AN IMPROVED PARTIAL COMPARISON OPTIMIZATION FOR UTILIZING LANDFILL FACILITIES IN A WASTE COLLECTION VEHICLE ROUTING PROBLEM

FAZLINI BINTI HASHIM

DOCTOR OF PHILOSOPHY
UNIVERSITI UTARA MALAYSIA
2025

Awang Had Salleh Graduate School of Arts And Sciences

Universiti Utara Malaysia

PERAKUAN KERJA TESIS / DISERTASI
(Certification of thesis / dissertation)

Kami, yang bertandatangan, memperakukan bahawa
(We, the undersigned, certify that)

FAZLINI HASHIM

calon untuk Ijazah **PhD**
(candidate for the degree of)

telah mengemukakan tesis / disertasi yang bertajuk:
(has presented his/her thesis / dissertation of the following title):

"AN IMPROVED PARTIAL COMPARISON OPTIMIZATION FOR UTILIZING LANDFILL FACILITIES IN A WASTE COLLECTION VEHICLE ROUTING PROBLEM"

seperti yang tercatat di muka surat tajuk dan kulit tesis / disertasi.
(as it appears on the title page and front cover of the thesis / dissertation).

Bahawa tesis/disertasi tersebut boleh diterima dari segi bentuk serta kandungan dan meliputi bidang ilmu dengan memuaskan, sebagaimana yang ditunjukkan oleh calon dalam ujian lisan yang diadakan pada : ***23 Mei 2024.***
That the said thesis/dissertation is acceptable in form and content and displays a satisfactory knowledge of the field of study as demonstrated by the candidate through an oral examination held on: ***23 May 2024.***

Pengerusi Viva: *(Chairman for VIVA)*	**Assoc. Prof. Dr. Jafri Haji Zulkepli Hew**	Tandatangan *(Signature*
Pemeriksa Luar: *(External Examiner)*	**Assoc. Prof. Dr. Zaitul Marlizawati Zainuddin**	Tandatangan *(Signature)*
Pemeriksa Luar: *(External Examiner)*	**Assoc. Prof. Ts. Dr. S. Sarifah Radiah Shariff**	Tandatangan *(Signature)*
Nama Penyelia/Penyelia-penyelia: *(Name of Supervisor/Supervisors)*	**Dr. Aida Mauziah Benjamin**	Tandatangan *(Signature)*
Nama Penyelia/Penyelia-penyelia: *(Name of Supervisor/Supervisors)*	**Assoc. Prof. Dr. Syariza Abdul Rahman**	Tandatangan *(Signature)*

Tarikh:
(Date) ***23 May 2024***

Permission to Use

In presenting this thesis in fulfilment of the requirements for a postgraduate degree from Universiti Utara Malaysia, I agree that the Universiti Library may make it freely available for inspection. I further agree that permission for the copying of this thesis in any manner, in whole or in part, for scholarly purpose may be granted by my supervisor(s) or, in their absence, by the Dean of Awang Had Salleh Graduate School of Arts and Sciences. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to Universiti Utara Malaysia for any scholarly use which may be made of any material from my thesis.

Requests for permission to copy or to make other use of materials in this thesis, in whole or in part, should be addressed to:

Dean of Awang Had Salleh Graduate School of Arts and Sciences
UUM College of Arts and Sciences
Universiti Utara Malaysia
06010 UUM Sintok

Abstrak

Masalah Penghalaan Kenderaan Pengumpulan Sisa (WCVRP) melibatkan pengoptimuman laluan kenderaan bagi meminimumkan jarak perjalanan, pelepasan karbon dioksida (CO_2), dan bilangan kenderaan yang digunakan. Walau bagaimanapun, model sedia ada sering mengabaikan tapak pelupusan yang terletak jauh, secara tidak langsung menyebabkan ketidakseimbangan penggunaan tapak pelupusan dan memendekkan jangka hayat tersebut. Oleh itu, kajian ini memperkenalkan satu kekangan baharu bagi memastikan penggunaan yang berkesan bagi semua tapak pelupusan dalam WCVRP. Bagi mengintegrasikan kekangan ini, satu penambahbaikan ke atas algoritma Pengoptimuman Perbandingan Separa (PCO) telah dicadangkan, PCO ialah suatu metaheuristik berasaskan penyelesaian tunggal yang terbukti berkesan dalam menyelesaikan Masalah Penghalaan Kenderaan (VRP). PCO yang ditambah baik ini menggabungkan algoritma Tamak Terhampir (NG) bagi pembinaan penyelesaian awal, pelarasan parameter secara dinamik, serta dua operator kejiranan tambahan. Algoritma ini diuji ke atas set data yang merangkumi sehingga 2000 pelanggan dalam tiga senario kapasiti tapak pelupusan. Senario 1 mengandaikan kapasiti tapak pelupusan yang tidak terhad, Senario 2 mengagihkan sisa secara sama rata antara tapak pelupusan, manakala Senario 3 menetapkan kapasiti yang lebih tinggi kepada tapak pelupusan tertentu. Hasil kajian menunjukkan bahawa Senario 2 dan 3 meningkatkan jarak perjalanan dan jumlah kenderaan berbanding Senario 1. Namun begitu, kedua-dua senario tersebut mencapai agihan penggunaan tapak pelupusan yang lebih seimbang. Secara purata, NG menghasilkan 1157.37 kg pelepasan CO_2, yang dikurangkan sebanyak 3.49% dengan menggunakan PCO dan 10.07% dengan PCO yang ditambah baik. Begitu juga, jarak perjalanan NG sebanyak 1208.11 batu berkurang sebanyak 15.77% dengan PCO dan 29.57% dengan PCO yang ditambah baik. Selain itu, NG memerlukan 106 kenderaan, iaitu pengurangan sebanyak enam melalui PCO dan PCO yang ditambah baik. Penemuan ini menunjukkan bahawa PCO yang ditambah baik secara signifikan mengatasi kedua-dua NG dan PCO. Oleh itu, pendekatan yang dicadangkan menawarkan penyelesaian yang lebih cekap dan mampan dari segi alam sekitar untuk WCVRP. Kajian ini turut memberikan panduan yang bernilai kepada pihak berkuasa pengurusan sisa dalam memilih strategi operasi yang mengoptimumkan penggunaan sumber dan impak alam sekitar.

Kata Kunci: Algoritma Tamak Terhampir (NG), Operator Kejiranan, Algoritma Pengoptimuman Perbandingan Separa (PCO), Masalah Penghalaan Kenderaan (VRP), Masalah Pengumpulan Sisa

Abstract

The Waste Collection Vehicle Routing Problem (WCVRP) involves optimizing vehicle routes to minimize travel distance, carbon dioxide (CO_2) emissions, and the number of vehicles used. However, existing models often neglect distant landfill sites, leading to imbalanced landfill utilization and shortened facility lifespans. Thus, this study introduces a new constraint to ensure the effective use of all landfill sites in WCVRP. To integrate this constraint, an enhanced Partial Comparison Optimization (PCO) algorithm is proposed. PCO is a single-solution-based metaheuristic previously shown to be effective in solving Vehicle Routing Problems (VRP). The improved PCO incorporates a Nearest Greedy (NG) algorithm for initial solution construction, dynamic parameter adjustment, and two additional neighborhood operators. The algorithm is tested on datasets containing up to 2000 customers across three landfill capacity scenarios. Scenario 1 assumes unlimited landfill capacity, Scenario 2 distributes waste equally among landfills, while Scenario 3 assigns higher capacities to certain landfills. The results indicate that Scenarios 2 and 3 increase travel distances and vehicle counts compared to Scenario 1. However, both scenarios achieve a more balanced distribution of landfill usage. On average, NG produced 1157.37 kg of CO_2 emissions, reduced by 3.49% using PCO and 10.07% with improved PCO. Similarly, NG's travel distance of 1208.11 miles decreased by 15.77% with PCO and 29.57% with improved PCO. Additionally, NG required 106 vehicles, which is reduced by six through PCO and improved PCO. These findings demonstrate that the improved PCO significantly outperforms both the NG and the existing PCO. Consequently, the proposed approach offers a more efficient and environmentally sustainable solution to WCVRP. This study provides valuable insights for waste management authorities in selecting operational strategies that optimize both resource utilization and environmental impact.

Keywords: Nearest Greedy (NG) Algorithm, Neighbourhood Operators, Partial Comparison Optimization (PCO) Algorithm, Vehicle Routing Problem (VRP), Waste Collection Problem

Acknowledgement

I would like to express my deepest appreciation and gratitude to everyone who contributed to the completion of this thesis. It has been an honor to study under the supervision of Associate Professor Dr. Aida Mauziah Benjamin. A simple 'thank you' does not suffice to convey my sincere gratitude for her unwavering guidance, which has been instrumental in helping me achieve my goal. Without her invaluable support, this thesis would not have been possible.

I extend my heartfelt thanks to my co-supervisor, Associate Professor Dr. Syariza Abdul Rahman, for her constructive comments, which have significantly enhanced the quality of my work. I also sincerely appreciate Associate Professor Dr. Zuryati Mohamed Yusoff, whose prayers and encouragement have been a great source of inspiration throughout my academic journey.

Additionally, I am deeply grateful to my late parents, my best friends, and my family for their unwavering love and support. My goal would not have been attainable without them. I dedicate this work to my late parents, Hashim bin Abdullah and Halimah binti Dollah. Their love has always been with me, guiding me to this moment.

