CONSTRUCTIVE HEURISTICS FOR WEATHER-TYPE MODELS OF CAPACITATED ARC ROUTING PROBLEMS IN WASTE COLLECTION

MOHAMMAD FADZLI BIN RAMLI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mathematics)

Faculty of Science
Universiti Teknologi Malaysia

JULY 2012

CONSTRUCTIVE HEURISTICS FOR WEATHER-TYPE MODELS OF CAPACITATED ARC ROUTING PROBLEMS IN WASTE COLLECTION

MOHAMMAD FADZLI BIN RAMLI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mathematics)

Faculty of Science
Universiti Teknologi Malaysia

JULY 2012

A precious dedication goes to:

My loving parent, Hajah Fatimah binti Zain and Haji Ramli bin Ayob @ Majid,
My lovely wife, Masseridewi binti Mohd Ariffin,
My siblings Fadzlina, Mohd Ridzuan, Rosyada and Mohd Farizudin.
Indeed, I owe you your endless patience, love and care.

ACKNOWLEDGEMENTS

I wish to express my appreciation to my supervisor, Prof. Dr. Zuhaimy bin Haji Ismail for giving me a great opportunity in going through this PhD journey. His wise advice, ideas, guidance, motivation and criticism along this journey is truly appreciated. I also wish to acknowledge Universiti Malaysia Perlis (UNIMAP) and the Ministry of Higher Education (MOHE), Malaysia for their sponsorship of this study under Skim Latihan Akademik IPTA (SLAI). This thesis is a partial contribution to an IRPA project (09-02-06-144EAR) with funding by the Ministry of Science, Technology and Innovation (MOSTI), Malaysia and the Fundamental Research Grant Scheme (9003-00291), awarded by MOHE.

Special thanks to Jefareza Daviano and Aditya Wirmansyah for their assistance in computer programming. My sincere appreciation also goes to all my colleagues, labmates, lecturers and friends. Finally, I am grateful to all UTM staff from the Faculty of Science, School of Postgraduate Studies, Research Management Centre, Perpustakaan Sultanah Zanariah and Bendahari UTM for their help and support.

ABSTRACT

In this thesis, a new problem of arc routing for a fleet of vehicles in waste collection is studied. Objectively, this study investigates the effect of external factor, precisely the rainy weightage to expect the optimum routing cost and the number of trips for a fleet of vehicles in domestic waste collection. Although the rain is considered a crucial factor in Malaysia due to its ability to change the demand behaviour, consequently increased the quantity and trips, this factor has never been studied within the context of routing problems. Thus, two problems namely capacitated arc routing problem with stochastic demand (CARPSD) and capacitated arc routing problem with delivery time window (CARPDTW) were formulated to present the vehicle operations in waste collection. In general, conventional CARP in waste collection lies on undirected network graph, where a vehicle starts with empty capacity at a depot, performs pick-up of the customer demands on a set of required edges and ends at the depot without exceeding its capacity. In order to produce optimum or near-optimum solutions, constructive heuristics (CH) with several techniques such as modified path-scanning, switching rule, route compactness rule and shortest route rule are implemented. The performance of CH is tested on four real-life instances and a set of established benchmark dataset. In conclusion, the CH is able to produce optimum or near-optimum results in terms of routing cost and trips for a fleet of vehicles within a very fast computation time and is stable without any variation when compared to other methods, such as tabu search, reactive tabu search and column generation.

ABSTRAK

Dalam tesis ini, satu masalah baru laluan teraruh bagi sebilangan kenderaan pengumpulan sampah dikaji. Secara objektif, penyelidikan ini mengkaji kesan faktor luaran iaitu pemberat hujan bagi menjangka kos laluan optimum dan juga bilangan trip untuk sebilangan kenderaan dalam pengumpulan sampah domestik. Walaupun hujan dianggap faktor kritikal di Malaysia berdasarkan keupayaannya mengubah corak permintaan, seterusnya meningkatkan kuantiti dan trip, faktor ini tidak pernah dikaji dalam konteks masalah laluan. Sehubungan itu, dua permasalahan iaitu Masalah Laluan Teraruh Berkapasiti Dengan Permintaan Stokastik (MLTBPS) dan Masalah Laluan Teraruh Berkapasiti Dengan Tetingkap Masa Penghantaran (MLTBTMP) telah diformulasi untuk mewakili operasi kenderaan dalam pengumpulan sampah. Secara umum, MLTB konvensional bagi pengumpulan sampah merupakan graf rangkaian tidak teraruh, di mana sebuah kenderaan bermula dengan kapasiti kosong dari depot, melakukan pengumpulan permintaan pengguna bagi satu set penghubung dan berakhir di depot tanpa melebihi kapasiti. Bagi menghasilkan penyelesaian optimum atau hampir optimum, heuristik konstruktif (HK) dengan beberapa teknik seperti modifikasi imbasan-jalan, peraturan pertukaran, peraturan kepadatan laluan dan peraturan laluan terpendek telah dilaksanakan. Prestasi HK diuji terhadap empat kes sebenar dan satu set data piawai yang telah terbukti. Kesimpulannya, HK berupaya menghasilkan keputusan optimum atau hampir optimum bagi kos laluan dan trip untuk sebilangan kenderaan dengan masa komputasi yang sangat pantas dan stabil tanpa sebarang variasi bila dibandingkan dengan kaedah-kaedah lain seperti carian tabu, carian tabu reaktif dan penjanaan lajur.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

α	-	alpha
β	-	beta
γ	-	gamma
λ	-	lambda
ξ	-	xi

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Routing Problems at a Glance

Routing problems at a glance began with Dantzig and Ramser first introducing the truck dispatching problem in 1959 and proposed a linear programming based heuristic as its solution. It has been more than half a century since they described and formulated the vehicle routing problem and then solved the problem with twelve delivery points and one terminal. Theory, practice and computer technology have come a long way since then; so that today vehicle routing is considered one of the great success stories in operations research.

In the early 1970s, research in transportation routing problems evolved drastically after the increment of oil prices in the entire world had such a big impact on vehicle operational cost. Continuous hiking-up of oil prices thus urged transportation operators and managers to find a minimum-cost route plan in servicing their customers, obviously to keep the cost low. This caused practitioners and industry players in the transportation business from time to time actively seeking ways to reduce the operational cost on vehicles and improve their services at the same time.

Optimization in vehicle routing could be traced back to the first invention of the vehicle engine itself in the late nineteenth century, when the first pick-up truck was built by the German automotive pioneer, Gottlieb Daimler in 1896. Since men have been able to drive, they have always taken the shortest path, so that their vehicle consumes less energy and in a shorter time. Less energy consumption (e.g.: petrol, diesel or gasoline) means a less amount of money spent. Thus, finding the minimum and cost-effective routing is one of paramount importance in the transportation business and is considered to be very important. Primarily in the transportation business, whether pick-up, delivery or both operation styles, efficient routing with minimum cost is put above other considerations.

In order to produce an efficient and cost-effective routing, mathematics plays an important role especially in operational research which uses a lot of mathematical models in optimization, modelling and procedures to assist the managers in their decision making. Heuristics or metaheuristics are among the more popular methods that have been used extensively by mathematicians and researchers in searching for optimum solutions. Metaheuristics such as Tabu Search (TS), Genetic Algorithms (GA) and Simulated Annealing (SA) seems competing with each other since no method could be claimed as the best so far. One method usually fits for a specific problem and only suitable for a certain routing model. These metastrategies are proven and frequently can produce optimum solutions, but require long computation times. On the other hand, heuristics and other methods are faster, but rarely produce optimum solutions since the approach usually is to find a quick near-optimum solution. To this extent, advances in computer technology consequently make all this possible in providing a good quality solution.

