Systemy Logistyczne Wojsk
Zeszyt 58 (2023)
ISSN 1508-5430, s. 197-218
DOI: 10.37055/slw/176021

Instytut Logistyki
Wydział Bezpieczeństwa, Logistyki i Zarządzania
Wojskowa Akademia Techniczna
w Warszawie

Military Logistics Systems
Volume 58 (2023)
ISSN 1508-5430, pp. 197-218
DOI: 10.37055/slw/176021

Institute of Logistics
Faculty of Security, Logistics and Management
Military University of Technology
in Warsaw

Optimizing Municipal Waste Collection: a Case Study of a City in Poland

Optymalizacja zbiórki odpadów komunalnych: studium przypadku miasta w Polsce

Monika Roman
monika_roman@sggw.edu.pl; ORCID: 0000-0003-1799-0445
Department of Logistics, Warsaw University of Life Sciences, Poland

Michał Waśkiewicz
michal.waskiewicz.sggw@gmail.com; ORCID: 0009-0008-7629-8946
Faculty of Economics, Warsaw University of Life Sciences, Poland

Abstract. The main problem of waste management is the increasing amount of municipal waste, and one of the key processes generating high costs is the waste collection process. The aim of the article was to optimize the route of a garbage truck using information technology (IT) software in one of the most populated Polish cities. The article tests the study hypothesis: the use of route optimization software will reduce the route length traveled by the garbage truck of the MZO in Pruszków. The data for the study was made available with the consent of the Municipal Treatment Plant in Pruszków. The received materials included information on, among others, Global Positioning System (GPS) readings of the garbage truck, including route start and end times, route length, average speed, driving time, and time of stops, points selected by the planners to collect waste along the route, information on the amount of waste collected during the implementation of the route, technical data on the moving vehicle and characteristics of the sorting plant were received. The article proposes the optimization of the routes of collection and transportation of municipal waste using the traveling salesman problem (TSP). The minimization of route length was assumed as the optimization criterion. All calculations were made in the Routimo program dedicated to route planning and optimization. As a result of the optimization, the route length was reduced by nearly 32%, and the working time by 9%. Thus, the research hypothesis stated in the article was positively verified.
Keywords: waste collection, municipal waste, route optimization, traveling salesman problem, transportation

Abstrakt. Głównym problemem gospodarki odpadami jest rosnąca ilość odpadów komunalnych, a jednym z kluczowych procesów generujących wysokie koszty jest proces zbierania odpadów. Celem artykułu była

optymalizacja trasy przejazdu śmieciarki z wykorzystaniem oprogramowania informatycznego w jednym z najbardziej zaludnionych miast Polski. W artykule weryfikowano hipotezę badawczą: zastosowanie oprogramowania optymalizującego trasę skróci długość trasy pokonywanej przez śmieciarkę MZO w Pruszkowie. Dane do badań zostały udostępnione za zgodą Miejskiego Zakładu Oczyszczania w Pruszkowie. Otrzymane materiały zawierały informacje m.in. o odczytach Global Positioning System (GPS) śmieciarki, w tym o czasie rozpoczęcia i zakończenia trasy, długości trasy, średniej prędkości, czasie jazdy i czasie postojów, zbiór wybranych przez planistów punktów odbioru odpadów na trasie, informację o ilości odpadów zebranych w trakcie realizacji trasy, dane techniczne poruszającego się pojazdu oraz charakterystykę sortowni. W artykule zaproponowano optymalizację trasy odbioru i transportu odpadów komunalnych z wykorzystaniem problemu komiwojażera (TSP). Jako kryterium optymalizacji przyjęto minimalizację długości trasy. Wszystkie obliczenia wykonano w programie Routimo przeznaczonym do planowania i optymalizacji tras. W wyniku optymalizacji długość trasy uległa skróceniu o blisko 32%, a czas pracy o 9%. Tym samym zweryfikowano pozytywnie postawioną w artykule hipotezę badawczą.
Słowa kluczowe: zbiórka odpadów, odpady komunalne, optymalizacja tras, problem komiwojażera, transport

Introduction

The main problem of waste management is the increasing amount of municipal waste. Approximately 2.01 billion tons of municipal solid waste (MSW) are generated annually worldwide, and this number is expected to increase by 70% in about 30 years. The United States tops the list of countries with the highest daily amount of MSW per capita (2.58 kg), followed by Canada (2.33 kg/per capita) and Australia (2.23 kg/per capita). In the global comparison, Poland ranks 11th in the world in terms of MSW generated, with each Pole generating about 1 kg of MSW per day (STATISTA, 2023). Municipal waste management requires coordination of multiple processes that include generation, segregation, storage, collection, transportation, processing and recovery, and disposal (Rada et al., 2013; Bui et al., 2023; Kanh et al., 2023, Munir et al., 2023). The smooth flow of these processes is the responsibility of municipalities, which aim to create a cost-effective integrated municipal waste management system (Weng and Fujiwara, 2011). And one of the key processes generating high costs is the waste collection process, which can generate up to 70% of the total system costs (Boskovic et al., 2016; Jędrczak, 2021). These costs are high due to the high labor intensity and the very large number of vehicles used in the collection and transportation process (Amponsah,Salhi, 2004). Giulio Greco et al. (2015) analyzed the factors that determine the costs of solid waste collection. Based on Italian municipalities, the authors' findings show that the economies of scale and cost drivers vary by waste type. The cost drivers significantly affecting different types of waste include population size and density, percentage of separate collection, percentage of home collection and private deliveries. They are factors that directly affect the costs of waste transportation. Therefore, municipal authorities should strive to reduce these costs. Therefore, the research problem was to answer the following question: What are the benefits of information technology (IT) in planning waste collection routes?