My time at Universiti Utara Malaysia (UUM) was truly enjoyable. The university not only boasts a beautiful natural environment but also has helpful staff, particularly at the Awang Had Salleh Graduate School (AHSGS). I would also like to express my deepest gratitude to the Ministry of Higher Education (KPT) for awarding me the MyBrain15 scholarship, which has been instrumental in supporting my academic journey. This generous support has not only eased my financial burden but also motivated me to strive for greater achievements.

In conclusion, I sincerely thank all my friends for their encouragement throughout my studies

Table of Contents

List of Tables

List of Figures

List of Appendices

CHAPTER ONE
INTRODUCTION

1.1 Overview

The Waste Collection Problem (WCP) was introduced by Beltrami and Bodin (1974) to manage the collection of 25,000 tons of waste in New York City. Over time, WCP has expanded significantly and has attracted the attention of researchers from various fields, particularly in routing problems. Consequently, this problem is commonly referred to as Waste Collection Vehicle Routing Problem (WCVRP).

In WCVRP, most researchers focus on the economic aspects related to operational costs, aiming to minimize travel distances, transportation costs, and the total number of vehicles used in solving the problem, as summarized in Table 1.1.

Table 1.1

WCVRP Objectives in Terms of Economic Aspects

Objective	**Authors**
Minimize travel distance	Gruler, Juan & Bolton (2018); Louati, Son & Chabchoub (2019), Mat, Benjamin & Abdul-Rahman (2018a); Nevrlý, Šomplák & Popela (2019)
Minimize travel time	Wy, Kim & Kim (2013); Hauge, Larsen, Lusby & Krapper (2014)
Minimize travel cost	Hemmelmayr, Doerner, Hartl & Rath (2013); Babaee Tirkolaee & Aydın (2021); Gómez, Pacheco, & Gonzalo-Orden (2015)
Minimize the number of vehicles	Benjamin & Beasley (2013, 2010), Benjamin (2011); Campos & Arroyo (2017); Gruler et al. (2018)

REFERENCES

Adhi, A., Santosa, B., & Siswanto, N. (2018). A meta-heuristic method for solving scheduling problem: crow search algorithm. *IOP Conference Series: Materials Science and Engineering, 337*(1), 012003. IOP Publishing.

Adhi, A., Santosa, B., & Siswanto, N. (2019a). A new metaheuristic for solving traveling salesman problem: partial comparison optimization. *IOP Conference Series: Materials Science and Engineering, 598*(1), 012021. IOP Publishing.

Adhi, A., Santosa, B., & Siswanto, N. (2019b). A new metaheuristic for solving vehicle routing problem: partial comparison optimization. *IOP Conference Series: Materials Science and Engineering, 598* (1), 012023. IOP Publishing.

Adhi, A. (2019). A new metaheuristic for solving production leveling (heijunka) problem: partial comparison optimization. *International Conference on Industrial Revolution for Polytechnic Education*, *1*(1).

Akhtar, M., Hannan, M. A., Begum, R. A., Basri, H., & Scavino, E. (2017). Backtracking search algorithm in CVRP models for efficient solid waste collection and route optimization. *Waste Management, 61*, 117-128.

Almufti, S. M., Marqas, R. B., Othman, P. S., & Sallow, A. B. (2021). Single-based and population-based metaheuristics for solving NP-hard problems. *Iraqi Journal of Science, 62*(5), 1710–1720.

Aliahmadi, S. Z., Barzinpour, F., & Pishvaee, M. S. (2020). A fuzzy optimization approach to the capacitated node-routing problem for municipal solid waste collection with multiple tours: A case study. *Waste Management & Research*, *38*(3), 279-290.

April, Glover, & Laguna. (2003). Practical introduction to simulation optimization. *Proceedings of the 2003 Winter Simulation Conference, 2003. 1*, 71-78. IEEE.

Assaf, R., & Saleh, Y. (2017). Vehicle-routing optimization for municipal solid waste collection using genetic algorithm: The case of southern Nablus city. *Civil and Environmental Engineering Reports*, *26*(1), 43–57.

Bautista, J., Fernández, E., & Pereira, J. (2008). Solving an urban waste collection problem using ants heuristics. *Computers & Operations Research, 35*(9), 3020–3033.

Babaee Tirkolaee, E., Abbasian, P., Soltani, M., & Ghaffarian, S. A. (2019a). Developing an applied algorithm for multi-trip vehicle routing problem with time windows in urban waste collection: A case study. *Waste Management & Research*, *37*(1_suppl), 4-13.

Babaee Tirkolaee, E., Mahdavi, I., Seyyed Esfahani, M. M., & Weber, G. W. (2019b). A hybrid augmented ant colony optimization for the multi-trip capacitated arc routing problem under fuzzy demands for urban solid waste management. *Waste Management & Research*, *38*(2), 156-172.

Babaee Tirkolaee, E., & Aydın, N. S. (2021). A sustainable medical waste collection and transportation model for pandemics. *Waste Management & Research*, *39*(1_suppl), 34-44.

Baldacci, R., Mingozzi, A., & Roberti, R. (2012). Recent exact algorithms for solving the vehicle routing problem under capacity and time window constraints. *European Journal of Operational Research, 218*(1), 1-6.

Barma, P. S., Dutta, J., Mukherjee, A., & Kar, S. (2023). A bi-objective latency-based vehicle routing problem using hybrid GRASP-NSGAII algorithm. *International Journal of Management Science and Engineering Management, 18*(3), 190-207.

Barma, P. S., Dutta, J., & Mukherjee, A. (2019). A 2-opt guided discrete antlion optimization algorithm for multi-depot vehicle routing problem. *Decision Making*: *Applications in Management and Engineering, 2*(2), 112-125.

Beliën, J., De Boeck, L., & Van Ackere, J. (2014). Municipal solid waste collection and management problems: a literature review. *Transportation Science, 48*(1), 78-102.

Beltrami, E. J., & Bodin, L. D. (1974). Networks and vehicle routing for municipal waste collection. *Networks, 4,* 65-94. doi: 10.1002/net.3230040106.

Benjamin, A. M., & Beasley, J. E. (2010). Metaheuristics for the waste collection vehicle routing problem with time windows, driver rest period and multiple disposal facilities. *Computers & Operations Research, 37*(12), 2270-2280.

Benjamin, A. M. (2011). *Metaheuristics for the waste collection vehicle routing problem with time windows* (Doctoral dissertation). Brunel University.

Benjamin, A.M., & Beasley, J. E. (2013). Metaheuristics with disposal facility positioning for the waste collection VRP with time window. *Optimization Letters, 7*(7), 1433-1449. doi: 10.1007/s11590-012-0549-6.

Bianchessi, N., & Righini, G. (2007). Heuristic algorithms for the Vehicle Routing Problem with simultaneous Pick-up and Delivery. *Computers & Operations Research, 34*, 578–594. doi: 10.1016/j.cor.2005.03.014.

Braekers, K., Ramaekers, K., & Van Nieuwenhuyse, I. (2016). The vehicle routing problem: State of the art classification and review. *Computers & Industrial Engineering*, *99*, 300-313.

Bräysy, O., & Gendreau, M. (2005). Vehicle routing problem with time windows, Part I: Route construction and local search algorithms. *Transportation Science*, 39(1), 104–118.

Buhrkal, K., Larsen, A., & Ropke, S. (2012). The waste collection vehicle routing problem with time windows in a city logistics context. *Procedia - Social and Behavioral Sciences*, *39*, 241–54.

Campos, A. A & Arroyo, J. E. C. (2017). An ILS heuristic for the waste collection vehicle routing problem with time windows. *Intelligent Systems Design and Applications*, *557*, 889–899.

Chen, A. L., Yang, G. K., & Wu, Z. M. (2006). Hybrid discrete particle swarm optimization algorithm for capacitated vehicle routing problem. *Journal of Zhejiang University-Science A, 7*(4), 607-614.

Cherkesly, M., Desaulniers, G., Irnich, S., & Laporte, G. (2016). Branch-price-and-cut algorithms for the pickup and delivery problem with time windows and multiple stacks. *European Journal of Operational Research*, *250*(3), 782-793.

Clarke, G., & Wright, J. W. (1964). Scheduling of vehicles from a central depot to a number of delivery points. *Operations Research*, *12*(4), 568–582.

Cooray, P. L. N. U., & Rupasinghe, T. D. (2016). An analysis of methodologies for solving green vehicle routing problem: A systematic review of literature. In *Proceedings of the Conference in Colombo, Sri Lanka, June 3–4, 2016*.

Cordeau, J. F., Gendreau, M., Hertz, A., Laporte, G., & Sormany, J. S. (2005). New heuristics for the vehicle routing problem. In G. Laporte, & F. Vigo (Eds.), *Logistics systems: Design and optimization* (pp. 279-297). Springer.

Dantzig, G. B., & Ramser, J. H. (1959). The truck dispatching problem. *Management Science*, *6*(1), 80–92. doi:10.1287/mnsc.6.1.80

De Jaegere, N., Defraeye, M., & Van Nieuwenhuyse, I. (2014). *The vehicle routing problem: State of the art classification and review (*Report No. KBI 1415, pp. 1-30*)*. Research Center for Operations Management, Faculty of Economics and Business, KU Leuven, Belgium.