This study emphasizes the real problem that occurs in routing problems which has never been studied and heuristics as its solution method. In this thesis, we investigated and had a look at the real problem in rainy day scenarios for vehicle operation in residential waste collection. Our approach is to study a new problem in waste collection, construct an accurate and reliable waste collection routing problem model and solve it by using various combinations of heuristics. Further explanations of the problem will be described in the next section.

1.2 Routing Problems in Waste Collection

In most countries, waste collection problems are frequently considered as environmental and pollution issues thus many approaches have been carried out onto development of policies and improving of waste management at administrative level (see Thorneloe *et al.* (2007); Simonetto and Borenstein (2007); and Metin *et al.* (2003)). Apart from the studies conducted, very few researches have been done to improve the vehicle operations in waste collection.

There are deep and diverse vehicle routing problems facing the solid waste industry today. Managing waste is a mammoth task as it needs to be collected, transported and finally disposed of. Beltrami and Bodin (1974) did one of the early classic vehicles routing problem in municipal waste collection for New York City and Washington D.C where different types of vehicles (trucks, barges, tugboats and mechanical brooms) were involved in the operations. In determining the optimal routing, they improved on saving heuristic proposed by Clarke and Wright in 1964.

Golden *et al.* (2002) categorized routing problem in waste collection into three segments:

(i) *Node routing problem*

This commercial problem involves the collection of refuse from large containers.

(ii) *Arc routing problem*

Residential collection involves collecting household refuse along a street network.

(iii) *Roll-on-roll-off problem*

This segment combines elements of node routing and bin packing where the operation consists of pick-up, transportation, unloading and drop-off of large containers.

Routing problems today play an important role in the transportation and logistic business. It contains many characteristics found in basic routing problems models (such as constraints on vehicle capacity), but it may also contain many complicating issues (such as time windows and stochastic elements) that affect the route configuration. Obviously, the dynamic variables complicating the solutions are a richer problem compared to the conventional static routing problems. These differences then inherit various dynamic vehicle routing problems and many methods have been proposed to seek the most optimum solutions.

In context, some researchers look at waste collection problem as capacitated arc routing problem (CARP) model, while other researchers modelled it as various dynamic vehicle routing problems (VRP). The main difference is this; in an arc routing model, the focus is on the route of the vehicles itself, not the nodes. This main difference relies on the fact that the vehicles are giving service when they are on the routes. In other words, in waste collection problem from arc routing point of view, the customers are located along the arcs, not at the nodes. Additionally, the capacity of the vehicles is capacitated when the vehicle performs door-to-door collection and has moved from one arc to another arc.

1.2.1 Vehicle Routing Problem

Vehicle routing problem (VRP) is a generalized problem based on the Travelling Salesman Problem (TSP) and is considered a NP-hard problem in the sense that it is unsolvable in polynomial time (Lenstra and Kan, 1981). VRP is also known as node-based routing problem, meaning the vehicle gives its services when it arrives at a certain node or point. Transporting goods from a warehouse to a set of retailers is one example in a delivery system. While picking-up agriculture products from a set of scattered locations to a wet market in the city is another different example. In addition, passenger buses and mail couriers do both kinds of delivery and picking-up activities.

The main target of VRP is to service a set of customers and return to the depot after having completed all tasks. All customers must be visited exactly once within some given constraints and the total customer demands of a route must not exceed the vehicle capacity. Given a set of geographically dispersed customers, each showing a non-negative demand $(q > 0)$ for a given commodity, the VRP consists of finding a set of tours of minimum cost for a fleet of vehicles.

By definition, VRP can be stated as a set of locations and defined on a directed graph $G = (V, A)$ where $V = (v_o, v_1,..., v_n)$ is a vertex set and $A = ((v_i, v_j): v_i, v_j \in V; i \neq j)$ is an arc set (Barbarosoglu and Ozgur, 1999). The vertex v_o represents a depot and v_i to v_n are customers to be serviced without exceeding the vehicle's capacity.

One research on VRP in waste collection was carried out by Tung and Pinnoi (2000), where the application of operations research techniques in waste collection activities in Hanoi, Vietnam was developed. They formulated the problem into a mixed-integer program and proposed a heuristic procedure consisting of construction and improvement phases. They used a modification of Solomon's heuristic for the construction routine while the improvement phase combined the power of Or-opt and 2-opt* together as one for improvements in both total cost and the number of vehicles utilized.

Aringhieri *et al.* (2004) then studied the problem in the collection and disposal of bulky recyclable waste such as paper, metals, green and garden waste, wood, glass, etc., and considered this problem as a delivery and pick-up problem. They also constructed a graph model based on asymmetric vehicle routing problem (AVRP) formulation and solved it using heuristics.

Kim *et al.* (2006) emphasized a real-life waste collection vehicle routing problem with time windows (VRPTW), with consideration of multiple disposal trips and drivers' lunch breaks. Their aims were to minimize the number of vehicles and total travelling time while taking into consideration two factors; route compactness and workload balancing. In order to improve the route compactness and workload balancing, they developed a capacitated clustering-based waste collection VRPTW algorithm and implemented the program at Waste Management Inc., in North America.

Alumur and Kara (2007) worked further on hazardous waste and developed a large-scale implementation of the model in the Central Anatolian region of Turkey, with the objectives being to minimize the total cost and the transportation risks. The aim of the proposed model was to determine the locations for open treatment and disposal centres, how to route different types of hazardous waste to whichever compatible treatment technologies and how to route waste residues to disposal centres.

Irhamah (2008) then considered waste collection as a VRP with stochastic demand (VRPSD), where demand was unknown when the route plan was designed.

This VRPSD objective was to find a priori route under preventive restocking that minimized the total expected cost. Various metaheuristics based on genetic algorithm and tabu search were developed to solve the model.

Conventional VRP handled deterministic parameters, where elements like demands, cost and distance are known and fixed. However, many VRP variants today tackle complicated and uncertain factors that make them more dynamic and difficult to solve. Some research developments in VRP with specific cases in waste collection will be explained further in Chapter 2.

1.2.2 Capacitated Arc Routing Problem

In general, CARP is another kind of routing problem specifically designed to formulate vehicle routing operations in solid waste, snow ploughs, street maintenance, mail couriers and other street services. This routing model was introduced by Golden and Wong (1981) and was considered as a special domain of VRP, but on the other hand, CARP has been comparatively neglected. Both classes of problems are NP-hard and extremely rich in theory and applications. CARP problems were raised by operations on street networks, such like urban waste collection, snow ploughing, sweeping, gritting and road mapping. Certainly, the major CARP application is municipal programs or contractors in waste collection, road maintenance or other street cleaning businesses. The single objective for CARP deals only with minimizing the total cost of the trips. Similarly with VRP, this special problem aims to construct a feasible route that minimizes the total cost within some pre-specified constraints.

Figure 1.1 and Figure 1.2 illustrate the main difference between the VRP and CARP. In these figures, node 1 represents the depot and node 2 until node 4 is the locations. For each edge, a demand and cost (q_{ij}, c_{ij}) is assigned and assumed symmetric in both directions.

