Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

ISSN: 0972-6268	Vol. 13	No. 1	pp. 177-184	2014

Original Research Paper

Optimization of MSW Collection Routing System to Reduce Fuel Consumption and Pollutant Emissions

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com
Received: 22-12-2013
Accepted: 22-1-2014

Key Words:
Municipal solid waste
MSW collection routing
3D GIS model
Systems engineering

ABSTRACT

With development of economy and modern socialization, the daily yield of household solid waste becomes a serious problem nowadays. To dispose of these solid wastes, people should collect the wastes and transport to municipal solid waste treatment plant to handle it. Usually, municipal solid waste (MSW) collection can account for more than 70% costs in the total MSW management system, and most of these costs are fuel costs. As we know, the emissions from vehicles contribute acid rain and global warming a lot in recent years. Therefore, it is necessary and urgent to find an optimal solution to reduce the emission and minimize the fuel consumption. By applying systems engineering methods, some models can be designed and modified to simulate the routes for collecting and transporting the MSW in the major urban area, in order to get an optimal solution which can achieve the goal of reducing fuel consumption from transportation and emission. In this study, an optimization for MSW collection routing using 3D GIS modeling is reviewed to get some new knowledge and idea. The main purpose of this study is to introduce a successful example and methodology which is used to optimize the MSW collection routing system, and design a model to find an optimal solution to minimize the fuel consumption and reduce the emissions in one area of St. John's, Newfoundland, by applying systems engineering methods.

INTRODUCTION

With development of economy, modern socialization and rapid growth of population, the daily yield of household solid waste becomes a serious problem since several decades ago. Daily human activities create huge amounts of solid waste, especially in the urban areas and developed places (Tavares et al. 2009). China municipal solid waste (MSW) generation increased significantly from 1981 to 2007 (Table 1). The average municipal solid waste generation per capita had increased from 1.0 kg/day to 1.42 kg/day between 1986 and 1998 (Wang & Nie 2001). There is a report from U.S. EPA showing that the U.S. residents, businesses and institutions produced more than 251 million tons of municipal solid waste equal to approximately 4.6 pounds of waste per person per day in 2006 (EPA 2008). Since 1980, Canada's municipal solid waste generated per capita has been steadily increasing. The State of Canada's Environment 1996 Report states that the average Canadian generated 1.7 kg of solid waste per day in 1992.

As it is known to all, household solid waste is one major source of municipal solid waste (MSW). According to the U.S. EPA's description, municipal solid waste is more commonly known as the household waste or domestic waste, and consists of the daily life items, such as bottles, product packaging, food scraps, grass clippings, papers, waste wood, waste metal, plastic containers, newspapers, furniture, clothing, appliances, paint, batteries and miscellaneous organic wastes form residential, commercial, and industrial non-process sources (EPA 2008). Comparing with the industrial wastes, municipal solid waste contains less toxic and harmful pollutants than industrial wastes. However, municipal solid waste can also cause many adverse impacts on environment. Therefore, there are abundant management practices to control this kind of pollution.

The solid waste management processes can be commonly divided into six parts, including generation, collection, storage, processing, transportation and disposal (Tchobanoglous et al. 1993). To dispose of those municipal solid wastes, people should collect the wastes and transport to municipal solid waste treatment plant or landfill to handle them. Usually, municipal solid waste collection can account for more than 70% costs in the total MSW management system, and most

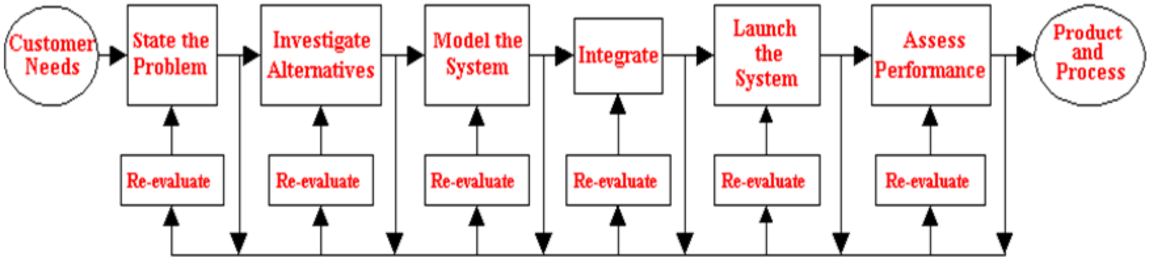

Fig. 1: The Systems Engineering Process (SIMILAR process) Source: Bahill & Gissing (1998).