Delgado-Antequera, L., Laguna, M., Pacheco, J., & Caballero, R. (2019). A bi-objective solution approach to a real-world waste collection problem. *Journal of the Operational Research Society*, *71*(2), 183-194.

Delgado-Antequera, L., Caballero, R., Sánchez-Oro, J., Colmenar, J. M., & Martí, R. (2020). Iterated greedy with variable neighborhood search for a multiobjective waste collection problem. *Expert Systems with Applications*, *145*, 101–113.

Dell'Amico, M., Righini, G., Salani, M. (2006). A branch-and-price approach to the vehicle routing problem with simultaneous distribution and collection. *Transportation Science*, *40*, 235–247.

Dumitrescu, I., & Stützle, T. (2003). Combinations of local search and exact algorithms. In G. R. Raidl, & J. Gottlieb (Eds.), *Workshops on applications of evolutionary computation* (pp. 211-223). Springer Berlin Heidelberg.

Elgarej, M., Mansouri, K., Youssfi, M., Benmoussa, N., & Elfarissi, H. (2017). Distributed swarm optimization modeling for waste collection vehicle routing problem. *International Journal of Advanced Computer Science and Applications*, 8(9), 306-312.

Endler, K. D., Scarpin, C. T., Steiner, M. T., & Choueiri, A. C. (2023). Systematic review of the latest scientific publications on the vehicle routing problem. *Asia-Pacific Journal of Operational Research*, 40(3), 2250046.

Eren, E., & Tuzkaya, U. R. (2021). Safe distance-based vehicle routing problem: Medical waste collection case study in COVID-19 pandemic. *Computers & Industrial Engineering, 157*, 107328.

Fauziah, S. H., & Agamuthu, P. (2010, September). *Landfills in Malaysia: Past, present and future.* Paper presented at the 1st International Conference on Final Sinks, Vienna, Austria.

Farrokhi-Asl, H., Tavakkoli-Moghaddam, R., Asgarian, B., & Sangari, E. (2017). Metaheuristics for a bi-objective location-routing-problem in waste collection management. *Journal of Industrial and Production Engineering*, *34*(4), 239-252.

Florios, K., Kiranoudis, C., & Mavrotas, G. (2005). *Heuristics for urban solid waste collection*. Presented at the Heleco 2005 Conference, TEE, Athens, Greece.

Fukasawa, R., He, Q., & Song, Y. (2016). A branch-cut-and-price algorithm for the energy minimization vehicle routing problem. *Transportation Science*, *50*(1), 23-34.

Gendreau, M., & Potvin, J.-Y. (2010). Handbook of metaheuristics (2nd ed.). Springer.

Ghannadpour, S. F., & Zandiyeh, F. (2020). An adapted multi-objective genetic algorithm for solving the cash in transit vehicle routing problem with vulnerability estimation for risk quantification. *Engineering applications of artificial intelligence, 96*, 103964.

Glover, F. (1989). Tabu search—part I. *ORSA Journal on computing*, *1*(3), 190-206.

Gruler, A., Juan, A. A., & Bolton, C. C. (2018). A biased-randomized heuristic for the waste collection problem in smart cities. *Applied Mathematics and Computational Intelligence*, 730, 255-263.

Gómez, J. R., Pacheco, J., & Gonzalo-Orden, H. (2015). A Tabu search method for a bi-objective urban waste collection problem. *Computer-Aided Civil and Infrastructure Engineering*, *30*(1), 36-53.

Han, H., & Ponce-Cueto, E. (2015). Waste Collection Vehicle Routing Problem: Literature Review. *PROMET-Traffic&Transportation*, *27*(4), 345-358.

Hannan, M. A., Akhtar, M., Begum, R. A., Basri, H., Hussain, A., & Scavino, E. (2017). Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using PSO algorithm. *Waste management*, *71*, 31-41.

Hannan, M. A., Begum, R. A., Al-Shetwi, A. Q., Ker, P. J., Al Mamun, M. A., Hussain, A., ... & Mahlia, T. M. I. (2020). Waste collection route optimisation model for linking cost saving and emission reduction to achieve sustainable development goals. *Sustainable Cities and Society*, *62*, 102393.

Hashim, F., Benjamin, A. M., & Abdul-Rahman, S. (2019). Estimation of Carbon Dioxide Emissions in a Waste Collection Vehicle Routing Problem. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *53*(2), 204-212.

Hauge, K., Larsen, J., Lusby, R. M., & Krapper, E. (2014). A hybrid column generation approach for an industrial waste collection routing problem. *Computers & Industrial Engineering*, *71*, 10-20.

Hemmelmayr, V., Doerner, K. F., Hartl, R. F., & Rath, S. (2013). A heuristic solution method for node routing based solid waste collection problems. *Journal of Heuristics*, *19*(2), 129-156.

Hokama, P., Miyazawa, F. K., & Xavier, E. C. (2016). A branch-and-cut approach for the vehicle routing problem with loading constraints. *Expert Systems with Applications*, *47*, 1-13.

Huang, S. H., & Lin, P. C. (2015). Vehicle routing–scheduling for municipal waste collection system under the "Keep Trash off the Ground" policy. *Omega*, 55, 24-37.

Islam, R., & Rahman, M. S. (2012, May). An ant colony optimization algorithm for waste collection vehicle routing with time windows, driver rest period and multiple disposal facilities. In *2012 International Conference on Informatics, Electronics & Vision (ICIEV)* (pp. 774-779). IEEE.

Kallehauge, B. (2008). Formulations and exact algorithms for the vehicle routing problem with time windows. *Computers & Operations Research*, *35*(7), 2307-2330.

Kim, B. I., Kim, S., & Sahoo, S. (2006). Waste collection vehicle routing problem with time windows. *Computers & Operations Research*, *33*(12), 3624-3642.

Kuo, R. J., Zulvia, F. E., & Suryadi, K. (2012). Hybrid particle swarm optimization with genetic algorithm for solving capacitated vehicle routing problem with fuzzy demand – A case study on garbage collection system. *Applied Mathematics and Computation*, *219*(5), 2574–2588.

Le Hoang, S. O. N. (2014). Optimizing municipal solid waste collection using chaotic particle swarm optimization in GIS based environments: A case study at Danang city, Vietnam. *Expert Systems with Applications*, *41*(18), 8062-8074. Elsevier.

Lin, C., Choy, K. L., Ho, G. T., Chung, S. H., & Lam, H. Y. (2014). Survey of green vehicle routing problem: past and future trends. *Expert Systems with Applications*, *41*(4), 1118-1138.

Liu, J., & He, Y. (2012). A clustering-based multiple ant colony system for the waste collection vehicle routing problems. In *Proceedings of the Fifth International Symposium on Computational Intelligence and Design (ISCID)*,2, 182-185. IEEE.

Liu, L., & Liao, W. (2021). Optimization and profit distribution in a two-echelon collaborative waste collection routing problem from economic and environmental perspective. *Waste Management, 120*, 400-414.

Louati, A., Son, L. H., & Chabchoub, H. (2019). Smart routing for municipal solid waste collection: a heuristic approach. *Journal of Ambient Intelligence and Humanized Computing*, *10*, 1865-1884.

López-Sánchez, A. D., Hernández-Díaz, A. G., Gortázar, F., & Hinojosa, M. A. (2018). A multiobjective GRASP–VND algorithm to solve the waste collection problem. *International Transactions in Operational Research*, *25*(2), 545-567.

MacGregor, K. (2017). How long is the average landfill open? Retrieved from http://sciencing.com/long-average-landfill-open-7103.html

Malandraki, C., & Daskin, M. S. (1992). Time dependent vehicle routing problems: Formulations, properties and heuristic algorithms. *Transportation science, 26*(3), 185-200.

Mat, N. A., Benjamin, A. M., & Abdul-Rahman, S. (2018a). Efficiency of heuristic algorithms in solving waste collection vehicle routing problem: A case study. *The Journal of Social Sciences Research*, Special Issue 6, 695-700.

Mat, N. A., Benjamin, A. M., & Abdul-Rahman, S. (2018b). Enhanced heuristic algorithms with a vehicle travel speed model for time-dependent vehicle routing: A waste collection problem. *Journal of Information and Communication Technology*, *17*, 55–78.

Min, H. (1989). The multiple vehicle routing problem with simultaneous delivery and pick-up points. *Transportation Research Part A: General, 23*(5), 377-386.

Mofid-Nakhaee, E., & Barzinpour, F. (2019). A multi-compartment capacitated arc routing problem with intermediate facilities for solid waste collection using hybrid adaptive large neighborhood search and whale algorithm. *Waste Management & Research*, 37(1), 38-47.

Nawaz, M., Enscore Jr, E. E., & Ham, I. (1983). A heuristic algorithm for the m-machine, n-job flow-shop sequencing problem. *Omega, 11*(1), 91-95.

Nevrlý, V., Šomplák, R., & Popela, P. (2019). Heuristics for waste collection arc routing problem. *MENDEL*, *25*(1), 15-22.

Otoo, D. (2012). *Capacitated arc routing problem: Collection of solid waste at Kwadaso estate Kumasi*. (Doctoral dissertation). University of Ghana, 1-95.

Otoo, D., Amponsah, S. K., & Sebil, C. (2014). Capacitated clustering and collection of solid waste in kwadaso estate, Kumasi. *Journal of Asian Scientific Research*, *4*(8), 460-472.