Despite CARP and VRP lying on the same network graph, however they originated from different problem background. In VRP, the vehicle delivers its service when it arrives at a certain node or point (see Figure 1.1). Otherwise, for CARP, customers' demands are located on the edges, and the vehicle giving service while moving from one edge to another edge, thus increasing vehicle capacity (see Figure 1.2). In other words, CARP intends to seek a solution for all edges (arcs), but VRP on the other hand is to find the solution for all nodes.

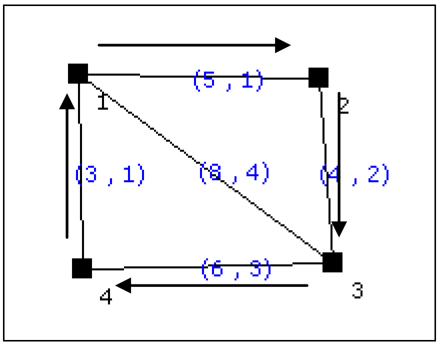

Figure 1.1: VRP.

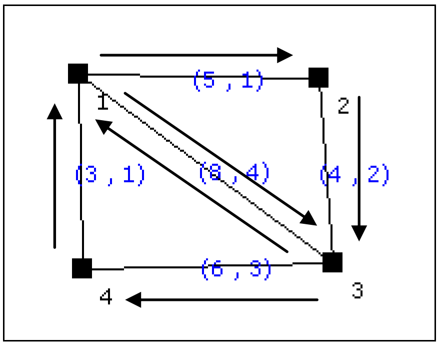

Figure 1.2: CARP.

Santos *et al.* (2009) defined CARP as an undirected graph, $G = (N, E)$ where $N = \{v_0, \ldots, v_n\}$ is a node set and $E = \{(v_i, v_j) : v_i, v_j \in N, i < j\}$ is an edge set. Vertex v_0 represents a depot node and each edge (v_i, v_j) of E has a non-negative commodity; cost, c_{ij} and demand (or weight), q_{ij}.

The above arguments support the idea that the waste collection problem can be modelled as CARP as mentioned in Gelders and Cattrysse (1991). Amponsah and Salhi (2004) designed a constructive heuristics based on CARP that takes into account the environmental aspect as well as the cost in order to solve the routing aspect of garbage collection. Their method is based on a look-ahead strategy that is enhanced by single and multi-objective route planning.

Lacomme *et al.* (2005) modelled periodic CARP (PCARP) where the trips must be planned over a multi-period horizon. They proposed a mimetic algorithm based on a sophisticated crossover that was able to simultaneously change tactical (planning) decisions, such as the treatment days of each arc, and operational (scheduling) decisions, such as the trips performed for each day.

A study by Chu *et al.* (2005) also considered the periodic capacitated arc routing problem (PCARP), a natural extension of the CARP to a weekly horizon. The objective was to assign a set of service days to each edge in a given network and to solve the resulting CARP for each period, in order to minimize the required fleet size and the total cost of the trips on the horizon. This problem has various applications in periodic operations on street networks, like waste collection and sweeping. They also developed a greedy heuristic and a scatter search that evaluated on two sets of PCARP instances derived from classical CARP benchmarks (see Chu *et al.*, 2006).

Belenguer *et al.* (2006) developed a linear formulation, valid inequalities, and a lower and upper bounding procedure for the mixed capacitated arc routing problem (M-CARP). They developed three constructive heuristics (path-scanning, augment-merge and Ulusoy's heuristics) and a mimetic algorithm. Bautista *et al.* (2008) then considered waste collection problem in Sant Boi de Llobregat, Barcelona as a CARP and developed ant colony metaheuristics to obtain the solutions.

The similarity between VRP and CARP cases is that their vehicles start travelling from a depot to a set of scattered destination points before returning back to the depot after completing all serviced nodes or arcs. In both cases, all destination points (known as clients or customers) are serviced exactly once.

However, very few researches considered external factors (such as weather and temperature) in modelling CARP or VRP. To our knowledge, Amponsah and Salhi (2004) is the one single study that considered the element of hot weather in modelling CARP and developed a constructive heuristic based on look-ahead strategy that takes into account the environmental aspect as well as the cost to solve the routing of garbage collection. Another work was done by Chaug-Ing Hsu *et al.* (2007) where the time-varying temperatures and human interaction during cargo opening have an effect on the VRP model. Their work however was done on perishable food transportation and in contrast was applied to VRP, which in practice its vehicle's operations are different than CARP. An extensive literature review on CARP in waste collection and its up-to-date developments will be addressed in Chapter 2.

1.3 The Importance of Minimum-Cost Routing

In recent years, many service suppliers and distributors have recognized the importance of designing efficient transportation strategies to improve the level of customer service and reduce transportation cost. In a typical distribution system, vehicles (e.g., trucks or school buses) provide delivery or customer pick-up, where a common objective is to find a set of routes for the vehicles that satisfies a set of constraints and helps to minimize the total fleet operating cost.

In general, the aim of a routing problem is to construct an efficient and optimal routing for a fleet of vehicles so that the delivering or picking-up process can be smoothly expedited. Objectively, the goal of constructing the optimal routing is for minimizing the transportation or routing cost for the vehicles. Toth and Vigo (2002a) mentioned this matter and stated that the use of computerized procedures for the distribution process planning produced substantial savings from 5% to 20% in the global transportation costs in North America and Europe. Furthermore, the transportation process involves all stages of the production and distribution systems and represents a relevant component (generally from 10% to 20%) of the final cost of the goods.

In Malaysia, the local authorities spend about RM1 billion a year to manage solid waste generated throughout the country. In fact, this budget is approximately 70 to 80 percent of their revenue in solid waste management. It was reported that in 2002, Malaysians generated 17,000 tons of solid waste daily, 19,000 tons in 2005 and was estimated to reach 30,000 tons by the year 2020 (2010, 17 June).

Fuel costs such like petrol, diesel or gas are highly related to transportation cost besides labour, maintenance and toll charges. Without a good plan and efficient routing for vehicles, delivering of goods or services will increase the total cost and would become a major burden to companies. As a consequence, even small improvements in routing efficiency can result in large cost reductions. The consequences of poor planning are very costly, and a decision maker must frequently fine-tune the system to ensure that the needs of customers are being met in a timely and cost-effective manner.

1.4 Background of the Problem

The conducted interviews of the real case study had shown significant vehicle routing problem when it came to rainy days. On rainy days, rain drops into the garbage and increases the waste weights. Similar conditions happen when the top-open container truck is used for picking-up the waste. In other words, the household refusal on rainy days does not increase in volume, but in weight due to moisture in the waste from the rain drops. This variable thus affects the vehicle's capacity in total weight.

More trips frequently occur on rainy days due to uncertainty in customer demands. During good and clear weather, the total quantity $\sum q_{ij} \leq W$, where W is the maximum capacity for a truck. The demand or quantity q_{ij} is probabilistic to a certain distribution, and W is a fixed constant. However, rain drops or water level is a new variable that affects the total weight of collected garbage if the truck operates on a rainy day. Section 1.6 describes this problem in further detail.

This problem inherits the time window issue when a longer service time (because of more trips being added due to heavier weights), consequently prolonging the total operational time. In time window problem, the arcs that require service must be serviced between certain time periods. In our case, the truck must operate within a specific time window constraint due to a limited time for disposal activity. Due to safety reasons, the dumpsite will be closed at 7 pm, so all emptying activities must be completed before that hour. Thus, $1 \leq t_p \leq 11$, where t_p is the total operational time allowed from 8 am to 7 pm.