of these costs are fuel costs, because solid waste collection processes are mainly carried out by using trucks with fuels (Tavares et al. 2009). In the meantime, the trucks also emit to environment different emissions from their exhausts (Apaydin & Gonullu 2007). These undesirable atmospheric pollutant emissions, including carbon dioxide, sulfur dioxide and nitrogen oxides, are the major concern for human beings because of their contribution to the global warming and acid rain. Due to these reasons, it is necessary to optimize a municipal solid waste collection routing system to reduce the fuel consumption and emissions from vehicle exhaust. The main purpose of this study is to introduce a successful example and methodology which is used to optimize the MSW collection routing system, and design a model to find an optimal solution to minimize the fuel consumption and reduce the emissions in one area of St. John's, Newfoundland, by applying systems engineering methods.

BACKGROUND OF SYSTEMS ENGINEERING AND OPTIMIZATION PROGRAM

System engineering: Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to make sure that the stakeholders and customers' needs can be satisfied with cost-efficiency, high quality, trustworthy, and schedule compliant manner throughout a system's entire life cycle. International Council on Systems Engineering (INCOSE) also gave a definition for system engineering as "An interdisciplinary approach and means to enable the realization of successful systems (Vodden 2008). Usually, the systems engineering process is comprised of seven components and tasks, including state the problem, investigate alternatives, model the system, integrate, launch the system, assess performance and reevaluate. Those functions can be summarized with an acronym SIMILAR process, which can be seen in the Fig. 1. By using these processes, people can find and get a solution to meet the requirement of customers and achieve the goals of cost-efficient and low energy consumption. In this study, the system engineering methods are applied to design a model to get an optimal routing system for collection of municipal solid waste in a specific area in St. John's, Newfoundland.

Optimization: Optimization problem can be described as mathematical programming and refers to a series of problems which seek to minimize or maximize a real function which can demonstrate the real cases and practical problems by systematically choosing the values of real or integer variables from within an allowed set. The objective of the optimization is to select the best possible decision for a given set of circumstances without having to enumerate all of the possibilities (Vodden 2008). When it comes to real problems, the main purpose of optimization is try to find optimal solution to get the maximum profit and minimum cost. If it is related to environmental problems, the main goal can summarize to find an optimal solution to achieve low energy consumption, and low amount of discharged pollutants by the cost-efficiently environmental approaches.

As it is mentioned above, there are many engineering systems related to environmental management, such as air pollution control system, sewerage system, waste management system, water quality management, cleaner production systems, etc. (Vodden 2008). In this study, the case study will only focus on finding an optimal routing for the municipal solid waste collection system. The meaning for this design is to find a shortest routing system for municipal solid waste collection in a specific area of St. John's to reduce the fuel consumption and emissions from exhaust of vehicle.

AN OVERVIEW OF MSW COLLECTION ROUTING SYSTEM AND EARLIER STUDIES

Solid waste management is a very typical optimization problem in the real world. As it is mentioned before, there are six processes, including generation, collection, storage, processing, transportation and disposal, and each process has a lot of opportunities to be optimized to achieve the environmental goals for stakeholders and costumers. Because the concerns on climate change and global warming are rising recent years, the emissions from vehicle exhaust mainly containing carbon dioxide and nitrogen oxide should be controlled to a high extent. It is known to all that municipal solid waste management systems release many pollutant emissions from the collection and transportation, and the amount of pollutant emissions is mainly related to the amount of fuel consumption. On the other hand, although the municipal solid waste management systems are a public service, the return on investment and profit margins are not the major priorities. However, because municipal solid waste collection process is a high-cost activity, and it is necessary to justify and evaluate the investment in terms of environmental, technological and economic feasibility (Tavares et al. 2009). Therefore, from different points of view, it is very important to optimize municipal solid waste management systems, particularly in management of routing networks for waste collection and transportation (Tavares et al. 2009).