Ombuki-Berman, B. M., Runka, A., & Hanshar, F. (2007). Waste collection vehicle routing problem with time windows using multi-objective genetic algorithms. In *Proceedings of the Third IASTED International Conference on Computational Intelligence* (pp. 91-97). International Association of Science and Technology for Development.

Osman, I. H., & Laporte, G. (1996). Metaheuristics: A bibliography. *Annals of Operations Research*, 63(5), 511–623.

Rabbani, M., Farrokhi-asl, H., & Rafiei, H. (2016). A hybrid genetic algorithm for waste collection problem by heterogeneous fleet of vehicles with multiple separated compartments. *Journal of Intelligent & Fuzzy Systems*, *30*(3), 1817-1830.

Rajpurohit, J., Sharma, T. K., & Abraham, A. (2017). Glossary of metaheuristic algorithms. *International Journal of Computer Information Systems & Industrial Management Applications*, *9*, 1-20.

Rinaldi, M., Bottani, E., Solari, F., & Montanari, R. (2022). The vehicle routing problem in the dairy sector: a case study. *International Journal of Food Engineering, 18*(3), 239-252.

Sackmann, D., Hinze, R., Michael, B., Krieger, C., & Halifeoglu, E. (2017). A heuristic for the solution of vehicle routing problems with time windows and multiple dumping sites in waste collection. *Investigación Operacional*, *38*(3), 206-215.

Sahoo, S., Kim, S., Kim, B.-I., Kraas, B., & Popov, A. (2005). Routing optimization for waste management. *Interfaces*, 35(1), 24-36.

Samsuddin, S., Othman, M. S., & Yusuf, L. M. (2018). A review of single and population-based metaheuristic algorithms solving multi depot vehicle routing problem. *International Journal of Software Engineering and Computer Systems*, *4*(2), 80-93.

Saputra, I. W., Sutopo, W., & Hisjam, M. (2017). Optimization of distribution channel vehicle routing problem with time windows using differential evolution algorithm a case study in newspaper industry. *Asia-Pacific Management and Business Application, 10*, 1-10.

Shi, Y., Lv, L., Hu, F., & Han, Q. (2020). A heuristic solution method for multi-depot vehicle routing-based waste collection problems. *Applied Sciences, 10*(7), 2403.

Solomon, M. M. (1987). Algorithms for the Vehicle Routing and Scheduling Problems with Time Window Constraints. *Operations Research, 35*(2), 254-265.

Talbi, E.-G. (2009). *Metaheuristics: From design to implementation*. Wiley.

Thammano, A., & Rungwachira, P. (2021). Hybrid modified ant system with sweep algorithm and path relinking for the capacitated vehicle routing problem. *Heliyon*, 7(9), e07920.

Toro, E., Escobar A. & Granada, M. (2016). Literature review of vehicle routing problem in the green transportation context. *Revista Luna Azul*, *42*, 362-387. Retrieve from http://200.21.104.25/lunazul/index.php?option=com_content&view=article&id=143

Úbeda, S., Arcelus, F. J., & Faulin, J. (2011). Green logistics at Eroski: A case study. *International Journal of Production Economics*, *131*(1), 44-51.

Úbeda, S., Faulin, J., Serrano, A., & Arcelus, F. J. (2014). Solving the green capacitated vehicle routing problem using a tabu search algorithm. *Lecture Notes in Management Science*, *6*, 141-149.

Ustohalova, V., Ricken, T., & Widmann, R. (2006). Estimation of landfill emission lifespan using process oriented modeling. *Waste management*, *26*(4), 442-450.

Wang, W. Y., Cheng, C. Y., & Leu, Y. G. (2004). An online GA-based output-feedback direct adaptive fuzzy-neural controller for uncertain nonlinear systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), 34*(1), 334-345.

Wang, S., Lu, Z., Wei, L., Ji, G., & Yang, J. (2016). Fitness-scaling adaptive genetic algorithm with local search for solving the Multiple Depot Vehicle Routing Problem. *Simulation, 92*(7), 601-616.

Wu, H., Tao, F., & Yang, B. (2020). Optimization of vehicle routing for waste collection and transportation. *International Journal of Environmental Research and Public Health, 17*(14), 4963.

Wy, J., Kim, B-I., & Kim, S. (2013). The rollon–rolloff waste collection vehicle routing problem with time windows. *European Journal of Operational Research. Elsevier B.V, 224*(3), 466–476.

Wy, J., & Kim, B. I. (2013). A hybrid metaheuristic approach for the rollon–rolloff vehicle routing problem. *Computers & Operations Research*, *40*(8), 1947-1952.

Xue, W., & Cao, K. (2016). Optimal routing for waste collection: a case study in Singapore. *International Journal of Geographical Information Science*, *30*(3), 554-572.

Yang, X. S. (2011). Metaheuristic optimization. *Scholarpedia*, *6*(8), 11472.

Yazdani, M., Kabirifar, K., Frimpong, B. E., Shariati, M., Mirmozaffari, M., & Boskabadi, A. (2021). Improving construction and demolition waste collection service in an urban area using a simheuristic approach: A case study in Sydney, Australia. *Journal of Cleaner Production, 280*, 124138.

Zadek, H., & Schulz, R. (2010). Methods for the calculation of CO2 emissions in logistics activities. In Dangelmaier, W., Blecken, A., Delius, R., & Klöpfer, S. (Eds.), *Advanced Manufacturing and Sustainable Logistics* (Lecture Notes in Business Information Processing, vol. 46). Springer, Berlin, Heidelberg. Retrieved from https://doi.org/10.1007/978-3-642-12494-5_24

APPENDICES

APPENDIX A: EXPERIMENTS ON ITERATION SIZE

DATASET 102

Initial solution of Random Search (100 iterations)

Number of iterations = *randi* (100, 100)

Run time	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)
1	1932.115	1722.2	4	50.989772
2	1928.326	1794.031	4	50.998952
3	1826.642	1609.030	4	51.082390
4	1878.599	1682.057	4	52.721091
5	1944.712	1782.909	4	52.622146
6	**1632.441**	**1568.288**	**4**	**51.373632**
7	1900.508	1814.232	4	51.063332
8	1887.207	1711.965	4	55.130857
9	1897.096	1838.711	4	50.843862
10	1718.910	1584.432	4	50.978451

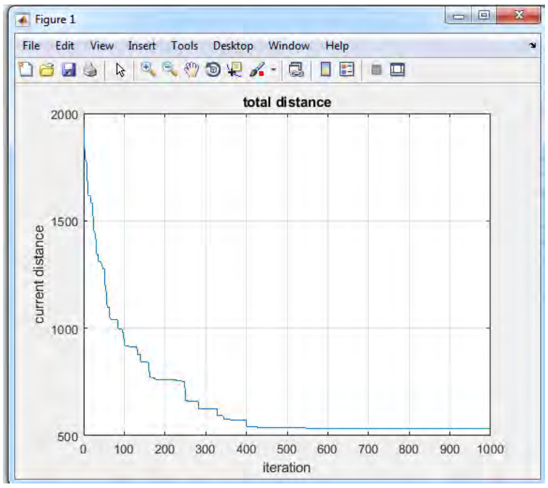
Initial Solution of Random Search (1000 iterations)

Number of iterations = *randi* (100, 1000)

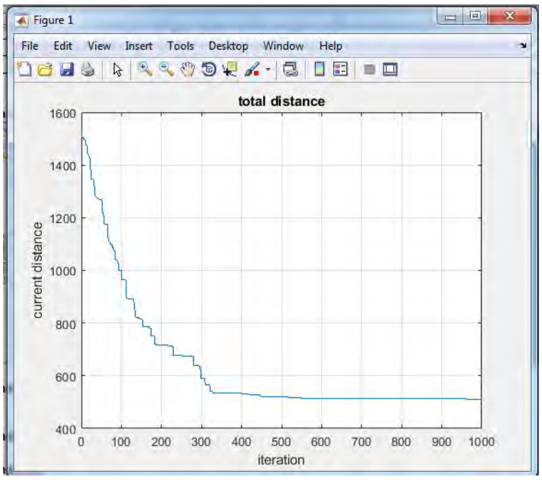
Run time	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)
1	1854.683	534.342	3	566.341
2	1530.114	510.571	4	572.531
3	1763.497	403.515	3	562.656
4	1487.382	382.950	3	573.609
5	1911.091	522.592	3	552.190
6	1507.896	386.735	3	573.508
7	1777.020	374.913	3	567.071
8	1414.141	389.641	4	596.027
9	1507.035	350.354	3	557.212
10	**1776.079**	**349.267**	**4**	**586.602**

Graph of best travel distance for 1000 iterations (Based on the Table Initial Solution of Random Search, 1000 iterations)

