a day, one in the morning and one in the afternoon. Those customers who could not be served in the ith day have to be automatically prioritize for (i+1) th day. So, the algorithm needed further modification and enhancement such that the priority customers would be served with higher priority the following day. This has been implemented such that while choosing customers, the nearest priority customer from the depot was chosen as initial node and then subsequent nodes are chosen on the basis of shortest distance from the preceding node ultimately having at least one priority customer in one trip.

Taking an example of customer distribution as of December 12, 2013, total 11 customers’ needs to be served. The details of the attribute of the customers is shown in Figure 4 and the spatial distribution of the customers is shown in Figure 5. From the figure, it is clear that 11 customers’...
was being served by three vehicles. The Actual cost and the shortest path cost for the particular date was 100.63 Km and 67.98 Km respectively whereas the cost was found to be 48.21 Km only for the same day using three vehicles. Here, in this example vehicle 12618, 12619 and 12617 have served seven, one and three customers respectively.

<table>
<thead>
<tr>
<th>start_time</th>
<th>end_time</th>
<th>id</th>
<th>eid</th>
<th>vct1_gps_</th>
<th>v_id</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00:19</td>
<td>09:24:49</td>
<td>188</td>
<td>1729</td>
<td>20130912</td>
<td>12618</td>
</tr>
<tr>
<td>09:52:20</td>
<td>10:15:21</td>
<td>176</td>
<td>1530</td>
<td>20130912</td>
<td>12619</td>
</tr>
<tr>
<td>10:22:51</td>
<td>10:45:52</td>
<td>184</td>
<td>1891</td>
<td>20130912</td>
<td>12619</td>
</tr>
<tr>
<td>10:59:22</td>
<td>11:14:22</td>
<td>191</td>
<td>1948</td>
<td>20130912</td>
<td>12618</td>
</tr>
<tr>
<td>11:45:53</td>
<td>12:05:54</td>
<td>201</td>
<td>2053</td>
<td>20130912</td>
<td>12618</td>
</tr>
<tr>
<td>12:37:55</td>
<td>13:00:55</td>
<td>211</td>
<td>2161</td>
<td>20130912</td>
<td>12618</td>
</tr>
<tr>
<td>13:36:36</td>
<td>13:50:37</td>
<td>222</td>
<td>2253</td>
<td>20130912</td>
<td>12618</td>
</tr>
<tr>
<td>14:43:33</td>
<td>15:23:33</td>
<td>148</td>
<td>1468</td>
<td>20130912</td>
<td>12618</td>
</tr>
<tr>
<td>09:07:33</td>
<td>09:24:32</td>
<td>240</td>
<td>2457</td>
<td>20130912</td>
<td>12617</td>
</tr>
<tr>
<td>09:45:42</td>
<td>10:02:32</td>
<td>247</td>
<td>2504</td>
<td>20130912</td>
<td>12617</td>
</tr>
<tr>
<td>10:21:22</td>
<td>10:52:52</td>
<td>253</td>
<td>2562</td>
<td>20130912</td>
<td>12617</td>
</tr>
</tbody>
</table>

Figure 4. Attribute of customers as of September 12, 2013

Figure 5. Customer distribution of customers as of September 12, 2013

Though, in real data there was no any priority customers, but to check whether the application provides the optimal route or not 2534, 1784, 2011, 2226 and 1388 customers were assumed as priority customers. All the customers have equal demands of 1,500 liters. Three vehicles with the capacity of 6,000 liters has been assumed.
The optimal route was obtained using the distance matrix calculated from the actual road network and was used in the algorithm. Three routes were generated:

- Plant – 1918 – 1784 – 1845 – 2226 – Plant for vehicle 12619
- Plant – 2114 – 1680 – 1388 – 2011 – Plant for vehicle 12618
- Plant – 2404 – 2479 – 2534 – Plant for vehicle 12617

Actual cost of travelling, the cost calculated using shortest path and the cost using route optimization was compared among each other to analyze the result (Figure 6). The result obtained by comparing the datasets for 176 days implies that the optimized cost was the lowest in majority of days (Figure 7(a)). The accumulated total cost in the long run also supports the same result. Moreover, the average distance travelled to serve each customer in case of route optimization was also seen lowest among them (Figure 7(b)).

![Figure 6. Comparison of cost for each day](image)

![Figure 7. (a) Frequency of the best algorithm (b) Cost per route](image)
Analyzing the number of customers, a vehicle has served per trip, it was identified that the vehicles were optimally used in case of tabu search based application as compared to the actual data (Figure 8). This was the important part of optimization to maximize resource utilization. In actual cases there were many cases where vehicles had returned to the plant with empty space. They could go to serve another customer before returned to the plant.

![Figure 8. Number of customers per trip](image)

5. CONCLUSION

Collection of fecal sludge in urban environment is complex due to multifarious road network. Study conducted by Bill & Melinda Gates Foundation (Chowdhry and Kone, 2012) revealed that 76% of the operating expenses for African businesses are variable costs, while in Asia, fixed costs make up 62% of the operating expenses. This fact is important as small improvement in the collection part can effect a significant saving in the overall cost. Therefore, interest in the analysis of sludge collection systems arises to optimize the operation of existing systems and to develop data and advanced techniques to design and evaluate new systems for urban areas. Implementation of GIS approach in Nonthaburi city has shown reasonable improvement in length of the routes. The results obtained from this study are encouraging to expand the scope to implementing other algorithms for optimization of the routes.

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