The aim of the article was to optimize the route of a garbage truck using information technology software in one of the most populated Polish cities. As part of the main objective, the following specific objectives were analyzed: recognition of the current route planning method, identification of problems in the collection of municipal waste, and determination of the importance of using programs that optimize route planning. The research object was the MZO in Pruszków and the research was carried out in 2022. The article presents the following study hypothesis: The use of the route optimization software will reduce the route length traveled by the garbage truck of the MZO in Pruszków. This article mainly focuses on the collection, transfer and transportation of municipal waste from all sources of waste generation to the processing plant. To this end, a comparison was made between the length and time of the actual waste collection route completed and the route optimized using IT software. The article proposes the optimiziation of the route of collection and transportation of municipal waste using the traveling salesman problem (TSP). In the proposed route, an optimized municipal waste management system was designed and the minimization of the length of transportation routes was assumed as a criterion. All calculations were made in the Routimo program dedicated to route planning and optimization. The further part of the article describes the literature study, material and methods of the study. Then the results of the study are described with a breakdown into the current state of the route, the characteristics of the components and the optimized route. The next section includes a discussion, and the article concludes with a summary.

Literature study

The issues of waste collection route optimization are described in the literature both in the purely theoretical context and the functionality of the problem itself. Functionality is understood in this case as its application, support of specific optimization software, as well as work on real examples, where the authors present the applied study methodology along with the results and conclusions of the optimization performed. The increasing volume of waste and the seasonality of its generation means that municipal vehicles fill up faster, and thus they have to go to the base for unloading and return again for uncollected waste, which generates extra, empty journeys. Therefore, route optimization helps the company to make better use of its vehicle fleet and minimizes the risk of additional journeys.

An attempt to optimize routes in the city of Kampala was conducted by Joel Robert Kinobe et al. (2015). In the capital and at the same time the largest city of Uganda, the waste collection system was determined as ineffectively implemented, which gave grounds for its optimization. The minimization of waste collection route length was assumed as the optimization criterion. A Geographic Information

System (GIS) tool was used in the study. A GPS technology was used to collect landfill and route data. After optimization, the distance on all routes decreased by 19%, and collection time by 17%. The task of optimizing routes was also undertaken by Amirhossein Malakahmad et al. (2014), who optimized waste collection routes in the city of Ipoh. The authors optimized the distance and travel time for five selected routes. The total distance on all routes was reduced by 18%. In turn, Ömer Apaydin and Mustafa Talha Gonullu (2007) performed an optimization in Turkish Trabzon. It was decided to record the waste collection and transportation process with a video camera to analyze it. The minimization of route lengths was again the optimization criterion. The shortest path model was used, and Route View Pro™ software integrated with GIS elements was used as the optimization tool. As a result of the study, the optimization process reduced distances by 25% and collection and transportation times by 44%. Similar results from another Turkish city were obtained by Louati Amal et al. (2018). Attempts to optimize travel routes were also made by the authors in Poland. The optimization of routes for the collection of a specific group of waste, which is the used electrical and electronic equipment, in the city of Ruda Śląska, was undertaken by Bogna Mrówczyńska and Piotr Nowakowski (2015). Another example of route optimization is a study by Michał Jakubiak and Paweł Hanczar (2016), who optimized two routes in Kraków. Using route length minimization as a criterion, they reduced route 1 by about 24%, and route 2 by about 15%. Some researchers also optimized the costs of municipal waste collection. For example, Nguyen-Trong Khanh et al. (2017) presented a case study on the city of Hagiang in Vietnam that resulted in an 11% reduction in MSW collection costs. In turn, Gianpaolo Ghiani et al. (2021) considered the collection phase and analyzed the possibility of implementing intermediate solid waste transfer stations. This involves transferring solid waste from small collection vehicles to larger long-distance transport vehicles. The use of transfer stations as well as trams in waste collection was also written about by Miroslav Zilka et al. (2021) on the example of Prague in the Czech Republic.