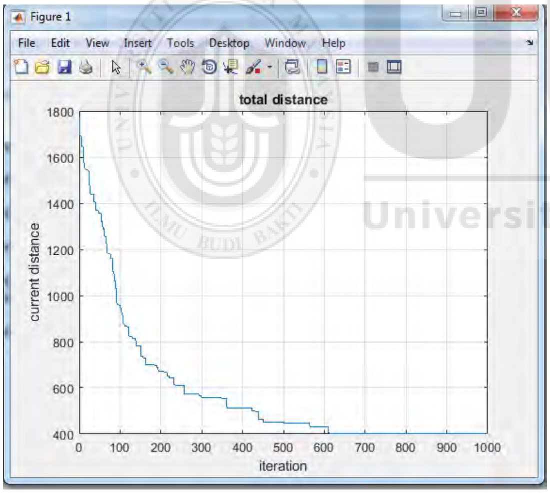
Run time 1: 534.342 miles



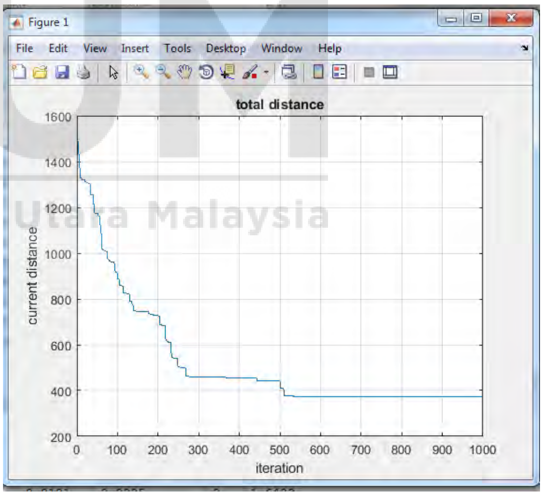
Run time 2: 510.571 miles



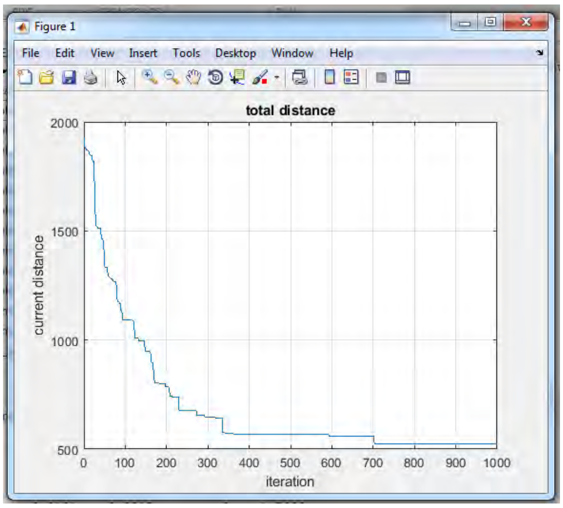
Run time 3: 403.515 miles



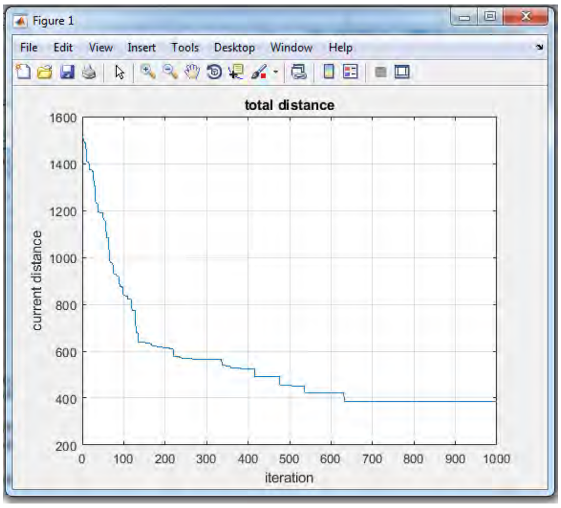
Run time 4: 382.950 miles



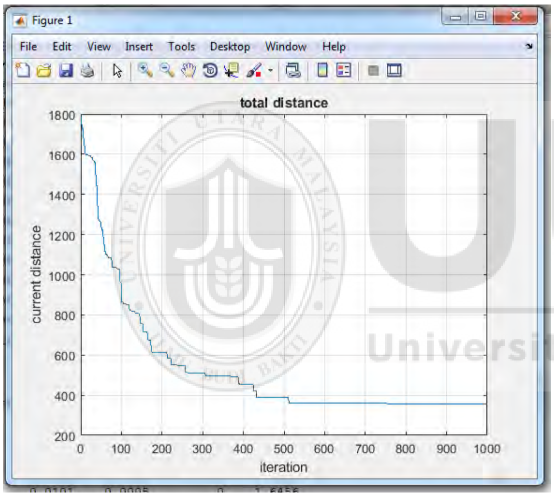
Run time 5: 522.592 miles



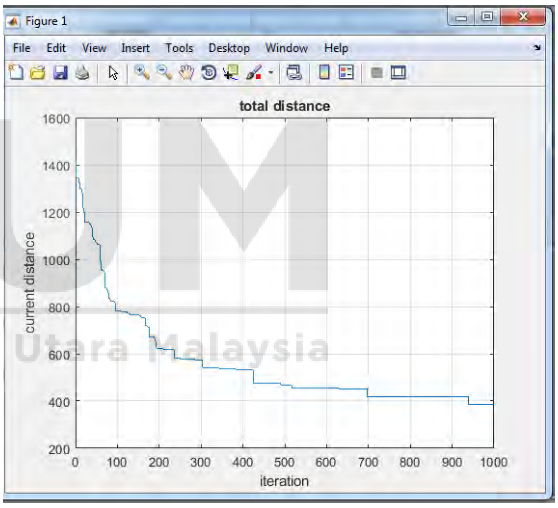
Run time 6: 386.735 miles



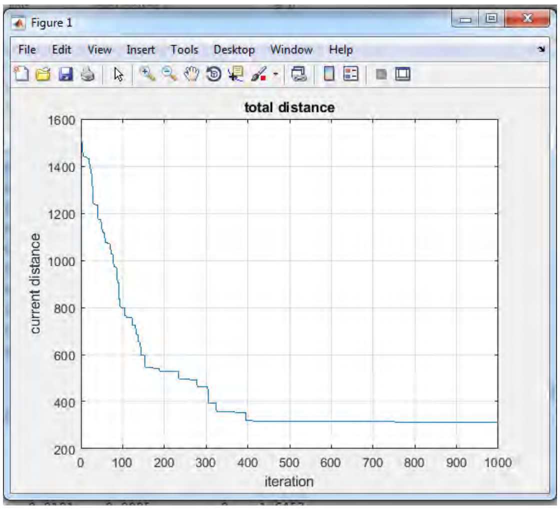
Run time 7: 374.913 miles



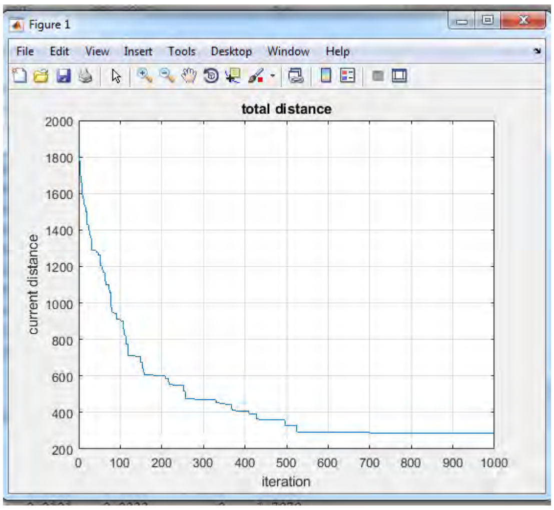
Run time 8: 389.641 miles



Run time 9: 350.34 miles



Run time 10: 349.267 miles



APPENDIX B: EXPERIMENTS ON SELECTION TECHNIQUE FOR INITIAL SOLUTIONS

DATASET 102

Using initial from random selection, Max size block: 10, CN step: (*n+1: n*+10), Iteration: 1000

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	SD	Best solution (Travel distance/no. of vehicle)
1.	1811.967	655.132	3	35.576	50.73	**156.9 (3)** (Benjamin & Beasley, 2013)
2.	1799.222	688.012	3	36.430		
3.	1667.631	645.264	3	35.986		
4.	**1298.221**	**512.575**	**3**	**36.477**		
5.	1804.720	629.570	3	36.375		
6.	1601.681	581.464	3	35.412		
7.	1505.774	563.044	3	35.914		
8.	1784.853	619.575	3	35.572		
9.	1699.017	594.117	3	35.729		
10.	1508.401	668.847	3	35.420		

Using initial from Nearest Greedy (NG), Max size block: 10, CN step: (n+1:n+10), Iteration: 1000

Run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (sec)	SD	Best solution (Travel distance/no. of vehicle)
1.	344.237	327.684	3	35.208	0.94	**156.9 (3)** (Benjamin & Beasley, 2013)
2.		327.555	3	35.677		
3.		327.947	3	35.081		
4.		329.136	3	36.443		
5.		329.058	3	34.466		
6.		326.730	3	35.495		
7.		**326.258**	**3**	**34.363**		
8.		328.699	3	36.298		
9.		328.563	3	36.036		
10.		327.123	3	35.715		

DATASET 277

Using initial from random selection, Max size block: 28, CN step: (n+1:n+28), Iteration: 1000

Random run	**Initial travel distance (miles)**	**Best travel distance (miles)**	**Number of vehicles**	**Elapsed time (sec)**	**SD**	**Best solution (Travel distance/ no. of vehicle)**
1.	1828.641	759.990	3	90.976	8.097	**394.0 (2)** (Campos & Arroyo, 2017)
2.	1941.292	710.635	3	107.835		
3.	1843.668	792.586	3	98.446		
4.	1939.603	634.931	3	81.309		
5.	1905.910	706.788	3	85.152		
6.	1803.853	752.003	3	85.432		
7.	**1855.202**	**609.506**	**3**	**83.588**		
8.	1874.623	656.026	3	83.339		
9.	1887.671	672.943	3	83.700		
10.	2060.097	744.156	3	82.907		

