Journal of Vasyl Stefanyk Precarpathian National University
http://journals.pnu.edu.ua
Vol. 10, No. 4 (2023), 6-16

UDC 352+658
doi: 10.15330/jpnu.10.4.6-16

OPTIMIZING SEGREGATED WASTE COLLECTION ROUTES AS A DECISION-MAKING PROBLEM IN THE MUNICIPAL SOLID WASTE MANAGEMENT SYSTEM IN SMALL TOWN

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Abstract. Routing vehicles is a generic decision-making problem of strategic management in any business serving customers in distributed locations with a limited fleet including municipal solid waste collection. This paper introduces an approach tailored for optimizing waste collection routes in small towns and rural areas where dead-end streets are typical in the road network. Leveraging the Traveling Salesperson Problem (TSP), the approach employs optimal route determination taking advantage of the specific character of a road network with many dead-end streets. The service area for waste collection was aggregated, so the graph representing the map results in a relatively small data instance. This facilitated the application of the exact method, i.e. Mixed-Integer Programming using the OpenSolver tool in Excel. Conducted in collaboration with a municipal agency in southeastern Poland, this study outlines a comprehensive methodology, emphasizing the reduction of complex dead-end streets into singular nodes within the graph for effective route optimization. A comprehensive methodology is outlined alongside the solutions attained. Computational experiments focused on minimizing total travel distance during waste collection operations, demonstrating the methodology's success. Beyond efficiency gains, optimized routes hold potential for significant environmental impact reduction. The reduced travel distances result in decreased fuel consumption and emissions, aligning with sustainability goals. Developing an Excel-based decision support tool for municipal solid waste management is a significant contribution, particularly for decision-makers less familiar with Operations Research. The tool's compatibility within the spreadsheet environment streamlines waste management processes for municipal units, enhancing decision-making efficiency in optimizing waste collection routes.

Keywords: municipal solid waste management, recyclables collection, route optimization, travelling salesperson problem, sustainable transport, sustainable development, circular economy.

JEL Classification: C61, D81

1. INTRODUCTION

The upswing in economic development and quality of life has led to a significant upsurge in municipal solid waste production, necessitating enhanced Municipal Solid Waste Management (MSWM). The spectrum of municipal solid waste management encompasses urban cleaning, solid waste collection, sorting, transportation, landfilling, and disposal, and ICT and OR methods are widely adopted in MSWM (Saukenova et al., 2022; e Souza Melare et al., 2016). Among these, transportation constitutes a substantial expense and an organizational challenge, especially in areas of lesser population density. In less urbanized regions, like rural areas with scattered settlements and dead-end streets, travel times and distances escalate notably compared to equivalently waste-heavy urban areas. This underscores the importance of modern decision-support tools for efficient fleet routing which is an important part of MSWM in smaller towns as it can influence the cost efficiency of the system. For decision-makers, solving the routing problem is all the more important as, due to the separate collection of recyclables and non-segregated solid waste, each site is visited several times during the planning period for the collection of a particular type of solid waste (Sundberg et al., 1994; Gellens et al., 1995; Korcyl et al., 2019).

This article introduces a useful tool designed to optimize the routing of solid waste collection within small towns, based on the Traveling Salesperson Problem (TSP), a renowned NP-hard optimization challenge (Applegate et al., 2011; Cook et al., 2011). Mathematical models and heuristic algorithms for solving TSP are invariably the subject of research and development work. Significance on the size of data instances and the entire scientific and research world strives to find optimal solutions for the largest possible data instances. A different approach is to aggregate the data to reduce the size of the data instance and solve the TSP using well-known methods in an acceptably short time In our specific endeavor, achieving optimal routes hinged on ingeniously representing the solid waste collection zones as compact data instances. This was accomplished through a shrewd reduction of complex dead-end streets into singular nodes within the graph. This approach yielded solvable data instances employing exact methods, such as Mixed-Integer Programming (MIP) through the publicly available OpenSolver tool in Excel. Creating an Excel-based decision-support tool for municipal solid waste management marks a noteworthy contribution, given its practical usability. Furthermore, the familiar spreadsheet environment simplifies integration within waste management units.

This article delves into a research study focused on enhancing the efficiency of solid waste collection routes in small towns. The core approach involves creating an effective model of road networks and employing mixed-integer programming for the TSP. The primary objective was to minimize the total distance traveled during waste collection operations. The study conducted computational experiments within a small town located in southeastern Poland, exhibiting specific characteristics. In the present scenario, the planning of solid waste collection routes in this town relies solely on manual processes driven by the experience and expertise of the waste collection crew. This practice aligns with the prevalent approach in municipal waste management.

The article is organized as follows: Chapter two provides an in-depth understanding of the municipal waste management system. In chapter three, the mixed-integer program and the approach used for generating data instances are elaborated upon. Chapter four presents the computational experiments, and chapter five presents the results that were achieved.