There are many research papers introducing how to optimize the routing network for solid waste collection and transportation. Many authors have investigated routing optimization, for example, the authors used operational research methodologies to develop computer software for vehicle routing optimization (Cordeau et al. 2002). Particularly, in the municipal solid waste collection field, Bodin et al. (1989), Tung & Pinnoi (2000) and Angelleli & Speranza (2002) performed optimization for vehicle routing for solid waste collection by applying the operational research methodologies. A study presented a model to calculate time taken during waste collection processes, which operate on the basis of total distance travelled and also took the stoppage times into account (Everett & Riley 1997), and their work made a series of economic analysis (Tavares et al. 2009). Another study extended the aforementioned researches and also considered the energy and fuel consumption during haulage and waste compaction process (Sonesson 2000). Those researches indeed developed the methodologies for optimization of routing systems for municipal solid waste collection, and gave enough hints for the further research.

Many authors reviewed the papers related to the optimization of solid waste collection routing using GIS system model. They thought it is possible to take advantage of new technologies including geographic information system (GIS), since routing systems make extensive use of spatial data. According to some previous studies, GIS is able to provide effective handling, display and manipulation based on both geographic and spatial information (Armstrong & Khan 2004). They performed a model about the generation of route heuristics using GIS which focuses on the vehicle routing problem applied to the optimization of solid waste collection system. In order to solve the vehicle routing problem, a model based on the ArcGIS and its Network Analyst extension was developed by us, running on the Clarke and Wright savings heuristic and the genetic algorithm (Tavares et al. 2009). Based on those previous researches related to GIS system methodologies, the authors proposed a GIS-based model that took into account of relief of the terrain to calculate fuel consumption of vehicles during the municipal solid waste collection and transport processes. It means that the optimal routing is defined as the one which minimize the fuel consumption, and does not necessarily correspond to the shortest travelled distance. Due to this reason, it is possible to find a longer route to become optimal in terms of fuel consumption depending on the slopes of the roads. This model can be used as a decision support tool to improve the efficiency of waste management systems and thus reduce the cost from the processes of waste collection and transfer to disposal sites (Tavares et al. 2009). The main advantage of this study is using the 3D model to simulate the real situation of the waste collection and transportation, and can demonstrate the real fuel consumption when the terrain condition was taken into account.

The study by Tavares et al. (2009) chose Praia, the capital of Cape Verde, as a case study. The authors proposed a model to determine an optimal routing network which can minimize the fuel consumption and associated emissions for collecting the municipal solid waste and transporting those wastes to the thermal treatment plant. The methodology for that study can be described and divided into three phases: phase 1 is to create a 3D road network by making use of the ArcGIS 3D Analyst extension; phase 2 is to calculate segment-wise fuel consumption along the entire road network during the collection and transportation processes; and phase 3 is to perform the optimization of municipal solid waste collection for minimizing fuel consumption by applying the ArcGIS Network Analyst extension software. In the phase 1, authors developed 3D models of Santiago Island and of Praia city based on available 2D digital maps provided as CAD files by municipality of Praia in order to take the effect of terrain elevation into account (Tavares et al. 2009). The Fig. 2 shows the 3D digital map for the road network of the city of Praia.

By applying their methodology, they got their results of optimization for the MSW collection and transportation routing. The Fig. 3 (Tavares et al. 2008) shows the optimal route for the shortest 3D distance required to collect MSW from 20 collection points in the Praia city, and the Fig. 4 shows the optimal route for the lowest fuel consumption to collect MSW from the same collection points.