Using initial from NG, Max size block: 28, CN step: (n+1:n+28), Iteration: 1000

Run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (sec)	SD	Best solution (Travel distance/no. of vehicle)
1.	491.082	413.100	3	79.546	22.382	**394.0 (2)** (Campos & Arroyo, 2017)
2.		347.283	3	79.298		
3.		346.740	3	82.827		
4.		404.551	3	77.472		
5.		378.100	3	78.850		
6.		369.695	3	77.356		
7.		383.131	3	84.257		
8.		**343.160**	3	**78.360**		
9.		367.949	3	77.698		
10.		373.588	3	85.337		

DATASET 335

Using initial from random selection, Max size block: 33, CN step: (n+1:n+33), Iteration: 1000

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	SD	Best solution (Travel distance/no. of vehicle)
1.	1119.771	465.583	7	93.933		
2.	1116.003	459.501	7	104.627		
3.	1150.362	480.683	7	112.662		
4.	1113.437	477.988	7	99.772		
5.	1040.573	469.821	7	98.717		**182.1 (6)**
6.	**1117.050**	**459.248**	**7**	**104.091**	7.930	(Buhrkal et al., 2012)
7.	1114.904	460.325	7	96.417		
8.	1098.875	479.652	7	95.067		
9.	1100.202	463.810	7	104.764		
10.	1061.441	467.771	7	100.228		

Using initial from NG, Max size block: 33, CN step: (n+1: n+33), Iteration: 1000

Run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	SD	Best solution (Travel distance/no. of vehicle)
1.	219.2869	210.122	6	99.800	1.041	**182.1 (6)** (Buhrkal et al., 2012)
2.		211.006	6	101.867		
3.		211.967	6	107.436		
4.		212.001	6	112.572		
5.		211.158	6	97.572		
6.		**208.889**	**6**	**105.765**		
7.		211.817	6	117.920		
8.		211.376	6	98.750		
9.		209.374	6	103.206		
10.		210.191	6	111.500		

DATASET 444

Using initial solution from random selection, Max size block: 45, CN step: (n+1:n+45), Iteration: 1000

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	SD	Best solution (Travel distance/no. of vehicle)
1.	307.262	133.255	11	137.476	7.227	**72.8 (10)** (Campos & Arroyo, 2017)
2.	295.521	145.358	11	136.002		
3.	307.342	129.788	11	138.624		
4.	307.223	145.773	11	143.384		
5.	308.129	141.458	11	142.034		
6.	300.830	135.879	11	145.121		
7.	304.661	152.175	11	137.835		
8.	**300.018**	**129.430**	**11**	**139.652**		
9.	308.125	134.274	11	137.832		
10.	300.160	134.328	11	133.497		

Using initial from NG, Max size block: 45, CN step: (n+1:n+45), Iteration: 1000

Run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	SD	Best solution (Travel distance/no. of vehicle)
1.	93.751	61.919	11	130.606	1.911	**72.8 (10)** (Campos & Arroyo, 2017)
2.		63.083	11	130.986		
3.		62.707	11	131.966		
4.		61.633	11	130.204		
5.		**61.239**	**11**	**161.735**		
6.		61.468	11	178.662		
7.		61.417	11	156.801		
8.		67.720	11	162.687		
9.		61.526	11	171.127		
10.		64.361	11	160.587		

APPENDIX C: EXPERIMENTS ON FIXED BLOCK SIZE AND FIXED CN SIZE

INITIAL SOLUTION USING RANDOM SELECTION FOR SCENARIO 1 (FIXED BLOCK SIZE AND FIXED CN SIZE) DATASET 102

Using 10% block size (Max size block: 10, CN step: 10, Max. Iteration: 1000)

Random run	Initial travel distance (miles)	Best travel distance (miles)	No. of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	1751.565	685.232	3	36.576	95.34	78.09	1.93	1.10	48.386	**156.9 (3)** (Benjamin & Beasley, 2013)
2.	1801.342	658.512	3	35.430	95.61	79.14	1.79	1.21		
3.	1767.351	688.234	3	36.986	95.57	77.70	1.89	1.15		
4.	**1798.200**	**522.475**	**3**	**34.477**	**95.56**	**77.60**	**1.73**	**1.19**		
5.	1704.520	625.970	3	35.375	96.24	79.80	1.95	1.21		
6.	1651.610	588.464	3	36.412	97.12	78.88	2.01	1.16		
7.	1675.774	590.044	3	36.914	95.59	78.46	1.97	1.24		
8.	1780.553	625.575	3	36.572	96.12	79.01	1.93	1.18		
9.	1690.445	602.117	3	37.729	96.48	79.50	2.00	1.44		
10.	1608.500	657.747	3	36.420	95.71	78.67	2.03	1.20		

DATASET 277

Using 10% block size (Max size block: 28, CN step: 28, Max. Iteration: 1000)

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	1828.641	759.990	3	90.976	95.70	89.50	5.20	2.12	8.097	**394.0 (2)** (Campos & Arroyo, 2017)
2.	1941.292	710.635	3	107.835	94.98	88.24	5.42	2.16		
3.	1843.668	792.586	3	98.446	95.10	88.50	5.31	2.42		
4.	1939.603	634.931	3	81.309	95.27	87.90	5.12	2.07		
5.	1905.910	706.788	3	85.152	95.12	88.36	5.01	2.44		
6.	1803.853	752.003	3	85.432	96.26	88.28	5.97	2.09		
7.	**1855.202**	**609.506**	**3**	**83.588**	**95.12**	**88.46**	**5.93**	**1.98**		
8.	1874.623	656.026	3	83.339	95.48	89.02	5.05	1.80		
9.	1887.671	672.943	3	83.700	94.71	89.21	5.24	2.20		
10.	2060.097	744.156	3	82.907	95.57	87.76	5.14	2.15		

DATASET 335

Using 10% block size (Max size block: 33, CN step: 33, Iteration: 1000)

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	1119.771	465.583	7	93.933	85.14	63.37	2.25	0		
2.	1116.003	459.501	7	104.627	86.68	67.37	2.27	1.05		
3.	1150.362	480.683	7	112.662	88.10	69.05	2.19	1.12		
4.	1113.437	477.988	7	99.772	87.12	66.74	2.05	0		
5.	1040.573	469.821	7	98.717	84.69	68.34	2.12	1.21	7.93	**182.1 (6)** (Buhrkal et al., 2012)
6.	**1117.050**	**459.248**	**7**	**104.091**	**84.21**	**68.63**	**2.29**	**1.11**	0	
7.	1114.904	460.325	7	96.417	85.68	66.10	2.25	0.80		
8.	1098.875	479.652	7	95.067	84.65	66.19	2.08	0.91		
9.	1100.202	463.810	7	104.764	82.10	64.25	1.98	1.10		
10.	1061.441	467.771	7	100.228	84.22	69.63	1.88	1.02		

DATASET 444

Using 10% block size (Max size block: 45, CN step: 45, Max. Iteration: 1000)

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	307.262	133.255	11	137.476	95.09	84.50	6.66	1.43		
2.	295.521	145.358	11	136.002	97.89	84.25	6.83	1.44		
3.	307.342	129.788	11	138.624	97.32	91.27	6.86	1.33		
4.	307.223	145.773	11	143.384	95.42	92.25	6.43	1.20		
5.	308.129	141.458	11	142.034	90.00	90.16	6.34	1.25	7.227	**66.447 (11)** (Campos & Arroyo, 2017)
6.	300.830	135.879	11	145.121	92.05	91.48	6.11	1.45		
7.	304.661	152.175	11	137.835	91.21	81.38	6.20	0.85		
8.	**300.018**	**129.430**	**11**	**139.652**	**95.37**	**88.94**	**6.22**	**0.90**		
9.	308.125	134.274	11	137.832	91.32	90.11	6.26	1.20		
10.	300.160	134.328	11	133.497	89.47	85.31	6.05	1.40		

DATASET 804

Using 10% block size (Max size block: 79, CN step: 79, Max. Iteration: 1000)

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	1829.122	1233.730	9	106.421	92.46	3.11	5.75	0.77		
2.	**1816.203**	**1178.204**	**8**	**106.958**	**93.80**	**3.27**	**5.33**	**0.75**		
3.	1850.263	1219.210	9	106.157	95.23	3.19	5.20	0.73		
4.	1831.734	1216.103	9	106.121	92.21	3.20	5.14	0.80		
5.	1827.375	1280.612	8	107.027	94.80	3.21	5.80	0.75	2.68	**604.1 (5)**
6.	1817.350	1223.245	8	106.470	93.05	3.33	5.17	0.45	8	(Buhrkal et al., 2012)
7.	1914.415	1340.375	9	105.743	95.33	3.42	5.80	0.85		
8.	1889.705	1229.442	9	105.490	92.34	3.18	5.75	0.90		
9.	1911.373	1226.305	9	105.624	93.47	3.02	5.44	1.10		
10.	1856.188	1219.215	9	105.577	90.69	3.14	5.77	1.02		

DATASET 1051

Using 10% block size (Max size block: 105, CN step: 105, Max. Iteration: 1000)