2. THEORETICAL FRAMEWORK

Establishing a sustainable waste management system hinges on cohesive efforts among all waste producers, ensuring proper sorting and preparation for selective collection. Municipal waste originates from households, property owners, and selectively collected solid waste sources (Pawul et al., 2015). According to Poland's Central Statistical Office, municipal waste generation exceeded 13 million tons in 2020, a 2.9% surge from the prior year. In 2020, rural areas collected 108 kg of waste per capita, while urban areas managed 144 kg. The pivotal factor influencing segregated waste amounts lies in the collection systems orchestrated by local authorities (Główny Urząd Statystyczny, 2021).

Municipalities bear the responsibility of maintaining cleanliness, managing waste collection, and operating waste processing facilities. Their tasks encompass organizing selective waste collection, establishing collection points, and imposing fees on property owners while encouraging recycling and minimizing landfill-bound biodegradable waste (Czyżyk & Strzelczyk, 2012). Effective waste collection management stands pivotal in cost reduction and minimizing waste disposal's environmental impact. In smaller towns and rural regions, challenges escalate due to scattered settlements and intricate road networks. Thus, modern decision-support tools are crucial to optimize waste collection routes and curtail expenses. These tools empower municipalities to plan and execute waste collection more efficiently, mitigating environmental effects and optimizing resource utilization.

The need for and advantages of integrating decision support systems into strategic management processes within the realm of Municipal Solid Waste Management were extensively investigated back in the 1980s (Wilson, 1985). The overarching objective of orchestrating the long-term strategic management of solid waste is to instill efficiency, reliability, and cost-effectiveness. Naturally, across these forty years, the facets constituting these goals have evolved in response to evolving demands and regulatory mandates governing MSWM. Bing et al. (2015) conducted a comparative analysis of MSWM methodologies across diverse European Union countries. The primary aim is to discern the distinctive attributes and pivotal concerns through the lenses of waste management and reverse logistics. Furthermore, an exploration of existing literature delves into the realm of modeling municipal solid waste logistics in a broader context of strategic (network design) and tactical (collection system) decision-making. Multi-Criteria Decision Analysis (MCDA) stands out as the prevailing framework utilized in prior investigations about MSWM, because it facilitates the assessment of a multitude of often conflicting criteria by various stakeholders. This enables them to articulate their distinct preferences, establish rankings, and prioritize MSWM strategies on, for example, plant location, landfill location, or treatment strategy (Hung et al., 2006; Soltani et al., 2014; Goulart Coelho et al., 2016; Hoang et al., 2018).

The fundamental necessity to arrive at well-informed decisions through a methodological approach that safeguards against their erosion has endured throughout. An effective avenue to bolster decision-making processes involves the utilization of methodologies that adeptly address optimization quandaries through the application of operational research tools. A brief review of the application of Operations Research to decision-making problems in MSWM identifies several fundamental groups of optimization problems, the solution of which is critical to the efficiency of system operation: fleet and crew composition, districting (or zoning), waste flow aggregation, route optimization, collection patterns, and fitting in time windows (Sharma et al., 2017). Ghiani et al. (2014) provide an exhaustive examination of strategic and tactical decision-making problems within the domain of solid waste management, which have been framed as optimization problems.

Asefi et al. (2015) developed a mixed-integer programming (MIP) model for the location-routing problem in an Australian municipal solid waste management system which takes into account various solid waste categories within a comprehensive municipal solid waste framework. The central objective is to diminish the overall expenses encompassing both transportation and facility setup. An important feature of the proposed approach is the division of the network nodes into different categories, which facilitated the search for the optimal solution. Another approach to solving the medium-size problem combining determining the location and/or capacity of garbage accumulation points, and the design and schedule of collection routes for vehicles was to decompose it into sub-problems, thus obtaining solutions for Bahía Blanca, Argentina in an acceptable time (Maheo et al., 2020; Maheo et al., 2023).

A framework integrating simulation-driven decision-making and optimization techniques, to comprehensively address the complexities of integrated MSWM was developed by Antmann et al. (2013). The method uses simulation-based optimization combined with a hybrid continuous-discrete topology. This configuration adeptly captures the discrete nature of operations and transfer events, like the arrivals and departures of transfer vehicles, while also accommodating continuous decision variables. The method incorporates a multi-criteria perspective, adeptly encompassing economic and environmental objectives.

The problem of vehicle routing is often solved using heuristics, which are easy to apply and quickly return a solution that may not be optimal but is feasible and good enough to satisfy the decision-maker's needs (an example for real-world data instances based on Bilaspur, India is presented by Sarmah et al. (2019)). A comparison of the use of mathematical models and heuristic methods to solve decision-making processes in integrated solid waste management was presented by Aseffi et al. (2019) for real-world data instances based on Teheran, Iran.