A significant problem arises when the driver has to re-route from the initial plan in order to collect the highest demand of waste before proceeding to disposal activity. Frequently during rainy days, the truck cannot complete their zone collection in one trip because of overcapacity demands and limited time. Sometimes, long queues from the entry point to the landfill site during rush hour make this situation become worse. In addition, the truck sometimes also fails to transport the loads to the dumpsite in the same operational day. Consequently, this incomplete task needs to be continued on the next operation day (next morning) and the truck must start its collection from the uncovered routes from the previous day (if occurs). For these reasons, a refined model of routing problem is needed for suitability with the problem case in Malaysia. Chapter 3 explains the case study in detail.

1.5 Introduction to Mesh Network

In this research, we also introduce a mesh network graph as the CARP model that closely represents the layout of residential housing in Malaysia. In a mesh network, the houses are located side by side along the alley and each alley is connected by a main road as the backbone (see Figure 1.3). The structure of a mesh network is assembled by three components; corner, outer and inner (see Figure 1.4a ~ 1.4d).

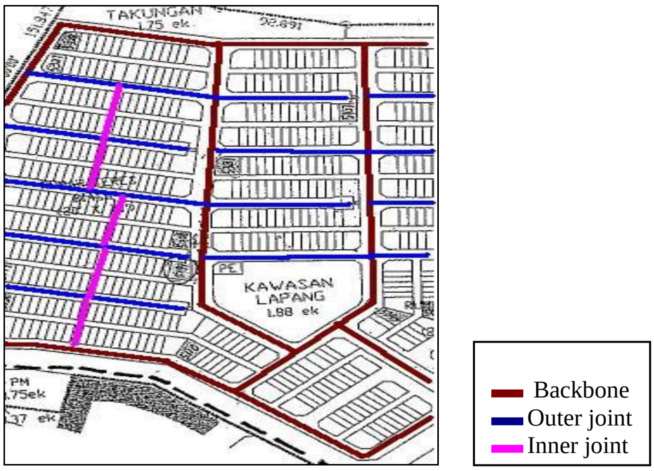

Figure 1.3: Typical residential housing layout in Malaysia.

Figure 1.4 displays the three components that assembled a mesh network. A complete but simple mesh network of 9 nodes and 12 arcs is depicted in Figure 1.4(d). Hence, we redefine our CARP according to Santos *et al.* (2009) as an undirected graph, $G = (V, E)$ where $V = \{v_o, v_1, v_2, \ldots, v_n\}$ is a vertex set and $E = \{(i, j) \in V, i \neq j\}$ is the customers edge set. Vertex v_o represents a depot and vertices $\{v_1, v_2, \ldots, v_n\}$ are link intersections. The corner vertex is denoted by V_C, where $V_C \in V$. The outer vertex is denoted by V_T, where $V_T \in V$ and the inner vertex is V_N, where $V_N \in V$, thus $(V_C, V_T, V_N \in V)$.

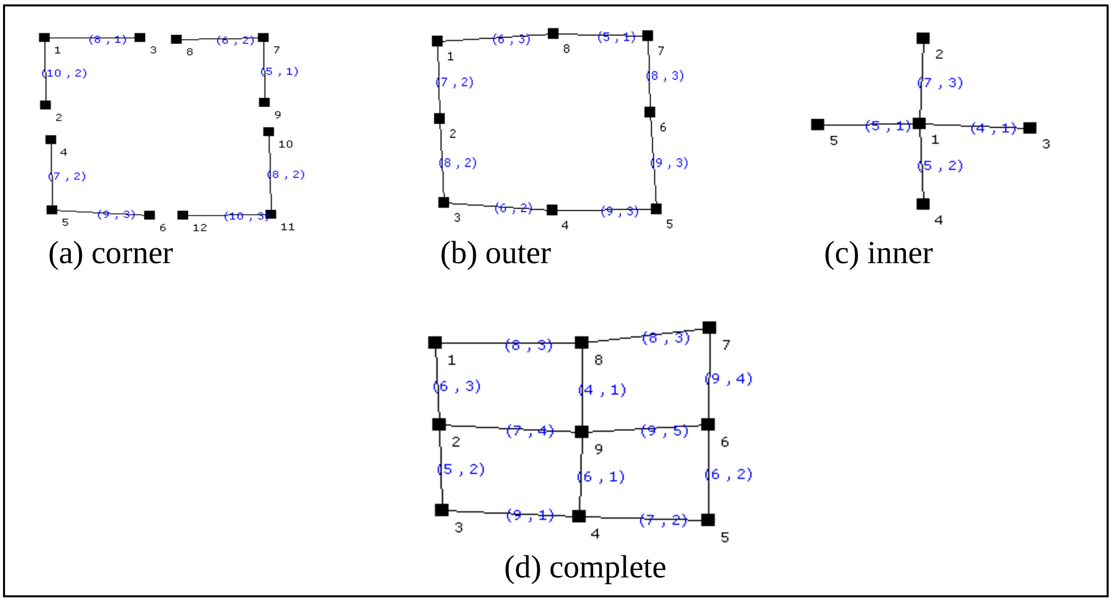

Figure 1.4: Components of a mesh network.

1.6 Problem Statement of Research

In stochastic environments, vehicle capacity may be exceeded during the service due to its randomness in customers' demands. An infeasible route occurs if the quantities of customers' demands exceed capacity and that alternative actions need to be taken at extra cost.

Firstly on rainy days, customer demand becomes more dynamic and changes the normal behaviour. The rain drop is the weightage that increases the customers' demands and burdens vehicle capacity in total. Customers have stochastic demands $\xi_i, i = 1,...,n$ which are non-negative and random discrete variables with a certain probability distribution $p_{ik} = prob(\xi_i = k), k = 0,1,...,K \le Q$. By adding a weightage parameter of rain drops *r*, hence $r\left[\sum_{(i,j)\in R} q_{ij} y_{ijk}\right] + \sum_{(i,j)\in R} q_{ij} y_{ijk} \le W$, where $r[0.1, 1.0]$.

This inequation suggests that the quantity of collected garbage q_{ij} might increase to double drastically and can easily exceed the truck capacity during rainy day operation. The load reaches capacity W faster during rainy days because of the waste weight is increases in the same relation. Consequently to this matter, chaotic routing happens when the truck needs to add more trips in order to collect all demands. This study tries to investigate the influence of rainy weather on vehicle's operation of waste collection. The different scenarios between normal and rainy weather operation needs to be further examined in order to recognize and segregate the model of the arc routing problem. In addition, this research also tries to refine the CARP model with stochastic demand (CARPSD) according to specific case in truck operation of waste collection by taking into account the element of rain drops.

Secondly on rainy days, the operation of the vehicle is longer than normal days because more trips are needed to accomplish all collections. This situation then prolongs the normal operational time frame. This time window constraint increases the complexity of determining optimal delivery routing. In this research, the model CARP with delivery time window (CARPDTW) is formulated and the penalty cost, P is implemented if any lateness occurs.

From the above explanation, CARPSD and CARPDTW were chosen to represent the residential waste collection operational problem. The proposed and redefined models are designed to seek the solutions of this question. How to minimize the routing cost and trips for a fleet of vehicles in residential waste collection when affected by weather?

Then, a constructive heuristics (CH) is developed to seek for optimum (or near-optimum) routing cost solution and trips for a fleet of vehicles in waste collection. Solution of routing problems begins with a careful description of the characteristics of the operational service under study. The type of problem then determines the solution techniques, (methods, procedures and algorithms) available to the decision maker. Algorithms for dynamic CARP are more intricate than deterministic, thus it calls for efficient algorithms that are able to work in accepted and reasonable results.