Comparing those two optimized routes, it is possible to observe that the direction and sequence for visiting all the collection sites is quite different. When applying the shortest 3D distance as the cost objective function, there is no difference for the solution of direction taken the vehicle because there is no difference on the total distance traveled by each direction. When optimized for the 3D route to mini-

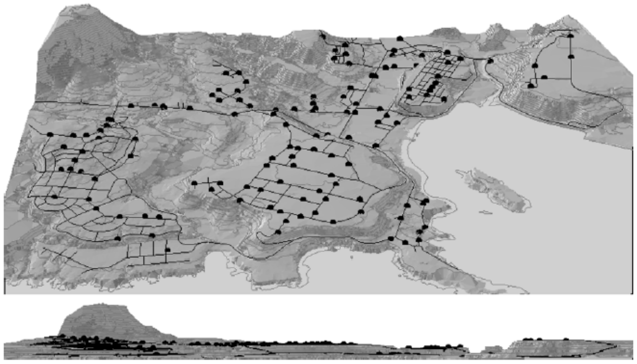

Fig. 2: A 3D digital map of Praia city showing its road network and MSW collection points. Source: Tavares et al. (2008).

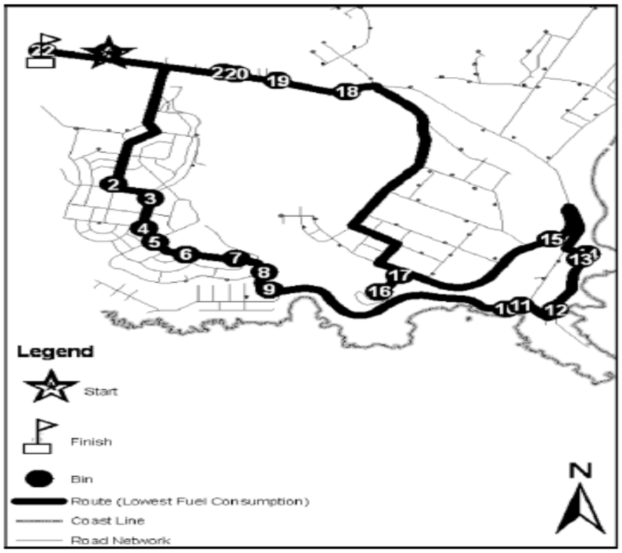

Fig. 3: The MSW collection route for Praia city optimized for the shortest 3D distance.

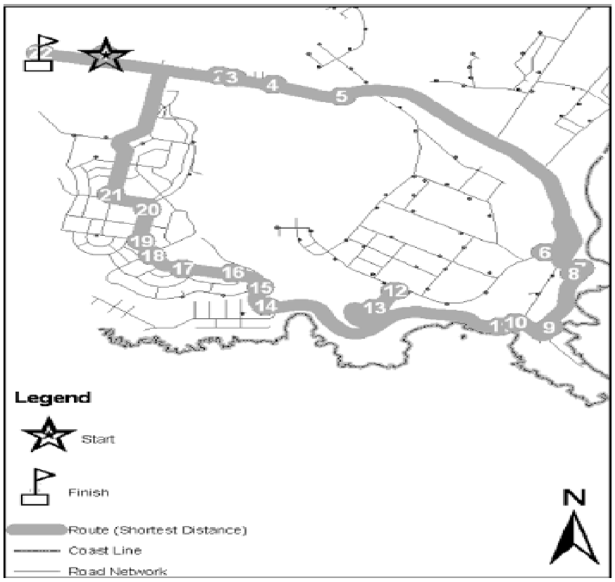

Fig. 4: The MSW collection route for Praia optimized in 3D for the lowest fuel consumption.

mize the fuel consumption, the priority is given to choose downhill routes to reduce vehicle elevation gain over the total trip, and moreover to reduce the fuel consumption (Tavares et al. 2009). From the Table 2 we can see that the optimization for the lowest consumption is longer than optimization for shortest distance. The main reason for this is that the authors considered the gradient and slope into a factor. As we know, the downhill route can save a lot of fuel and the uphill road cost more fuel, it can easily explain why the optimization for the lowest consumption choose a longer distance to have more distance on downhill road. The Table 2 also shows the other numerical results for the optimized waste collection routes for two different objectives. The differences of ascending 3D distance, descending 3D, fuel consumption and horizontal distance also can be clearly understood from the table. From these results we can also understand that the fuel consumption is not only corresponded with distance travelled by vehicle when the terrain condition is considered.