Mojtahedi et al. (2021) continued the multi-criteria approach introducing multiple objective functions within the context of Corporate Sustainable Waste Management (CSWM). These functions encompass financial, environmental, and social parameters, thereby constructing a holistic model for solving a sustainable vehicle routing problem. This intricate problem setting pertains to diverse vehicle fleets navigating a multi-tiered logistics network, all while pursuing optimization objectives.

3. RESEARCH OBJECTIVE, METHODOLOGY AND DATA

This paper presents a study conducted at a municipal waste collection facility in southeastern Poland, responsible for collecting segregated waste from a small town. Situated 5 kilometers away, the facility undertakes monthly waste collection every 29 days (Zakład Komunalny, 2023a). The solid waste is sorted into plastic and metal, collected during the initial vehicle run, followed by glass, paper, and biodegradable waste on the second run. The garbage truck team comprises a driver and a vehicle loader, making route choices based on individual preferences, leading to varying monthly travel distances.

Efficiently planning waste collection and vehicle routes is crucial for cost reduction. Multiple factors influence waste transportation management, encompassing fleet type, container volume and type, collection methods, crew working hours, vehicle load capacity, collection frequency, unloading time, and distance between collection areas (Pawul et al., 2015).

The surveyed town features numerous dead-end streets and an uneven distribution of households. With around 400 homes housing approximately 1,700 residents, the area is distinctly rural. Figure 1 depicts the waste collection route from the town and the journey from the municipal facility, performed by one of four drivers in the preceding year. The entire route covered 27.40 km.

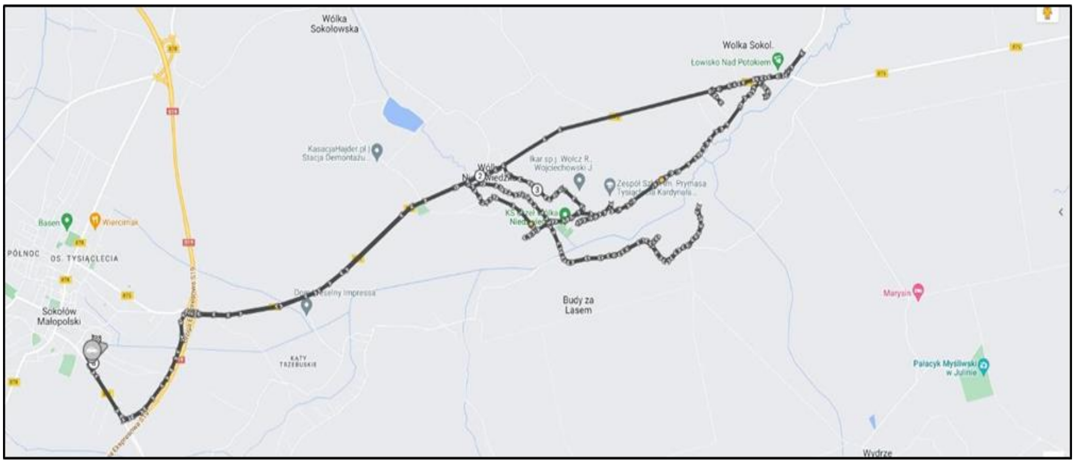

Fig. 1. Real segregated waste collection routes used in 2022

Source: Zakład Komunalny, 2023b

The municipal waste collection system in rural regions, exemplified by the surveyed area, employs a single vehicle to cover the entire route once, returning with a full load. This streamlines the waste collection route planning into finding the most cost-effective or shortest path that traverses all points. This corresponds to solving the Traveling Salesperson Problem, which seeks a Hamiltonian cycle passing through all vertices, except the initial one, just once. The Traveling Salesperson Problem is a renowned optimization challenge aiming to identify the shortest cyclic route connecting n nodes, each visited once. This problem can be illustrated as a network issue utilizing a graph, where edges signify all possible direct links between nodes (Cook et al., 2011). Each edge carries a weight signifying transportation cost or distance. One graph node symbolizes the departure and return point A for the traveling salesperson. Fig. 2 illustrates a Hamiltonian cycle A-B-C-D-E-A, with A as the starting vertex.