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	18801.081	11080.430	34	385.161	82.24	66.67	5.70	1.23		
2.	19000.426	10601.333	29	387.475	86.80	65.20	6.32	1.59		
3.	**18846.956**	**10453.543**	**29**	**386.119**	**85.33**	**67.10**	**6.25**	**1.40**		
4.	18814.271	11431.642	30	396.809	82.12	67.24	5.50	1.66		
5.	19142.100	11021.560	31	399.714	84.69	65.30	6.10	1.21	29236.15	**1876.8 (17)** (Campos & Arroyo, 2017)
6.	18962.361	11357.470	29	395.646	88.10	66.25	5.35	1.90		
7.	18850.800	11001.341	28	389.810	85.50	66.10	5.27	1.85		
8.	18855.971	11200.505	29	397.484	82.25	65.60	5.68	1.54		
9.	19024.575	10910.863	29	385.500	83.20	66.00	6.24	1.28		
10.	19902.671	10845.564	30	401.376	80.22	65.33	6.14	1.30		

DATASET 1351

Using 10% block size (Max size block: 135, CN step: 135, Max. Iteration: 1000)

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	1914.178	1402.011	8	419.407	87.23	60.21	3.15	0.97	49.065	**656.8 (8)** (Campos & Arroyo, 2017)
2.	1900.155	1378.210	8	421.210	86.22	60.27	3.22	0.59		
3.	**1920.242**	**1319.155**	**8**	**436.442**	**87.10**	**61.01**	**3.22**	**0.99**		
4.	1921.512	1421.310	8	434.217	87.25	60.24	3.05	1.12		
5.	1907.033	1470.212	8	423.626	86.95	62.19	3.28	1.21		
6.	1857.410	1432.242	8	426.124	85.30	60.37	3.32	1.21		
7.	1914.771	1440.255	8	436.144	86.21	61.28	3.25	0.85		
8.	1897.551	1329.221	8	426.572	86.60	61.10	3.28	0.78		
9.	1915.299	1461.110	8	437.212	86.21	61.35	3.11	1.35		
10.	1896.218	1431.621	8	436.418	87.22	60.33	3.02	1.29		

DATASET 1599

Using 10% block size (Max size block: 160, CN step: 160, Max. Iteration: 1000)

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	2225.510	1974.033	16	522.823	92.42	36.11	5.32	1.27	15.908	**1206.1 (13)** (Benjamin & Beasley, 2013)
2.	2280.236	1930.512	16	523.002	93.20	36.25	5.23	1.29		
3.	**2231.371**	**1920.218**	**16**	**528.246**	**93.30**	**36.22**	**5.19**	**1.99**		
4.	2227.215	1931.299	16	524.335	92.12	36.05	5.24	1.21		
5.	2317.310	1925.771	16	531.004	94.40	36.02	5.77	1.27		
6.	2314.217	1957.235	16	525.211	89.83	36.23	5.23	1.46		
7.	2289.005	1944.280	16	537.234	89.50	36.25	5.89	1.44		
8.	2411.133	1947.451	16	529.231	92.12	36.17	5.57	1.88		
9.	2356.772	1945.219	16	527.356	93.20	36.39	5.50	1.80		
10.	2321.225	1958.223	16	523.159	90.26	36.48	5.43	1.81		

DATASET 1932

Using 10% block size (Max size block: 193, CN step: 193, Max. Iteration: 1000

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	1951.565	1597.256	17	527.306	75.34	3.22	2.94	0.27	25.100	**1037.5 (16)** (Campos & Arroyo, 2017)
2.	**1952.500**	**1580.512**	**17**	**528.009**	**76.56**	**3.26**	**2.72**	**0.27**		
3.	1977.251	1620.218	18	527.910	77.28	3.29	2.75	0.29		
4.	1998.774	1582.129	17	527.880	77.29	3.21	2.57	0.28		
5.	1984.250	1625.100	18	527.885	76.28	3.14	2.82	0.21		
6.	1976.625	1653.511	17	528.023	75.20	3.17	2.68	0.26		
7.	1975.445	1642.299	17	528.038	76.35	3.12	2.29	0.29		
8.	1980.353	1647.280	17	527.899	76.60	3.18	2.73	0.88		
9.	1990.556	1623.771	17	527.897	76.12	3.12	2.71	1.21		
10.	1989.772	1598.257	17	527.332	77.22	3.24	2.72	1.20		

DATASET 2100

Using 10% block size (Max size block: 210, CN step: 210, Max. Iteration: 1000

Random run	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
					PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	2606.986	2033.328	20	634.585	82.37	6.22	4.93	0.87	20.249	**1461.91 (16)** (Campos & Arroyo, 2017)
2.	2658.117	2045.274	20	636.586	83.20	6.27	4.99	0.89		
3.	2688.089	2029.879	20	635.530	83.20	6.23	4.99	0.99		
4.	2622.475	2045.275	20	636.586	82.22	6.35	4.93	0.82		
5.	2625.772	2041.268	20	636.477	84.40	6.32	4.95	0.85		
6.	6588.122	2052.879	20	635.375	79.98	6.28	4.91	0.84		
7.	2690.237	2052.175	20	636.219	79.50	6.35	4.87	0.74		
8.	**2628.426**	**2029.430**	**20**	**636.214**	**82.43**	**6.38**	**4.93**	**0.82**		
9.	2612.849	2073.274	20	636.712	83.19	6.37	4.10	0.79		
10.	2625.677	2098.155	20	636.210	80.16	6.29	4.83	0.91		

APPENDIX D: EXPERIMENTS ON DYNAMIC BLOCK SIZE AND DYNAMIC CN SIZE

INITIAL SOLUTION USING NEAREST GREEDY FOR SCENARIO 1 (DYNAMIC BLOCK SIZE AND DYNAMIC CN SIZE)

DATASET 102

Max. Iteration = 1000; **total_customer** = 100; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	63.48	48.00		220.175	3	254.516	63.26	31.78	0.28	0.14		
2.	63.32	47.61		209.546	3	255.333	62.45	31.34	0.26	0.11		
3.	**62.02**	**46.68**		**208.935**	**3**	**257.738**	**64.74**	**31.57**	**0.25**	**0.17**		
4.	62.77	47.02		236.067	3	255.312	64.26	31.21	0.22	0.15		**156.9 (3)**
5.	64.49	49.22	**344.237**	234.276	3	254.244	63.29	31.35	0.27	0.14	10.381	(Benjamin & Beasley, 2013)
6.	64.51	48.33		238.146	3	254.362	63.54	32.01	0.21	0.14		
7.	64.68	48.26		236.221	3	257.455	64.32	31.48	0.22	0.18		
8.	63.36	49.45		231.542	3	255.348	62.45	31.76	0.28	0.13		
9.	63.76	49.21		233.156	3	255.218	62.72	31.43	0.25	0.14		
10.	64.52	49.39		227.442	3	261.201	63.45	31.38	0.27	0.17		

DATASET 277

Max. Iteration = 1000; **total_customer** = 275; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	**82.30**	**39.66**		**402.764**	**3**	**1032.242**	**75.46**	**43.33**	**3.01**	**1.23**		
2.	84.01	40.61		412.201	3	1017.511	74.12	42.53	3.09	1.25		
3.	84.06	40.32		441.083	3	1087.125	73.10	43.48	2.88	1.17		
4.	83.34	42.72		435.271	3	1067.227	73.27	43.25	3.23	1.15		
5.	84.72	41.83	**491.082**	422.160	3	1068.335	75.38	44.16	2.79	1.26	13.118	**394.0 (2)** (Campos & Arroyo, 2017)
6.	84.61	43.53		428.325	3	1100.382	74.69	42.39	2.57	1.29		
7.	84.45	42.47		423.116	3	1164.233	75.11	42.47	2.76	1.17		
8.	84.56	40.61		448.267	3	1088.342	75.88	44.38	3.10	1.34		
9.	83.63	40.39		439.473	3	1067.334	76.07	44.22	2.68	1.26		
10.	85.82	41.73		431.427	3	1065.221	76.32	43.17	2.82	1.38		

DATASET 335

Max. Iteration = 1000; **total_customer** = 330; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	77.00	41.00	219.287	200.733	6	1123.311	82.26	38.57	3.35	1.19	9.232	**182.1 (6)** (Buhrkal et al, 2012)
2.	88.70	37.00		187.403	6	1135.176	82.43	37.24	3.34	1.25		
3.	**89.61**	**36.77**		**185.368**	**6**	**1103.424**	**81.46**	**37.17**	**3.21**	**1.28**		
4.	77.27	38.20		202.001	6	1278.387	81.67	39.26	3.14	1.37		
5.	79.10	40.12		215.347	6	1236.324	83.28	37.47	3.38	1.21		
6.	78.69	41.34		208.326	6	1256.231	82.59	36.29	3.12	1.38		
7.	84.39	38.22		200.827	6	1247.238	78.21	36.28	3.46	1.74		
8.	86.17	37.98		204.168	6	1272.372	81.02	34.31	3.29	1.26		
9.	86.64	38.86		209.327	6	1157.317	79.93	34.28	3.04	1.19		
10.	87.32	39.21		211.242	6	1181.528	79.46	38.38	3.17	1.33		