CASE STUDY OF THE OPTIMIZATION OF MSW COLLECTION ROUTE FOR A SPECIFIC AREA OF ST. JOHN'S, NL

Similar to other major cities, the residents in St. John's, the capital city of Newfoundland and Labrador, produce a great amount of municipal solid waste everyday. The routing for collecting all the garbage from residential houses is necessary to be optimized to reduce the fuel consumption and pollutant emissions.

Current MSW collection systems in St. John's: The City of St. John's supports different kinds of public services to the residents including garbage and recycling service. The Department of Public Works and Parks Waste Management Division provides a regular municipal solid waste collection to residents once every five working days. The Department of Public Works and Parks Waste Management Division divide the St. John's into five collection areas, and provides each area an individual collection schedule. The waste management company appoints trucks to five collection areas for collecting municipal solid waste on different business days once a week, the residents just need to download a schedule belonging to their specific area from website to know when they can place their garbage at the kerb or street line for collection.

Optimization of MSW collection routing for the selected area: In this case study, the google map and satellite google

Table 1: Collected and transported MSW in China (Data source: China Statistical Yearbook 2001-2007).

	1981	1990	2003	2004	2005	2006	2007
Urban population (×10^4)	14,400	32,530	52,376	54,283	56,157	57,706	59,379
Collected and transported MSW (10^4 tonnes/year)	2606	6767	14,857	15,509	15,577	14,841	15,214
Per capita quantity of MSW (kg/day/capita)	0.50	0.57	0.78	0.78	0.76	0.70	0.70

Table 2: The results for the optimized waste collection routes in Praia city. Tavares et al. (2008).

Calculated parameters	Optimization criterion	
	Distance 3D	Fuel consumption 3D
Distance 2D (m)	8246	8395
Distance 3D (m)	8254	8401
Ascending 3D distance (m)	4012	3652
Descending 3D distance (m)	3326	3689
Horizontal distance (m)	916	1060
Fuel consumption 2D (g)	2266	2307
Fuel consumption 3D (g)	2920	2686
Difference in distance travelled (3D-2D) (m)	8	6
Difference in fuel consumption (3D-2D) (g)	654	379

map were used to show the selected area for optimization, which is located in close loop with boundary of Empire Avenue, Winchester Street, Cairo Street, Rankin Street, Merrymeeting Road and Freshwater Road (Figs. 5 and 6) . The waste collection trucks should go across every residential house to collect garbage; therefore, the trucks should travel the streets and roads which have residential houses. In this study, we assume the fuel consumption and pollutant emission only correspond with the distance travelled by trucks for collection, so the terrain condition, speed of truck, truck loading and traffic are not considered in this study. Therefore, the objective of this optimization design is to find the shortest way to collect the waste. There are two popular models, which can be used to solve this kind of problem, including the Travelling Salesman Problem (TSP) and Shortest Path Problem.

Methodology: The Travelling Salesman Problem is typical mathematic problem need to be optimized. Given a number of cities and the costs of travelling from any city to any other city; trying to find the least-cost round-trip route that visits each city exactly once and then returns to the starting city is the objective of these series of problems. The Shortest Path Problem of finding a path between two vertices (or nodes) such that the sum of the weights of its constituent edges is minimized (Weisstein 2009). When applying the Travelling Salesman Problem as the model of this case study, the "least-cost" is equal to shortest distance travelled by trucks, the cities is equal to MSW collection sites or can be said as residential houses. However, it is easy to find some disadvantages from the real situation of waste collection process. Firstly, it is not necessary for the truck to visit all the collection sites for collecting all the MSW in one day, which means the workload for whole area can be divided into several parts for different days. Secondly, the trucks for collection can be more than one, so it is also different from TSP. Thirdly, unlike visiting the sites exactly once in the TSP, in order to collect the MSW from both sides of the street, the truck should return at the same route to collect all the garbage from each street. The last but not the least, the trucks collect garbage and transport to landfill, therefore it is different from the TSP which mentions the salesman need to go back to starting site. Comparing with TSP, the shortest path problem can solve this problem in a better way. Due to those reasons above, the shortest path problem model has more practical meanings and is more suitable for this case study.