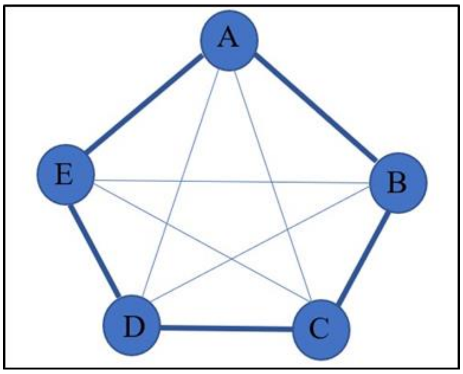

Fig. 2. Hamiltonian graph

Source: own elaboration

Addressing the optimal route problem for municipal waste collection in a network characterized by extensive dead-end streets involves framing it as an optimization problem rooted in the Traveling Salesperson Problem. Confronting this challenge, a Mixed-Integer Programming (MIP) formulation has been devised, leveraging the conventional Traveling Salesperson Problem (1)-(4). The binary decision variable aij signifies the direct travel from city i to city j by the salesperson, while parameter cij denotes the distance (or cost) between nodes i and j on the map (Jadczak, 2019).

$$Min \sum_{i=0}^{n} \sum_{i\neq j,j=0}^{n} c_{ij}\, a_{ij} \quad (1)$$
$$\sum_{i=0,i\neq j}^{n} a_{ij} = 1,\ j = 0, 1, \dots, n \quad (2)$$
$$\sum_{j=0,i\neq j}^{n} a_{ij} = 1,\ i = 0, 1, \dots, n \quad (3)$$
$$\sum_{(ij)\in S} a_{ij} \leq |S| - 1, S \in 2,3, \dots, \mathrm{n} \quad (4)$$
$$a_{ij} \in 0,1, i = 0,1, \dots, n, j = 0,1, \dots, n \quad (5)$$

The objective function (1) aims at minimizing the overall length (or cost) of the route. Constraints (2) and (3) ensure the precise visitation of each vertex; the traveling salesperson must enter and leave each node. Simultaneously, constraint (4) effectively eliminates any undesired subtours (Węgrzyn, 2014).

Searching for the optimal route, the goal is to find a sequence of nodes that effectively minimizes the cumulative lengths of roads connecting them. This is achieved while meticulously guaranteeing that each node is visited by the vehicle only once. To facilitate the application of the MIP model (1)-(5) to the Traveling Salesperson Problem, a compact data instance was needed. This, in turn, necessitated the identification of pivotal and sufficient nodes and edges to obtain the graph correctly representing the network under investigation (i.e. a road network with many dead-ended streets). Due to the presence of dead-ended streets sharing intersections, the intersections were chosen to become nodes in the graph. Intersections shared by dead-ended streets were duplicated so many times as the number of dead-ended streets incident with it. In consequence, dead-ended streets were represented by dummy edges linking the intersection with its clone or linking a pair of the intersection's duplicates. Moreover, with each edge, the time of service was attributed representing the time needed to collect solid waste along the street (i.e. the route segment between subsequent intersections). If an edge connects intersections i and j, all the waste collection locations along this street, including dead-end streets located along the sector (e.g. dead-ended streets H and J in Figure 3), so that the map gets reduced without losing any solid waste collection point, as illustrated in Figure 3.

Strategically positioned along the waste collection route are pivotal junctures, including intersections A, B, C, D, E, complemented by dead-end streets F, G, H, I, J, and K. A seamless coverage strategy incorporates dead-end streets linked to road segments, ensuring comprehensive service coverage. For instance, segment BC encompasses point L during waste collection, while segment DG encompasses points J and K. The tandem servicing of dead-end streets G and F is seamlessly executed. Notably, the route layout in Figure 3 is annotated with yellow, green, and blue lines, signifying access routes to dead-end streets F, G, and I from specific intersections D, E, and C, respectively.

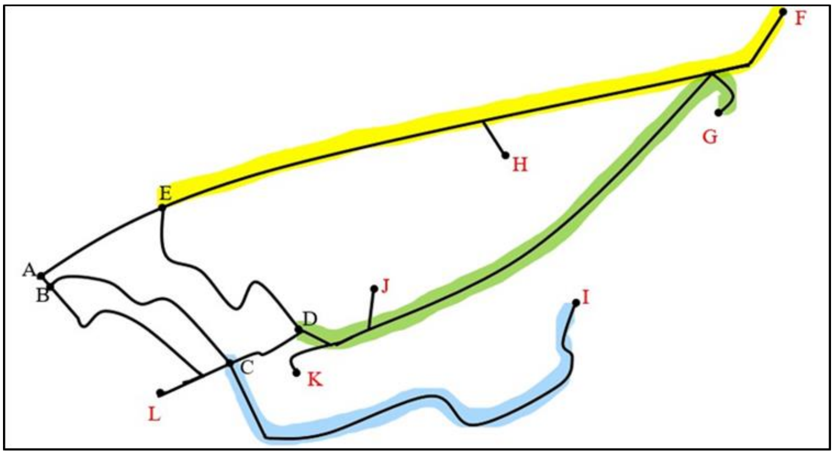

Fig. 3 A mapped scheme of the points served in a given locality

Source: own work

After meticulous route analysis and the delineation of diverse route possibilities at each intersection, the solution emerged by duplicating each intersection point, barring node C, which presented three route possibilities, encompassing dead-end street I. Hence, node C was substituted with dummy node C, effectively representing twice the length of dead-end street I. This dynamic refinement culminated in the updated route depicted in Figure 4, subsequently serving as the foundation for an Excel spreadsheet model.