1.7 Objectives of the Study

The objectives of this study are to:

(i) Highlight a new and real-life problem in waste collection that has never been studied by considering the effect of rainy weather on vehicle operation in domestic waste collection.

(ii) Investigate and distinguish the different behaviour of waste collection operational vehicles between normal and rainy days based on Johor Bahru data case.

(iii) Modelling the CARP according to the dynamic case of waste collection routing problems.

(iv) Develop constructive heuristics algorithms in order to find the optimum (or near-optimum) cost solution and trips for a fleet of vehicles in waste collection.

(v) Conduct analysis and comparative studies in order to establish the results of routing plans, trips and routing cost.

1.8 Scope of the Study

The scope of this study is as follows:

(i) This study addressed the waste collection vehicle operations in Malaysian weather (normal and rainy) for constructing the vehicles route from the depot to the dumpsite.

(ii) The CARP modelling and CH were specially designed to solve waste collection routing problem in residential area.

(iii) The methods developed might be limited to the specific CARPSD and CARPDTW models and might not be useful for other cases or models.

(iv) In terms of generalization, other CARP models that fall under certain stochastic distribution may also be able to be solved.

(v) The segregation of weather-type data (service time, routing distance and net weight of customer demands) is based on distribution analysis and goodness of fit tests using EasyFit Professional Version 5.2.

(vi) This study considered identical vehicles with a fixed constant capacity in one run time.

(vii) It is assumed that every customer demand has the same probability distribution but can have different values.

(viii) The simulated data in performance testing of constructive heuristic is randomly generated following a certain probability distribution.

(ix) The system and algorithms are coded in C# programming language, which is not similar to other programming languages in terms of source code and its environment.

1.9 Limits of the Study

The limits of this study are stated as follows:

(i) This study is not considered the winter seasonal weather such as snow and storm; and specifically addressed the Malaysian weather on how the rain can affect the waste collection vehicles in terms of routing cost and trips.

(ii) This study is not considered the heterogeneous vehicle, but only one identical truck is simulated in one run time.

(iii) The developed computer program only caters for a certain probability distribution for customers' demands.

(iv) The developed computer program is not for commercial or shortest path purposes.

1.10 Significance of the Study

The significance of this study is:

(i) This research introduced a new problem that has never been studied in waste collection routing problems, by taking into account vehicle operation during rainy days and considers rain drops as the new weightage or variable that affected the CARP model.

(ii) This study redefined the conventional CARP model by distinguishing the vehicle operation between normal and rainy days.

(iii) Real problems in waste collection are solved by using the constructive heuristics algorithms and a computer program was developed as its method of solution.

The findings of this study have been presented and published in international conferences and journals.

1.11 Structure of the Thesis

The thesis is structured as follows. Chapter 2 presents a review of the literature on CARP and VRP models in waste collection and their solution methods. In Chapter 3, the analysis on distributions and goodness of fit tests is described in order to recognise the different behaviour of vehicle operations in waste collection. The CARP models development and constructive heuristic design framework will be elaborated in Chapter 4. Chapter 5 explains how the CH and other heuristics work by showing comprehensive numerical calculations. In Chapter 6, various instances of computational results, analysis and comparative studies are given. Finally, Chapter 7 concludes with the summary, findings, discussions and related future research.

REFERENCES

Alumur, S. and Kara, B. Y. (2007). A New Model for the Hazardous Waste Location-Routing Problem. *Computers & Operations Research*, 34, 1406–1423.

Alvarez-Valdes, R., Benavent, E., Campos, V., Corberan, A., Mota, E., Tamarit, J. and Valls, V. (1993). ARC A Computerized System for Urban Garbage Collection. *Topology*, 1, 89–105.

Amaya, A., Langevin, A. and Trépanier, M. (2007). The Capacitated Arc Routing Problem With Refill Points. *Operations Research Letters*, 35, 45-53.

Amberg, A., Domschke, W. and Voß, S. (2000). Multiple Center Capacitated Arc Routing Problems: A Tabu Search Algorithm Using Capacitated Trees. *European Journal of Operational Research*, 124, 360-376.

Amponsah, S. K. and Salhi, S. (2004). The Investigation of a Class of Capacitated Arc Routing Problems: The Collection of Garbage in Developing Countries. *Waste Management*, 24, 711–721.

Angelelli, E. and Speranza, M. G. (2002). The Periodic Vehicle Routing Problem with Intermediate Facilities. *European Journal of Operational Research*, 137, 233-247.

Aringhieri, R., Bruglieri, M., Malucelli, F. and Nonato, M. (2004). An Asymmetric Vehicle Routing Problem Arising in the Collection and Disposal of Special Waste. *Electronic Notes in Discrete Mathematics*, 17, 41–47.

Baldacci, R. and Maniezzo, V. (2006). Exact Methods Based on Node-Routing Formulations for Undirected Arc-Routing Problems. *Networks*, 47(1), 52-60.

Barbarosoglu, G. and Ozgur, D. (1999). A Tabu Search Algorithm for the Vehicle Routing Problem. *Computers & Operations Research*, 26, 255-270.

Bautista, J., Fernández, E. and Pereira, J. (2008). Solving an Urban Waste Collection Problem Using Ants Heuristics. *Computers & Operations Research*, 35, 3020-3033.

Bautista, J. and Pereira, J. (2006). Modeling the Problem of Locating Collection Areas for Urban Waste Management. An Application to the Metropolitan Area of Barcelona. *Omega*, 34, 617 – 629.

Belenguer, J-M., Benavent, E., Lacomme, P. and Prins, C. (2006). Lower and Upper Bounds for the Mixed Capacitated Arc Routing Problem. *Computers & Operations Research*, 33, 3363–3383.

Beltrami, E. and Bodin, L. D. (1974). Networks and Vehicle Routing for Municipal Waste Collection. *Networks*, 4, 65-94.

Beullens, P., Muyldermans, L., Cattrysse, D. and Oudheusden, D. V. (2003). A Guided Local Search Heuristic for the Capacitated Arc Routing Problem. *European Journal of Operational Research*, 147, 629-643.

Bertsimas, D. J. (1992). A Vehicle Routing Problem with Stochastic Demand. *Operations Research*, 40, 574-585.

Bertsimas, D. J. and Simchi-Levy, D. (1996). A New Generation of Vehicle Routing Research: Robust Algorithms, Adressing Uncertainty. *Operations Research*, 44(2), 286-304.

Brandão, J. and Eglese, R. (2008). A Deterministic Tabu Search Algorithm for the Capacitated Arc Routing Problem. *Computers & Operations Research*, 35, 1112-1126.

Canen, A. G. and Pizzolato, N. D. (1994). The Vehicle Routeing Problem. *Logistics Information Management*, 7, 11-13.

Chaug-Ing Hsu, Sheng-Feng Hung and Hui-Chieh Li (2007). Vehicle Routing Problem with Time-Windows for Perishable Food Delivery. *Journal of Food Engineering*, 80, 465-475.

Choi, E. and Tcha, D-W. (2007). A Column Generation Approach to the Heterogeneous Fleet Vehicle Routing Problem. *Computers & Operations Research*, 34, 2080-2095.

Christiansen, C. H., Lysgaard, J. and Wøhlk, S. (2009). A Branch-and-Price Algorithm for the Capacitated Arc Routing Problem with Stochastic Demands. *Operations Research Letters*, 37, 392-398.