In order to simplify the problem, the typical collection sites are used for optimization. These typical sites are the intersections and a site in the middle of each road which has the residential houses. From view of Google satellite map, there are no residential houses on some roads. Therefore, if the optimal routing avoid these roads, it is still acceptable. Through this way, each road with residential houses cannot be avoided when doing the optimization. After selecting the collection sites, those sites can be numbered for the next steps. The simplified map for route optimization is shown in the Fig. 7. By using Google Earth software, the distances between each two collection sites can be known. The Table 3 shows the exact distance between the two collection sites.

Calculation procedure: Because the waste management company is located in the west of St. John's, the trucks will be appointed from the company where it is in the west of the study area. Therefore, site 1 should be the starting site for

Fig. 5: Map for MSW collection sites for the case study. Source: Google Earth 2008.

Fig. 6: Satellite map for MSW collection sites for the case study. Source: Google Earth 2008.

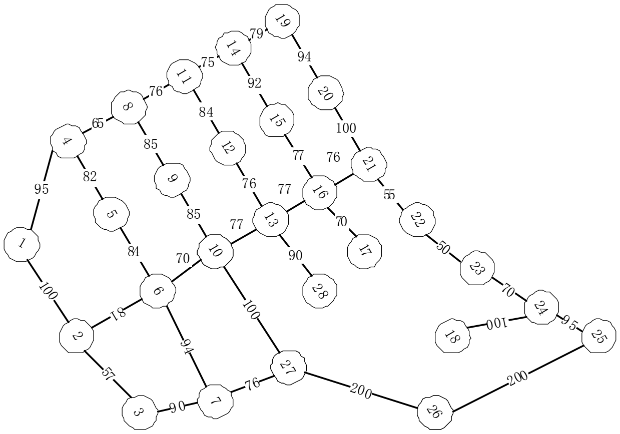

Fig. 7: The simplified map the case study area.

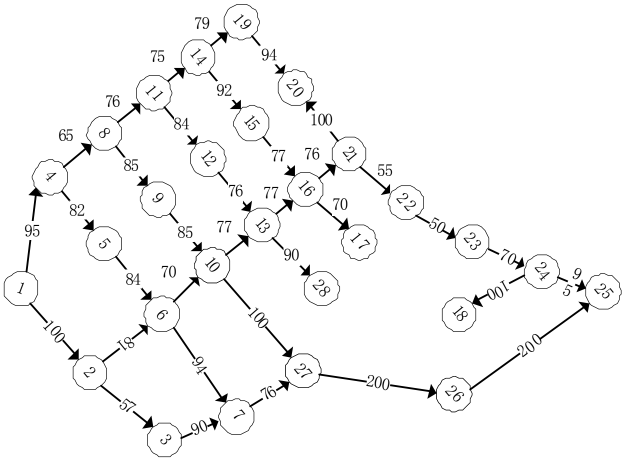

Fig. 8: The optimized routing for the case study area.

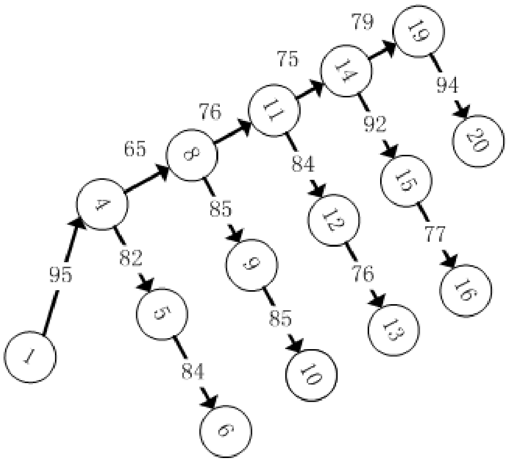

Fig. 9: The optimized routing for truck 1.