The computer experiments were conducted using Open Solver in Excel on a computer equipped with a two-core processor Intel Intel Core i5-10210U CPU @ 1.60GHz with RAM 8 GB. Open Solver was selected as the preferred tool for solving the problem due to its user-friendly interface. The model created using Open Solver has a high likelihood of being utilized in practice, particularly in municipal utility companies and municipal agencies where advanced models such as AMPL or Python may not be as commonly known as Excel, which was used to create the aforementioned model. An example data instance is presented in Table 1 and Table 2.

Tab. 1

A cost matrix showing the distance [km] between each pair of nodes if an arc between them exists [km]

	A	A'	B	B'	C	C'	C''	D	D'	E	F	G	G'
A	-	-	0.11	0.11	-	-	-	-	-	-	-	0.45	0.45
A'	-	-	0.11	0.11	-	-	-	-	-	-	-	0.45	0.45
B	0.11	0.11	-	-	1.35	1.35	1.35	-	-	-	-	-	-
B'	0.11	0.11	-	-	1.06	1.06	1.06	-	-	-	-	-	-
C	-	-	1.35	1.06	-	-	-	0.4	0.4	-	-	-	-
C'	-	-	1.35	1.06	-	-	5	0.4	0.4	-	-	-	-
C''	-	-	6.35	6.06	-	5	-	0.4	0.4	-	-	-	-
D	-	-	-	-	0.4	0.4	0.4	-	-	2.75	2.96	1.1	1.1
D'	-	-	-	-	0.4	0.4	0.4	-	-	2.75	2.96	1.1	1.1
E	-	-	-	-	-	-	-	3.48	3.48	-	0.73	3.25	3.25
F	-	-	-	-	-	-	-	3.25	3.25	0.73	-	3.48	3.48
G	0.45	0.45	-	-	-	-	-	3.25	3.25	3.25	3.48	-	-
G'	0.45	0.45	-	-	-	-	-	1.1	1.1	3.25	3.48	-	-

Source: own work

Tab. 2

An incidence matrix showing the existence of an arc between each pair of nodes [-]

	A	A'	B	B'	C	C'	C''	D	D'	E	F	G	G'
A	0	0	1	0	0	0	0	0	0	0	0	0	1
A'	0	0	0	1	0	0	0	0	0	0	0	1	1
B	1	0	0	0	0	0	1	0	0	0	0	0	0
B'	0	1	0	0	1	0	0	0	0	0	0	0	0
C	0	0	0	1	0	0	0	1	1	0	0	0	0
C'	0	0	0	0	0	0	1	1	1	0	0	0	0
C''	0	0	1	0	0	1	0	0	0	0	0	0	0
D	0	0	0	0	1	1	0	0	0	1	1	1	0
D'	0	0	0	0	1	1	0	0	0	1	1	1	0
E	0	0	0	0	0	0	0	1	1	0	1	0	1
F	0	0	0	0	0	0	0	1	1	1	0	0	1
G	0	1	0	0	0	0	0	1	1	0	0	0	0
G'	1	0	0	0	0	0	0	0	0	1	1	0	0

Source: own work

To get a solution, the resolution encompassed the elimination of prevailing subtours, leading to the eradication of 7 route subsegments. The mathematical model implemented in OpenSolver computed the optimal route with a total distance of 17.4 km. Subtracting the initial and terminal 5 km distance to and from the base where the driver commences and concludes the solid waste collection, the comprehensive waste collection journey spans 27.4 km. The pinnacle of efficiency is manifested in the optimal waste collection sequence: A-B-C''-C'-D-E-A'-B'-C-D'-G-F-E'-A. The trajectory of this optimal route, meticulously computed through OpenSolver, finds its visual representation in Figure 3 and in Table 3.