Chu, F., Labadi, N. and Prins, C. (2005). Heuristics for the Periodic Capacitated Arc Routing Problem. *Journal of Intelligent Manufacturing*, 16, 243-251.

Chu, F., Labadi, N. and Prins, C. (2006). A Scatter Search for the Periodic Capacitated Arc Routing Problem. *European Journal of Operational Research*, 169, 586-605.

Cordeau, J-F. and Laporte, G. (2002). Tabu Search Heuristics for the Vehicle Routing Problem. *Canada Research Chair in Distribution Management and GERAD Report*. Montreal, Canada.

Crainic, T. G., Gendreau, M. and Potvin, J-Y. (2005). Parallel Tabu Search in Parallel Metaheuristics: A New Class of Algorithms. *Edited by Enrique Alba. John Wiley and Sons, Inc*. New Jersey

D'Agostino, R. B. and Stephens, M. A. (1986). *Goodness-of-fit Techniques*. New York: Marcel Dekker.

Deng, X., Zhu, Z., Yang, Y., Li, X., Tian, Y. and Xia, M. (2007). A Genetic Algorithm for the Capacitated Arc Routing Problem. *Proceedings of the IEEE International Conference on Automation and Logistics 2007*. 18 – 21 August 2007. Jinan, China, 1551-1556.

Doerner, K. F., Hartl, R. F., Maniezzo, V. and Riemann, M. (2004). Applying Ant Colony Optimization to the Capacitated Arc Routing Problem. In Dorigo, M. *et al.* (Eds.) *ANTS 2004* (pp. 420-421). Berlin-Heidelberg: Springer-Verlag.

Dror, M., Laporte, G. and Trudeau, P. (1989). Vehicle Routing Problem with Stochastic Demands: Properties and Solution Frameworks. *Transportation Sciences*, 23, 166-176.

Dror, M. and Langevin, A. (2000). Transformations and Exact Node Routing Solutions by Column Generation. *Arc Routing: Theory, Solutions and Applications*. (pp. 277–326). Dordrecht: Kluwer Academic Publishers.

Eglese, R. and Murdock, H. (1991). Routing Road Sweepers in a Rural Area. *Journal of the Operational Research Society*, 42, 281–288.

Eglese, R. (1994). Routeing Winter Gritting Vehicles. *Discrete Applied Mathematics*, 48, 231-244.

Eskandarzadeh, S., Tavakkoli-Moghaddam, R. and Azaron, A. (2009). An Extension of the Relaxation Algorithm for Solving a Special Case of Capacitated Arc Routing Problems. *J. Comb. Optim.*, 17, 214-234.

Evans, M., Hastings, N. and Peacock, B. (2000). *Statistical Distributions*. (3rd Ed.) New York: John Wiley.

Fadhilah, Y., Zalina, MD., Nguyen, V.T.V., Suhaila, S. and Zulkifli, Y. (2007). Fitting the Best-fit Distribution for the Hourly Rainfall Amount in the Wilayah Persekutuan. *Jurnal Teknologi C*, 46, 49-58.

Fleury, G., Lacomme, P., Prins, C. and Ramdane-Chérif, W. (2002). Robustness Evaluation of Solutions for the Capacitated Arc Routing Problem. In *Conference AI Simulation and Planning in High Autonomy Systems*, 290-295.

Fleury, G., Lacomme, P. and Prins, C. (2004). Evolutionary Algorithms for Stochastic Arc Routing Problem. In Raidl, G. R. *et al.* (Eds.) *EvoWorkshops* (pp. 501-512). Berlin-Heidelberg: Springer-Verlag.

Fleury, G., Lacomme, P., Prins, C. and Ramdane-Chérif, W. (2005). Improving Robustness of Solutions to Arc Routing Problems. *The Journal of the Operational Research Society*, 56(5), 526-538.

Frizzell, P. W. and Giffin, J. W. (1995). The Split Delivery Vehicle Scheduling Problem with Time Windows and Grid Network Distances. *Computers Ops. Res.*, 22(6), 655-667.

Gelders, L. and Cattrysse, D. (1991). Public Waste Collection: A Case Study. *Belgian Journal of Operations Research Statistics and Computer Science*, 31, 5–15.

Gendreau, M. (2002). An Introduction to Tabu Search. Working paper. Departement d'informatique et de recherché operationnalle. Universite de Montréal. Montreal. Canada.

Gendreau, M., Guertin, F., Potvin, J-Y. and Taillard, E. (1999). Parallel Tabu Search for Real-time Vehicle Routing and Dispatching. *Transportation Science*, 33, 381-390.

Gendreau, M., Hertz, A. and Laporte, G. (1994). A Tabu Search Heuristic for the Vehicle Routing Problem. *Management Science*, 40, 1276 – 1290.

Gendreau, M., Laporte, G. and Séguin, R. (1996). Stochastic Vehicle Routing. *European Journal of Operational Research*, 88, 3-12.

Gendreau, M., Potvin, J-Y. and Tagmouti, M. (2008). A Variable Neighborhood Descent Algorithm for Arc Routing Problems with Time-dependent Service Cost. *EU/MEeting 2008*. 23-24 October. Troyes, France, 1-7.

Ghiani, G., Improta, G. and Laporte, G. (2001). The Capacitated Arc Routing Problem with Intermediate Facilities. *Networks*, 37(3), 134-143.

Ghiani, G., Laganà, D., Laporte, G. and Mari, F. (2010). Ant Colony Optimization for the Arc Routing Problem with Intermediate Facilities under Capacity and Length Restrictions. *Journal of Heuristics*, 16, 211-233.

Gillett, B. and Miller, L. (1974). A Heuristic Algorithm for the Vehicle Dispatching Problem. *Operation Research*, 22, 340-349.

Glover, F., Taillard, E. and de Werra, D. (1993). A User's Guide to Tabu Search. *Annals of Operations Research*, 41, 3-28.

Golden, B. L., Assad, A. A. and Wasil, E. A. (2002). Routing Vehicles in the Real World: Applications in the Solid Waste, Beverage, Food, Dairy and Newspaper Industries. In Toth, P. and Vigo, D. (Eds.) *The Vehicle Routing Problem* (pp. 245-286). Philadelphia: Society for Industrial and Applied Mathematics.

Golden, B. L., DeArmon, J. S. and Baker, E. K. (1983). Computational Experiments With Algorithms for a Class of Routing Problems. *Computers & Operations Research*, 10(1), 47-59.

Golden, B., Magnanti, T. and Nguyen, H. (1977). Implementing Vehicle Routing Algorithms. *Networks*, 7, 113-148.

Golden, B. L. and Wong, R. T. (1981). Capacitated Arc Routing Problems. *Networks*, 11, 305-315.

Gouveia, L., Mourão, M. C. and Pinto, L. S. (2010). Lower Bounds for the Mixed Capacitated Arc Routing Problem. *Computers & Operations Research*, 37, 692-699.

Greistorfer, P. (2003). A Tabu Scatter Search Metaheuristic for the Arc Routing Problem. *Computers & Industrial Engineering*, 44, 249-266.

Gribkovskaia, I., Halskau sr., Ø., Laporte, G. and Vlcek, M. (2007). General Solutions to the Single Vehicle Routing Problem with Pickups and Deliveries. *European Journal of Operational Research*, 180, 568-584.

Gueguen, C. (1999). *Exact Solution Methods for Vehicle Routing Problems*. Doctor Philosophy, Central School of Paris, Paris.