DATASET 444

Max. Iteration = 1000; total_customer = 442; block_size = 0.1*total_customer; count >= 0.2*block_size; count2 >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	82.62	34.26		94.443	11	1597.771	92.25	71.39	8.02	1.61		
2.	82.70	33.00		85.861	11	1517.677	92.17	72.24	8.23	1.64		
3.	**80.61**	**31.64**		**79.847**	**11**	**1587.258**	**92.06**	**71.28**	**9.01**	**1.83**		
4.	81.87	34.34		101.773	11	1567.278	92.26	71.37	8.82	1.80		
5.	81.79	33.18	**109.751**	97.458	11	1568.289	93.02	73.11	8.76	1.87	6.431	**72.8 (11)** (Campos & Arroyo, 2017)
6.	82.12	32.42		98.879	11	1600.283	90.15	72.48	6.79	1.01		
7.	83.24	33.21		89.175	11	1564.336	91.22	72.65	8.64	1.56		
8.	82.67	32.15		87.430	11	1608.218	92.38	73.57	7.78	1.63		
9.	81.25	32.27		96.274	11	1567.234	91.31	71.29	7.45	1.38		
10.	80.88	32.36		94.328	11	1565.335	91.27	71.13	8.36	1.66		

DATASET 804

Max. Iteration = 1000; **total_customer** = 784; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicle	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	82.10	23.00	**871.258**	780.851	5	2876.971	77.45	52.37	5.29	1.05	26.731	**604.1 (5)** (Buhrkal et al., 2012)
2.	84.70	25.00		783.130	5	2852.667	76.58	51.88	5.16	0.98		
3.	84.50	23.20		832.829	5	2900.234	74.21	51.37	5.38	1.52		
4.	**80.34**	**24.44**		**770.043**	**5**	**2934.191**	**74.28**	**53.28**	**5.66**	**1.16**		
5.	80.20	24.27		845.241	5	2868.289	73.54	52.32	5.78	1.23		
6.	81.64	23.24		774.824	5	2850.423	74.22	48.98	5.26	1.24		
7.	80.36	24.36		789.248	5	2824.233	73.37	51.05	5.34	1.58		
8.	82.88	24.15		834.158	5	2932.108	72.29	49.93	5.66	1.15		
9.	82.28	24.26		819.217	5	2927.217	73.86	49.86	4.86	0.89		
10.	84.38	23.16		821.042	5	2934.224	74.33	50.53	5.01	1.25		

DATASET 1051

Max. Iteration = 1000; **total_customer** = 1048; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	86.00	55.00	**2620.340**	2599.038	18	1597.771	92.33	61.54	7.00	1.24	12.413	**1876.8 (17)** (Campos & Arroyo,2017)
2.	98.60	67.50		2591.595	18	1517.677	93.10	61.42	7.01	1.36		
3.	97.74	67.85		2590.737	18	1563.375	92.72	61.27	7.06	1.27		
4.	97.23	65.12		2617.473	18	1567.278	92.54	61.11	7.11	1.45		
5.	97.10	64.35		2597.427	18	1568.289	93.12	62.65	7.00	1.62		
6.	98.32	67.26		2613.156	18	1600.283	93.05	62.57	6.79	1.66		
7.	98.24	65.36		2610.501	18	1564.336	92.21	62.29	7.14	1.58		
8.	**97.26**	**66.29**		**2574.135**	**18**	**1608.218**	**92.25**	**63.32**	**6.98**	**1.78**		
9.	98.52	67.10		2587.473	18	1567.234	92.16	61.22	7.05	1.77		
10.	97.31	64.62		2597.427	18	1565.335	91.17	62.39	7.16	1.89		

DATASET 1351

Max. Iteration = 1000; **total_customer** = 1347; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicle	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	86.10	17.20	**1000.766**	994.531	7	4825.117	68.24	40.82	5.37	1.17	5.789	**656.8 (8)** (Campos & Arroyo, 2017)
2.	88.20	17.24		995.381	7	4819.243	66.17	40.23	5.11	1.18		
3.	**86.88**	**20.21**		**978.497**	**7**	**4795.841**	**67.25**	**39.86**	**5.45**	**1.08**		
4.	87.23	18.21		984.311	7	4788.368	69.18	41.10	5.32	1.16		
5.	88.77	17.20		983.251	7	4785.536	68.47	40.33	5.27	1.21		
6.	89.20	16.32		992.110	7	4785.889	68.55	39.75	5.19	1.23		
7.	88.35	16.30		983.272	7	4799.117	67.51	38.97	5.41	1.38		
8.	88.27	17.43		993.168	7	4792.281	69.17	43.14	5.33	1.45		
9.	87.58	18.66		982.166	7	4793.398	68.51	43.39	5.24	1.11		
10.	88.46	19.28		991.448	7	4794.466	68.28	42.28	5.05	1.21		

DATASET 1599

Max. Iteration = 1000; **total_customer** = 1596; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicles	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	76.00	27.00	**1493.152**	1492.410	14	6337.626	73.65	61.54	6.77	1.84	8.912	**1206.1 (13)** (Benjamin & Beasley, 2013)
2.	78.60	27.40		1486.251	14	6437.553	74.74	61.42	6.41	1.26		
3.	88.70	21.60		1487.425	14	6410.244	74.05	62.45	6.25	1.18		
4.	87.00	20.00		1474.294	14	6468.223	73.21	63.11	6.29	1.26		
5.	**89.33**	**17.20**		**1463.751**	**14**	**6397.262**	**75.18**	**60.33**	**6.10**	**1.12**		
6.	77.40	26.32		1492.210	14	6400.413	75.25	61.27	6.39	1.23		
7.	78.30	26.21		1483.141	14	6524.430	76.11	60.21	6.24	1.28		
8.	78.43	27.15		1493.005	14	6508.328	76.27	63.44	4.98	1.05		
9.	77.12	18.26		1482.674	14	6346.317	75.31	62.39	6.75	1.21		
10.	88.23	20.10		1491.472	14	6455.325	74.38	62.28	6.87	1.12		

DATASET 1932

Max. Iteration = 1000; **total_customer** = 1927; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	Average Block size (%)	Average CN size (%)	Initial travel distance (miles)	Best travel distance (miles)	Number of vehicle	Elapsed time (seconds)	Feasibility rate (%)		Acceptance rate (%)		SD	Best solution (Travel distance /no. of vehicle)
							PC step (%)	CN step (%)	PC step (%)	CN step (%)		
1.	89.27	16.13	1445.511	1401.289	16	7529.522	52.28	33.42	8.87	0.12	65.239	**1127.7 (16)** (Benjamin & Beasley, 2013)
2.	86.23	20.10		1321.034	16	7523.113	50.43	31.35	8.81	0.11		
3.	87.38	18.20		1431.004	16	7525.316	49.26	32.88	8.35	0.12		
4.	87.20	16.22		1373.512	16	7521.225	52.10	31.15	9.12	0.15		
5.	**89.87**	**16.13**		**1205.318**	**16**	**7514.285**	**50.12**	**30.46**	**9.17**	**0.23**		
6.	89.87	18.43		1411.118	16	7522.321	52.33	32.37	9.43	0.19		
7.	89.23	16.66		1313.476	16	7523.108	52.17	31.17	8.88	0.31		
8.	87.34	16.28		1374.278	16	7521.332	51.24	33.14	8.75	0.21		
9.	88.21	17.21		1291.422	16	7522.342	51.32	30.26	9.13	0.18		
10.	88.35	16.13		1299.337	16	7521.228	53.00	32.21	8.86	0.12		

DATASET 2100

Problem 2100 Iteration = 1000; **total_customer** = 2092; **block_size** = 0.1*total_customer; **count** >= 0.2*block_size; **count2** >= 0.2*CN_size)

Run	**Average Block size (%)**	**Average CN size (%)**	**Initial travel distance (miles)**	**Best travel distance (miles)**	**Number of vehicle**	**Elapsed time (seconds)**	**Feasibility rate (%)**		**Acceptance rate (%)**		**SD**	**Best solution (Travel distance /no. of vehicle)**
							PC step (%)	**CN step (%)**	**PC step (%)**	**CN step (%)**		
1.	88.17	16.23	**1596.779**	1594.883	16	7877.301	65.18	46.84	3.87	0.33	5.057	**1558.1 (16)** (Benjamin & Beasley, 2013)
2.	88.24	16.80		1593.585	16	7789.557	67.25	46.76	3.61	0.36		
3.	86.42	17.20		1588.721	16	7800.442	67.43	47.18	3.75	0.41		
4.	**86.20**	**15.85**		**1580.706**	16	**7864.975**	**67.38**	**47.21**	**3.88**	**0.75**		
5.	86.27	15.93		1584.727	16	7567.281	65.73	47.33	3.47	0.43		
6.	86.70	16.10		1587.342	16	7568.329	65.82	47.31	3.35	0.39		
7.	88.10	17.31		1593.521	16	7710.283	65.68	47.27	3.33	0.37		
8.	87.20	17.22		1596.542	16	7756.218	67.13	47.31	3.37	0.48		
9.	86.23	17.00		1594.633	16	7768.227	65.37	47.19	3.24	0.35		
10.	88.24	16.92		1595.448	16	7612.113	65.24	46.87	3.69	0.72		

APPENDIX E: RESEARCH PUBLICATIONS

This thesis contains materials from published works, as follows:

Hashim, F., Benjamin, A. M., & Abdul-Rahman, S. (2019). Estimation of Carbon Dioxide Emissions in a Waste Collection Vehicle Routing Problem. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *53*(2), 204-212.

Hashim, F., Benjamin, A. M., & Abdul-Rahman, S. (2023). An Analysis of the Utilisation of Landfill Facilities in a Waste Collection Vehicle Routing Problem. *Journal of Sustainability Science and Management. 18(4),* 87-102.