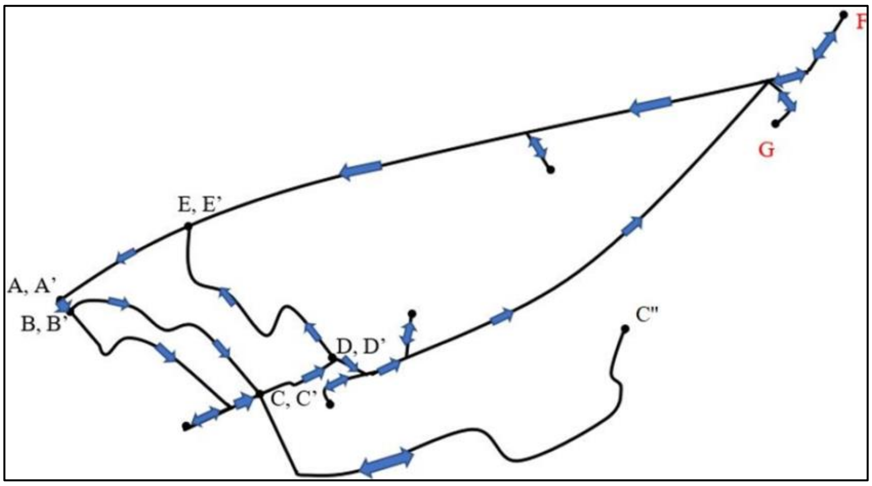

Fig. 4. Updated route scheme with final solution

Source: own work

Tab. 3

An incidence matrix showing the sequence of visiting the nodes computed as the optimal solution [-]

	A	A'	B	B'	C	C'	C''	D	D'	E	F	G	G'
A	0	0	1	0	0	0	0	0	0	0	0	0	0
A'	0	0	0	1	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	1	0	0	0	0	0	0
B'	0	0	0	0	1	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	1	0	0	0	0
C'	0	0	0	0	0	0	0	1	0	0	0	0	0
C''	0	0	0	0	0	1	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0	0	0	1	0
D'	0	0	0	0	0	0	0	0	0	1	0	0	0
E	0	0	0	0	0	0	0	0	0	0	1	0	0
F	0	0	0	0	0	0	0	0	0	0	0	0	1
G	0	1	0	0	0	0	0	0	0	0	0	0	0
G'	1	0	0	0	0	0	0	0	0	0	0	0	0

4. RESULTS AND DISCUSSION

OpenSolver solved the complex optimization problem, resulting in the identification of the shortest sequence for solid waste collection points. This optimized route deviates from the usual paths taken by the personnel of the municipal solid waste company. The implications of this optimal solution are extensive, envisioning an improved driving route not only for waste collection personnel but also for other drivers. This stands to significantly decrease both travel distance and waste collection time.

Taking into account the average fuel consumption of a waste collection vehicle, pegged at 16 liters per 100 kilometers, the incorporation of a singular optimal route across all drivers stands to yield substantial cost savings, notably in fuel expenditures. Furthermore, the ecological dimension emerges prominently, with exhaust emissions standing as a pivotal variable driven by fuel combustion. As per established research, each liter of diesel churns out around 2.6 kg of carbon dioxide (Zakład Komunalny, 2023a). Applying this metric, the determined route's aggregate emissions quantified at 11.7 kg, with a yearly aggregate of over 280.8 kg during the segregated waste collection cycle.

In the context explored within this paper, in companies operating locally in smaller towns, the solid waste collection routes are rarely subjected to the optimizing capabilities of decision support tools. Instead, driving routes tend to follow the inclinations and experienced judgments of the workers. The use of optimization tools for waste management challenges remained largely unexplored within the company under study. Therefore, the newly crafted spreadsheet serves as a useful solution, ready to guide solid waste management entities toward more efficient operations tailored to their specific requirements. Furthermore, this conceptual framework holds the potential to provide benefits not only for solid waste collectors but also for office personnel.

The key advantage driving the development of the route optimization tool lies in its seamless integration with Excel. This presents a significant opportunity for practical implementation, as the familiarity of the spreadsheet environment aligns well with the existing workforce. Nevertheless, the primary drawback of the model is the time-consuming nature of the data preparation phase, notably the process of eliminating subtours.

5. CONCLUSION

The development of a spreadsheet tailored to address the Traveling Salesperson Problem, coupled with its subsequent optimization utilizing OpenSolver, has yielded a reduction in the distance of the route taken for segregated solid waste collection within the specific road network under examination. This modeling approach, wielded to tackle such challenges, demonstrates its effectiveness and carries the promise of adaptability for more intricate route configurations through the inclusion of supplementary constraints. The optimization of solid waste collection routes assumes paramount significance in the context of environmental stewardship.

Central to this endeavor is the European Union's European Green Deal (EGD), a strategic initiative particularly focused on rural domains and encompassing a range of measures aimed at curbing emissions within these landscapes. Notably, optimizing waste collection routes emerges as a pivotal instrument aligning with the aspirations of the EGD. By curtailing the distances traveled, a substantial reduction in emissions becomes feasible. Once deployed, the refined route optimization tool could serve as a linchpin in systematically managing expansive rural territories, thereby fostering coherent and systematic servicing strategies.

The optimization of waste collection routes engenders an array of benefits. It bolsters the efficiency and economic viability of waste collection, transportation, and sanitation processes. The meticulous choreography of activities through strategic planning and harmonization leads to cost savings while curbing environmentally detrimental emissions. Moreover, optimized waste collection underscores the judicious utilization of finite resources, enhancing the overall quality of life for residents.