Hashimoto, H., Ibaraki, T., Imahori, S. and Yagiura, M. (2006). The Vehicle Routing Problem with Flexible Time Windows and Traveling Times. *Discrete Applied Mathematics*, 154, 2271-2290.

Haugland, D., Ho, S. C. and Laporte, G. (2007). Designing Delivery Districts for the Vehicle Routing Problem With Stochastic Demands. *European Journal of Operational Research*, 180, 997-1010.

Hertz, A., Laporte, G. and Mittaz, M. (2000). A Tabu Search Heuristic for the Capacitated Arc Routing Problem. *Operations Research*, 48, 129-135.

Hirabayashi, R., Nishida, N. and Saruwatari, Y. (1992). Tour Construction Algorithm for the Capacitated Arc Routing Problem. *Asia-Pacific Journal of Operational Research*, 9, 155-175.

Ho, S. C. and Haugland, D. (2004). A Tabu Search Heuristic for the Vehicle Routing Problem with Time Windows and Split Deliveries. *Computers & Operations Research*, 31, 1947-1964.

Hollis, B. L., Forbes, M. A. and Douglas, B. E. (2006). Vehicle Routing and Crew Scheduling for Metropolitan Mail Distribution at Australia Post. *European Journal of Operational Research*, 173, 133-150.

Huisman, D., Freling, R. and Wagelmans, A. (2003). Multiple-depot Integrated Vehicle and Crew Scheduling. *Erasmus Centre for Optimisation in Public Transport & Econometric Institute*. Erasmus University Rotterdam, Economic Institute Report. EI2003-02.

Irhamah (2008). *Metaheuristics Based on Genetic Algorithm and Tabu Search for Vehicle Routing Problem with Stochastic Demands*. Doctor Philosophy, Universiti Teknologi Malaysia, Skudai.

Irnich, S., Funke, B. and Grünert, T. (2006). Sequential Search and Its Application to the Vehicle-Routing Problems. *Computers & Operations Research*, 33, 2405-2429.

Kim, B-Y., Kim, S. and Sahoo, S. (2006). Waste Collection Vehicle Routing Problem with Time Windows. *Computers & Operations Research*, 33, 3624-3642.

Kindervater, G. and Savelsbergh, M. (1997). Vehicle Routing: Handling Edge Exchanges. In Aarts, E. and Lenstra, J. (Ed.) *Local Search in Combinatorial Optimization* (pp. 337). Chichester: Wiley.

Koskosidis, Y. A., Powell, W. B. and Solomon, M. M. (1992). An Optimization-Based Heuristic for Vehicle Routing and Scheduling with Soft Time Window Constraints. *Transportation Science*, 26, 69-85.

Lacomme, P., Prins, C. and Ramdane-Chérif, W. (2001). A Genetic Algorithm for the Capacitated Arc Routing Problem and Its Extensions. In Boers, E. J. W. *et al.* (Eds.) *EvoWorkshop 2001* (pp. 473-483). Berlin-Heidelberg: Springer-Verlag.

Lacomme, P., Prins, C. and Ramdane-Chérif, W. (2004). Competitive Memetic Algorithms for Arc Routing Problems. *Annals of Operations Research*, 131, 159-185.

Lacomme, P., Prins, C. and Ramdane-Chérif, W. (2005). Evolutionary Algorithms for Periodic Arc Routing Problems. *European Journal of Operational Research*, 165, 535-553.

Lacomme, P., Prins, C. and Sevaux, M. (2006). A Genetic Algorithm for Bi-objective Capacitated Arc Routing Problem. *Computers & Operations Research,* 33, 3473-3493.

Lambert, V., Laporte, G. and Louveaux, F. (1993). Designing Collection Routes Through Bank Branches. *Computers & Operations Research*, 20, 783-791.

Laporte, G., Gendreau, M., Potvin, J-Y. and Semet, F. (2000). Classical and Modern Heuristics for the Vehicle Routing Problem. *International Transactions In Operational Research*, 7, 285-300.

Larsen, A. (2001). *The Dynamic Vehicle Routing Problem*. Doctor Philosophy, Technical University of Denmark, Lyngby.

Lau, H. C., Sim, M. and Teo, K. M. (2003). Vehicle Routing Problem with Time Windows and A Limited Number of Vehicles. *European Journal of Operational Research*, 148, 559-569.

Lenstra, J. K. and Kan, A. H. G. R. (1981). Complexity of Vehicle Routing and Scheduling Problems. *Networks*, 11, 221-227.

Letchford, A. N. and Oukil, A. (2009). Exploiting Sparsity in Pricing Routines for the Capacitated Arc Routing Problem. *Computers & Operations Research*, 36, 2320-2327.

Longo, H., Aragão, M. P.d., Uchoa, E. (2006). Solving Capacitated Arc Routing Problems Using A Transformation to the CVRP. *Computers & Operations Research*, 33, 1823-1837.

Magnanti, T. L. (1981). Combinatorial Optimization and Vehicle Fleet Planning: Perspective and Prospects. *Networks*, 11, 179-213.

Mei, Y., Tang, K. and Yao, X. (2009). A Global Repair Operator for Capacitated Arc Routing Problem. *IEEE Transactions on Systems, Man and Cybernetics – Part B: Cybernetics*, 39(3), 723-734.

Metin, E., Erozturk, A. and Neyim, C. (2003). Solid Waste Management and Practices and Review of Recovery and Recycling Operations in Turkey. *Waste Management*, 23, 425-432.

Mourao, M. C., Pinto, L. S. and Gouveia, L. (2007). Modeling Capacitated Arc-Routing Problems. *Optimization2007*. 23-24 July 2007. Portugal.

Mourão, M. C. and Amado, L. (2005). Heuristic Method for a Mixed Capacitated Arc Routing Problem: A Refuse Collection Application. *European Journal of Operational Research*, 160, 139-153.

Mullaseril, P. A. (1997). *Capacitated Rural Postman Problem with Time Windows and Split Delivery*. Doctor Philosophy, University of Arizona, Tucson.

Muyldermans, L., Cattrysse, D., Oudheusden, D. V. and Lotan, T. (2002). Districting for Salt Spreading Operations. *European Journal of Operational Research*, 139, 521-532.

Nagy, G. and Salhi, S. (2005). Heuristic Algorithms for Single and Multiple Depot Vehicle Routing Problems with Pickups and Deliveries. *European Journal of Operational Research*, 162, 126-141.

Nanry, W. P. and Barnes, J. W. (2000). Solving the Pickup and Delivery Problem With Time Windows Using Reactive Tabu Search. *Transportation Research Part B*, 34, 107-121.

Norhazwani Md. Yunos. (2009). *Reactive Tabu Search Approach for Solving Capacitated Arc Routing Problem*. Master of Science, Universiti Teknologi Malaysia, Skudai.

Nunes, A. C., Mourao, M. C. and Prins, C. The Sectoring Arc Routing Problem: Heuristic Methods. *Optimization2007*. 23-24 July 2007. Portugal.

Orloff, C. S. (1974). A Fundamental Problem in Vehicle Routing. *Networks*, 4, 35-64.

Pearn, W. L. (1989). Approximate Solutions for the Capacitated Arc Routing Problem. *Computers & Operations Research*, 16, 589-600.

Pearn, W. L. (1991). Augment-Insert Algorithms for the Capacitated Arc Routing Problem. *Computers & Operations Research*, 18, 189-198.