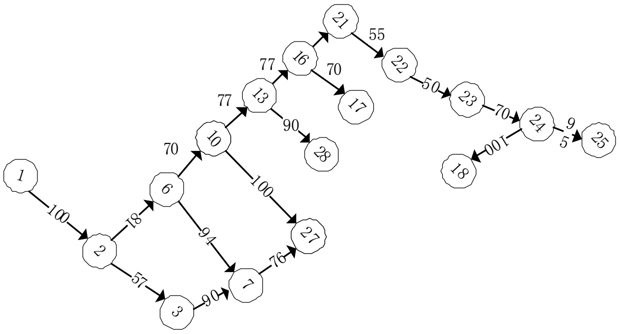

Fig. 10: The optimized routing for truck 2.

collecting the wastes in this case. Using mathematic algorithm to solve the shortest path problem, all solution procedures and the results are given in the calculation Table 4**,** where S is system, $\pi_{(i)}$ is the distance from site 1 to site i, and

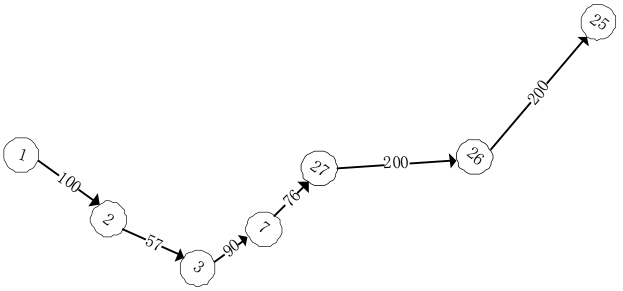

Fig. 11: The optimized routing for truck 3.

N is the number of sites in system (Vodden 2008). The shortest path will be selected to add into system for the following calculation. The "already in S" means the sites are already contained in system, and it just shows the direction for each two sites, and the sites with dark color mean the new sites need to be added into system. Through this way, the distance from starting site 1 to each site can be calculate to find the shortest path. After all the pathways are selected, the whole MSW collection routing formed, and the direction can help waste management company to reach each residential house in the shortest way.

Results and discussion: According to the results from the Table 3, the optimal routing is shown in Fig. 8. The arrow shows the direction of trucks travelled. The distance values from site 1 to each site are also calculated through algorithm. Through the results, the waste management company can find the shortest path to collect all the municipal solid waste from all the residential houses in order to reduce the fuel consumption and pollutant emissions.

From the Fig. 8, the amount of trucks and the routing for these trucks can be decided. The truck 1 can go from starting site 1 to visit sites 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 19 and 20 sequentially. When it reaches site 6, 10, 13, 16, 20, it need to turn back at the same way. The route for truck 1 is shown in Fig. 9. Similarly, the truck 2 can visit site 1, 2, 6, 7, 10, 27, 13, 28, 16, 17, 21, 20, 22, 23, 24, 18 and 25 as a round-trip sequentially, and the truck 3 can visit a round-trip from site 1 to 2, 3, 7, 27, 26 and 25. The optimized routing for the truck 2 and truck 3 are shown in Figs. 10 and 11 respectively. The reason for appointing three trucks to collect the MSW is to save time and avoid traffic jam in the morning, because the trucks usually collect the MSW in the early morning according to schedule of the waste management company and the Department of Public Works and Parks Waste Management Division. In fact, appointing one truck to collect all the MSW in that area is also feasible and reasonable. The sequence is starting with the route for truck 1 to route truck 2, and then to the route for site 3.

Table 3: Distance between each two collection sites. Source: Goolge Earth 2008.

Arc between two sites	Distance (m)	Arc between two sites	Distance (m)
1-2	100	2-3	57
1-4	95	2-6	81
4-5	82	5-6	84
6-7	94	3-7	90
4-8	65	8-9	85
9-10	85	6-10	70
10-27	100	8-11	76
11-12	84	12-13	76
13-10	77	16-17	70
11-14	75	14-15	92
15-16	77	13-16	77
16-17	70	14-19	79
19-20	94	20-21	100
16-21	76	21-22	55
22-23	50	23-24	70
24-18	100	24-25	95
25-26	200	26-27	200
27-7	76		

On the other hand, this optimized model is also quite useful for the other purposes. For instance, fire fighters and medicals can follow this routing system to get any residential house they want in the shortest pathway, and it can save a lot of time when the emergency happens. However, there are many limitations in this study.