REFERENCES

[1] Applegate, D.L., Bixby, R. E., Chvátal, V., & Cook, W. J. (2011). The Traveling Salesman Problem. Princeton University Press.

[2] Antmann, E. D., Shi, X., Celik, N., & Dai, Y. (2013). Continuous-discrete simulation-based decision making framework for solid waste management and recycling programs. *Computers & Industrial Engineering, 65(3)*, 438-454. https://doi.org/10.1016/j.cie.2013.03.010

[3] Asefi, H., Lim, S., Maghrebi, M., & Shahparvari, S. (2019). Mathematical modelling and heuristic approaches to the location-routing problem of a cost-effective integrated solid waste management. *Annals of Operations Research, 273*, 75-110. https://doi.org/10.1007/s10479-018-2912-1

[4] Bing, X., Bloemhof, J. M., Ramos, T. R. P., Barbosa-Povoa, A. P., Wong, C. Y., & van der Vorst, J. G. (2016). Research challenges in municipal solid waste logistics management. *Waste Management, 48*, 584-592. https://doi.org/10.1016/j.wasman.2015.11.025

[5] Cook, W. J., Applegate, D. L., Bixby, R. E., & Chvatal, V. (2011). The traveling salesman problem: a computational study. Princeton university press.

[6] Czyżyk, F., & Strzelczyk, M. (2012). System i zasady gospodarowania odpadami komunalnymi w gminie, w świetle nowych regulacji prawnych. ITP, Wrocław, 5-36.

[7] Gellens, V., Boelens, J., & Verstraete, W. (1995). Source separation, selective collection and in reactor digestion of biowaste. *Antonie van Leeuwenhoek, 67*, 79-89. https://doi.org/10.1007/bf00872196

[8] Ghiani, G., Laganà, D., Manni, E., Musmanno, R., & Vigo, D. (2014). Operations research in solid waste management: A survey of strategic and tactical issues. *Computers & Operations Research, 44*, 22-32. https://doi.org/10.1016/j.cor.2013.10.006

[9] Główny Urząd Statystyczny, (2021). Ochrona środowiska. Analizy statystyczne. Warszawa, 155-190.

[10] Goulart Coelho, L. M., Lange, L. C., & Coelho, H. M. (2017). Multi-criteria decision making to support waste management: A critical review of current practices and methods. *Waste Management & Research, 35(1)*, 3-28. https://doi.org/10.1177/0734242x16664024

[11] Hoang, G. M., Fujiwara, T., Pham Phu, T. S., & Nguyen, L. D. (2019). Sustainable solid waste management system using multi-objective decision-making model: a method for maximizing social acceptance in Hoi An city, Vietnam. *Environmental Science and Pollution Research, 26*, 34137-34147. https://doi.org/10.1007/s11356-018-3498-5