Pérez-Delgado, M-L. (2010). Solving an Arc-Routing Problem Using Artificial Ants with a Graph Transformation. In Demazeau, Y. *et al.* (Eds.) *Advances in PAAMS* (pp. 241-246). Berlin Heidelberg: Springer-Verlag.

Perrier, N., Langevin, A. and Campbell, J. F. (2007). A Survey of Models and Algorithms for Winter Road Maintenance. Part IV: Vehicle Routing and Fleet Sizing for Plowing and Snow Disposal. *Computers & Operations Research*, 34, 258-294.

Perttunen, J. (1994). On the Significance of the Initial Solution in Traveling Salesman Heuristics. *Journal of the Operational Research Society*, 45, 1131-1140.

Reghioui, M., Prins, C. and Labadi, N. (2007). GRASP with Path Relinking for the Capacitated Arc Routing Problem with Time Windows. In Giacobini, M. *et al.* (Eds.) *EvoWorkshops* (pp. 722-731). Berlin Heidelberg: Springer-Verlag.

Rochat, Y. and Taillard, E. (1995). Probabilistic Diversification and Intensification in Local Search for Vehicle Routing. *Journal of Heuristics*, 1, 147 – 167.

Sankaran, J. and Wood, L. (2007). The Relative Impact of Consignee Behaviour and Road Traffic Congestion on Distribution Costs. *Transportation Research Part B*, 41, 1033–1049.

Santos, L., Coutinho-Rodrigues, J. and Current, J. R. (2009). An Improved Heuristic for the Capacitated Arc Routing Problem. *Computers & Operations Research*, 36, 2632-2637.

Secomandi, N. (2003). Analysis of a Rollout Approach to Sequencing Problems with Stochastic Routing Applications. *Journal of Heuristics*, 9, 321-352.

Sexton, T. R. and Choi, Y. M. (1986). Pickup and Delivery of Partial Loads with Soft Time Windows. *American Journal of Mathematical and Management Sciences*, 6, 369-398.

Simonetto, E. d. O. and Borenstein, D. (2007). A Decision Support System for the Operational Planning of Solid Waste Collection. *Waste Management*, 27, 1286-1297.

Sniezek, J., Bodin, L., Levy, L. and Ball, M. (2002). Capacitated Arc Routing Problem with Vehicle-Site Dependencies: The Philadelphia Experience. In Toth, P. and Vigo, D. (Eds.) *The Vehicle Routing Problem* (pp. 287-308). Philadelphia: Society for Industrial and Applied Mathematics.

Solomon, M. M. and Desrosiers, J. (1988). Time Window Constrained Routing and Scheduling Problems. *Transportation Sciences*, 22, 1-13.

Stuart, A. and Ord, J. K. (1991). *Kendall's Advanced Theory of Statistics*. (2^{nd} ed.) Oxford University Press.

Sturges, H. A. (1926). The Choice of A Class Interval. *J. American Statistical Association*, 65–66.

Tagmouti, M., Gendreau, M. and Potvin, J-Y. (2007). Arc Routing Problems with Time-dependent Service Costs. *European Journal of Operational Research*, 181, 30-39.

Tagmouti, M., Gendreau, M. and Potvin, J-Y. (2008). A Variable Neighborhood Descent for Arc Routing Problems with Time-Dependent Service Costs. In *CIRRELT-2008-27*. July 2008. Quebec, Canada.

Tan, K. C., Cheong, C. Y. and Goh, C. K. (2007). Solving Multiobjective Vehicle Routing Problem With Stochastic Demand Via Evolutionary Computation. *European Journal of Operational Research*, 177, 813-839.

Texeira, J., Antunes, A. P. and Sousa, J. P. (2004). Recyclable Waste Collection Planning – A Case Study. *European Journal of Operational Research*, 158, 543-554.

Thorneloe, S. A., Weitz, K. and Jambeck, J. (2007). Application of the US Decision Support Tool for Materials and Waste Management. *Waste Management*, 27, 1206-1220.

Tillman, F. (1969). The Multiple Terminal Delivery Problem with Probabilistic Demands. *Transportation Science*, 3, 192-204.

Toth, P. and Vigo, D. (2002a). An Overview of Vehicle Routing Poblems. In Toth, P. and Vigo, D. (Eds.) *The Vehicle Routing Problem* (pp. 1-26). Philadelphia: SIAM.

Toth, P. and Vigo, D. (2002b). Models, Relaxation and Exact Approaches for the Capacitated Vehicle Routing Problem. *Discrete Applied Mathematics*, 123, 487-512.

Tung, D. V. and Pinnoi, A. (2000). Vehicle Routing-scheduling for Waste Collection in Hanoi. *European Journal of Operational Research***,** 125, 449-468.

Ulusoy, G. (1985). The Fleet Size and Mix Problem for Capacitated Arc Routing. *European Journal of Operational Research*, 22, 329-337.

Vansteenwegen, P., Souffriau, W. and Sörensen, K. (2010). Solving the Mobile Mapping Van Problem: A Hybrid Metaheuristic for Capacitated Arc Routing with Soft Time Windows. *Computers & Operations Research*, 37, 1870-1876.

Waters, C.D.J. (1989). Vehicle-scheduling Problems with Uncertainty and Omitted Customers. *Journal of the Operational Research Society*, 40, 1099-1108.

Wøhlk, S. (2005). *Contributions to Arc Routing*. Doctor Philosophy, University of Southern Denmark, Denmark.

Xu, J., and Kelly, J.P. (1996). A Network Flow-based Tabu Search Heuristic for the Vehicle Routing Problem. *Transportation Science*, 30, 379-393.

Yang, Wen-Huei., Mathur, K. and Ballou, R. H. (2000). Stochastic Vehicle Routing Problem with Restocking. *Transportation Science*, 34, 99-112.

Zhu, Z., Li, X., Yang, Y., Deng, X., Xia, M., Xie, Z. and Liu, J. (2007). A Hybrid Genetic Algorithm for the Multiple Depot Capacitated Arc Routing Problem. *Proceedings of the IEEE International Conference on Automation and Logistics 2007*. 18 – 21 August 2007. Jinan, China, 2253 - 2258.

Zuhaimy Ismail and Mohammad Fadzli Ramli. (2008). Capacitated Arc Routing Problem With Time Window in Solid Waste Operation. In Shaharuddin Salleh (Ed.) *Advances in Fundamentals and Social Sciences* (pp. 25-34). Skudai: Penerbit UTM.

Zuhaimy Ismail and Mohammad Fadzli Ramli. (2009a). Weather-type Data Distribution in Solid Waste Collection Problem. *Proceedings of the 2nd International Conference and Workshops on Basic and Applied Science & Regional Annual Fundamental Science Seminar 2009*. 2-4 June 2009. Johor Bahru.

Zuhaimy Ismail and Mohammad Fadzli Ramli. (2009b). Modelling Two Variances of Capacitated Arc Routing Problem Based on Rainy Weather Condition in Solid Waste Collection. *Proceedings of the 4th International Conference on Mathematics and Statistics 2009*. 13-15 August 2009. Universitas Malahayati, Bandar Lampung, Indonesia.

Zuhaimy Ismail and Mohammad Fadzli Ramli. (2011). Implementation Weather-type Models of Capacitated Arc Routing Problem via Heuristics. *American Journal of Applied Sciences*, 8, 382-392.

(2010, 17 June). Solid waste management’s RM1bln tab yearly. Retrieved 22 July, 2010, from www.wmam.org.