Firstly, because some sites in the middle of the roads are chosen to make the trucks to go through all the roads when doing the optimization, there might be some problems occurred. For example, the trucks just go down half of the roads, and then turn back; the wastes in the rest half of the roads are collected by trucks from the opposite direction. Usually, it cannot occur in the real world due to traffic condition and rules. Therefore, it is a shortage of this model. Actually, because the case study area is quite small, the results show that this situation just occurred in site 21. The trucks will go from site 19 to site 20, and then turn back; the trucks will go down the rest of the road from site 21 to 20 and then turn back. In this case, we can find the 584m is only 3m longer than 581m, so we can just ignore this little difference and make the trucks go through roads from site 19 to 20, and then go to site 21.

Secondly, when it comes to fuel consumption problems and pollutant emissions, many constraints are not considered, such as terrain condition, speed of the truck, truck size, truck loading, wind speed, pollution control devices in truck, etc. In this study, we just assume the fuel consumption and pollutant emissions correspond with distance travelled. If more constraints can be taken into account and incorporate with current model, it can propose a better model to demonstrate its utility.

Table 4. Algorithm and procedure to solve the problem.

Number of site in S	Solved site (i)	Closest unsolved site (j)	Distance of path to unsolved site	Site added	Distance of shortest path
S = {1}, 1	1	4	95 ($\pi_4{}^* = \pi_1 + C_{14}$)	4	95
$\pi_4 = \pi^*_4 = 95$					
S = {1,4}, 2	1	2	100	2	100
	4	8	160 ($\pi^*_8 = \pi_4 + C_{48} = 95 + 65$)		
$\pi_2 = \pi^*_2 = 100$					
S = {1,2,4}, 3	2	3	157 ($\pi^*_3 = \pi_2 + C_{23} = 100 + 57$)	3	157
	4	8	160 ($\pi^*_8 = \pi_4 + C_{48} = 95 + 65$)		
$\pi_3 = \pi^*_3 = 157$					
S = {1...4}, 4	2	6	181 ($\pi^*_6 = \pi_2 + C_{26} = 100 + 81$)		
	3	7	247 ($\pi^*_7 = \pi_3 + C_{37} = 157 + 90$)		
	4	8	160 ($\pi^*_8 = \pi_4 + C_{48} = 95 + 65$)	8	160

The last but not the least, comparing with those big models, the area used for case study is quite small. When the area is big, the procedure of this model can become very complicated and even cannot be solved. If this model is incorporated with the Travelling Salesman Problem and other additional constraints, it can solve the complicated problem. The further study for this research is to continue to seek good constraints and incorporate with the Travelling Salesman Problem to get more reasonable results.

CONCLUSION

In this study, a real case about optimization of MSW collection routing in Cape Verde is reviewed, and the main optimization idea and methodology with consideration of terrain condition are summarized and in this paper. The authors gave many new ideas and advantages in the paper, and it can help people get comprehensive information to understand how to do an optimization problem for MSW collection routing.

In the other part, a case study in a specific area of St. John's, Newfoundland, is presented. Through the analysis and calculation, the optimal routing for MSW collection is obtained. By making use of this routing system, waste management company can appoint its trucks to follow the routing system to achieve the goal of reduction on fuel consumption and pollutant emissions. Through the optimization, appointing three trucks for collection in this area is also decided according to routing system and traffic rules.

Although, not considered in this paper, many constraints such as terrain condition, speed of truck, truck size, wind speed, efficiency of pollution control devices on truck, can also be incorporated into this model to develop it and make it more reasonable. In the future work, if the Travelling Salesman Problem can combine with this model, it definitely can solve more complicated problems.

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