[12] Hung, M. L., Ma, H. W., & Yang, W. F. (2007). A novel sustainable decision making model for municipal solid waste management. *Waste Management, 27(2)*, 209-219. https://doi.org/10.1016/j.wasman.2006.01.008
[13] Jadczak, R. (2019). Układanie tras pojazdu w łańcuchu dostaw. Wydawnictwo Uniwersytetu Łódzkiego, Łódź, 52-59.
[14] Korcyl, A., Książek, R., & Gdowska, K. (2019). A MILP model for the municipal solid waste selective collection routing problem. Decision Making in Manufacturing and Services, 13(1-2), 17-35. https://doi.org/10.7494/dmms.2019.13.1-2.3470
[15] Mahéo, A., Rossit, D. G., & Kilby, P. (2020, December). A Benders decomposition approach for an integrated bin allocation and vehicle routing problem in municipal waste management. In International Conference of Production Research–Americas 3-18. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-76310-7_1
[16] Mahéo, A., Rossit, D. G., & Kilby, P. (2023). Solving the integrated bin allocation and collection routing problem for municipal solid waste: a Benders decomposition approach. *Annals of Operations Research, 322(1)*, 441-465. https://doi.org/10.1007/s10479-022-04918-7
[17] Mojtahedi, M., Fathollahi-Fard, A. M., Tavakkoli-Moghaddam, R., & Newton, S. (2021). Sustainable vehicle routing problem for coordinated solid waste management. *Journal of Industrial Information Integration, 23*, 100220. https://doi.org/10.1016/j.jii.2021.100220
[18] Pawul, M., Kwiecień, J., & Śliwka, M. (2015). Wybrane zagadnienia optymalizacji transportu odpadów komunalnych. *Logistyka, 4*, s. 9585-9589. http://surl.li/nlstv
[19] Sarmah, S. P., Yadav, R., & Rathore, P. (2019). Development of Vehicle Routing model in urban Solid Waste Management system under periodic variation: *A case study. IFAC-PapersOnLine, 52(13)*, 1961-1965. https://doi.org/10.1016/j.ifacol.2019.11.490
[20] Saukenova, I., Oliskevych, M., Taranic, I., Toktamyssova, A., Aliakbarkyzy, D., & Pelo, R. (2022). Optimization of schedules for early garbage collection and disposal in the megapolis. Eastern-European *Journal of Enterprise Technologies, 1(3*), 115. https://doi.org/10.15587/1729-4061.2022.251082
[21] Sharma, N., Gupta, N., Ahuja, M., Jain, M., & Shah, M. (2017). Study of operations research in waste management. International *Journal of New Technology and Research, 3(10*), 263226. http://surl.li/nlsum
[22] Soltani, A., Hewage, K., Reza, B., & Sadiq, R. (2015). Multiple stakeholders in multi-criteria decision-making in the context of municipal solid waste management: a review. *Waste Management, 35*, 318-328. https://doi.org/10.1016/j.wasman.2014.09.010
[23] de Souza Melaré, A. V., González, S. M., Faceli, K., & Casadei, V. (2017). Technologies and decision support systems to aid solid-waste management: a systematic review. *Waste Management, 59*, 567-584. https://doi.org/10.1016/j.wasman.2016.10.045
[24] Sundberg, J., Gipperth, P., & Wene, C. O. (1994). A systems approach to municipal solid waste management: A pilot study of Göteborg. *Waste Management & Research, 12(1)*, 73-91. https://doi.org/10.1016/s0734-242x(94)90022-1
[25] Węgrzyn J. (2014). Gospodarka materiałowa i logistyka. Polskie Wydawnictwo Ekonomiczne, Warszawa, 11-12.
[26] Wilson, D. C. (1985). Long-term planning for solid waste management. *Waste Management & Research, 3(3)*, 203-216. https://doi.org/10.1016/0734-242x(85)90111-9
[27] Zakład Komunalny sp. z o.o. Official website. Timetables: www.sokolow-mlp.pl (accessed February 10, 2023)
[28] Zakład Komunalny sp. z o.o. – unpublished in-house data (accessed February 10, 2023)

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Received: August 30, 2023; **revised:** October 11, 2023; **accepted:** November 22, 2023; **published:** December 31, 2023

Домініка Ілаш, Ізабела Абрамчик, Катажина Гдовська. Оптимізація маршрутів роздільного збору відходів як проблема прийняття рішень у системі поводження з твердими побутовими відходами в малому місті. *Журнал Прикарпатського університету імені Василя Стефаника*, **10** (4) (2023), 6-16.

Маршрутизація транспортних засобів є типовою проблемою прийняття рішень у стратегічному управлінні будь-якою компанією, яка обслуговує клієнтів у розрізнених місцях з обмеженим автопарком, у тому числі в галузі збору твердих побутових відходів. У цій статті представлено підхід, спеціально розроблений для оптимізації маршрутів збору відходів у невеликих містах та сільській місцевості, де тупикові вулиці є типовою частиною дорожньої мережі. Використовуючи задачу комівояжера (ЗК), підхід полягає у визначенні оптимального маршруту з урахуванням особливостей дорожньої мережі з великою кількістю тупикових вулиць. Зона обслуговування інкасації була агрегована, тому граф, що представляє мережу, є відносно невеликим екземпляром даних. Це полегшило застосування точного методу, тобто змішаного цілочисельного програмування з використанням інструменту OpenSolver в Excel. Це дослідження, проведене у співпраці з муніципалітетом на південному сході Польщі, пропонує комплексний метод, спрямований на скорочення складних тупиків до окремих вузлів на графі для ефективної оптимізації маршрутів. Протокол дослідження описаний разом з отриманими рішеннями. Обчислювальні експерименти, спрямовані на мінімізацію загальної відстані, пройденої під час інкасаторських операцій, продемонстрували успішність розробленого методу. На додаток до підвищення ефективності, оптимізовані маршрути можуть значно зменшити вплив на навколишнє середовище. Зменшення відстані перевезень призводить до зниження споживання пального та викидів, що відповідає цілям сталого розвитку. Розробка інструменту підтримки прийняття рішень для управління твердими побутовими відходами на основі Excel є значним внеском, особливо для осіб, які приймають рішення, менш знайомих з дослідженнями операцій. Сумісність інструменту з електронними таблицями спрощує процеси управління відходами для муніципалітетів, підвищуючи ефективність прийняття рішень щодо оптимізації маршрутів збору відходів.

Ключові слова: управління твердими побутовими відходами, збір вторинної сировини, оптимізація маршрутів, проблема комівояжера, сталий транспорт, сталий розвиток, циркулярна економіка.