In addition to many case studies, there was also a theoretical approach to the optimization of waste collection routes. Paweł Hanczar and Katarzyna Michniewska (2006) point out the need to coordinate activities in the flow of selectively collected waste, as it is necessary before planning the optimal route. They put emphasis on the location of waste segregation containers. They further demonstrate the impact and usefulness of a computerized system in the processes of selective waste collection, as well as measurable benefits that could be provided by using this system. A comparison of the impact of the optimization methods used on the waste collection process was made, among others, by Alhassan Sulemna et al. (2018). The topics of mathematical programming and GIS were particularly exhaustively discussed. Debishree Khan and Sukha Ranjan Samadder (2014), on the other hand, reviewed the literature of municipal solid waste management (selection of a suitable landfill, route optimization and public acceptance) using GIS in conjunction with other tools. A literature review was also conducted by Hui Han and Eva Ponce-Cueto (2015), who divided waste collection into residential, commercial and industrial. The article presents the main findings for each of the distinguished types of waste collection, and analyzes the various methods and techniques used to address the issues of determining waste collection routes. Despite numerous studies, it should be noted that the issue of waste collection is current and some problems have still not been solved. Analyzing this problem using various IT tools in specific kinds of waste seems particularly important. Therefore, this study fills the research gap in analyzing municipal waste collection using a route planning and optimization program.

Material and methods

The study object was selected in a purposive manner. The population density and the city's development potential were used as the selection criterion. Pruszków is a city located in the Mazowieckie Voivodeship, in the Pruszków Poviat, which is part of the Warsaw agglomeration. The Pruszków Poviat is the most densely populated poviat in Poland. In 2021, 21,777.86 mega grams (Mg)of municipal waste was collected from residential real estate in the city of Pruszków. This is as much as 383 kg per capita, where the average in Poland is 358 kg/capita. The neighborhood of the capital influences the gradual increase in the number of Pruszków residents, which consequently influences the increase in the number of waste. It should be added that the area of the city is a difficult and expensive area for waste collection operations. This is due to the fact that the city is characterized by a high proportion of multi-family housing, which consequently means that most of the waste is mixed waste, which requires more expensive processing.

The data for the study was made available with the consent of the Municipal Treatment Plant in Pruszków by specialists from the transportation and environmental departments. The received materials included information on, among others, GPS readings of the garbage truck, including: route start and end times, route length, average speed, driving time, time of stops, apart from GPS data to be used in the optimization procedure, a set of points selected by the planners to collect waste along the route, information on the amount of waste collected during the implementation of the route, technical data on the moving vehicle and characteristics of the sorting plant were received.

The article proposes a scheme for optimizing the routes of collection and transportation of municipal waste using the traveling salesman problem. According to the definition, a traveling salesman must visit once and only once each of the waste collection points, starting from the base (waste storage area) and returning to the base. The task is for the traveling salesman to find the shortest possible route that visits each point exactly once (Dumitrescu et al. 2016, Renaud et al. 2002). This problem can be presented in a mathematical form, it takes the form of the following assumptions (Jadczak, 2019, pp. 73-74):

Data:

n – number of points serviced in the base area;

K – number of available vehicles;

c_{ij} – cost of transportation between point i and j, as well as between the i-th point of service and the bases;

[x-k-ij] – decision variable that takes the value 0 if vehicle k has a connection i and j on its route, or 1 if there is no such connection, whereas i ≠ j;

z_i, z_j– real variables, whereas i ≠ j.

Decision variables:

Number of decision variables is equal to the product of: *(n + 1)(n + 1)k*.

$$x_{ij}^k = \begin{cases} 0 \\ 1 \end{cases} \text{ for } i, j = 0, 1, \ldots, n \text{ and } k = 1, \ldots, K \quad (1)$$

Bounds:

– each service point is uniquely assigned to the route of one vehicle

$$\sum_{i=0}^{n} \sum_{k=1}^{K} x_{ij}^k = 1 \text{ for } j = 0, 1, \ldots, n \quad (2)$$

– each service point (and base) will be visited

$$\sum_{i=0}^{n} x_{ip}^k - \sum_{j=0}^{n} x_{pj}^k = 0 \text{ for } p = 0, 1, \ldots, n \text{ and } k = 1, \ldots, K \quad (3)$$

– vehicle starts and ends the course at the base

$$\sum_{j=1}^{n} x_{0j}^k \leq 1 \text{ for } k = 1, \ldots, K \quad (4)$$

– possibility of routes being the shortened cycles is eliminated

$$z_i - z_j + (n+1) \sum_{k=1}^{K} x_{ij}^k \leq (n+1) - 1 \text{ for } i, j = 1, \ldots, n \text{ and } i \neq j \quad (5)$$

Objective function:

$$\min . F(x) = \sum_{i=0}^{n} \sum_{j=0}^{n} \sum_{k=1}^{K} c_{ij} x_{ij}^k \quad (6)$$

All calculations were made in Routimo, a software developed by Softline Polska, which enables planning and optimizing routes.

Results

Current route status

The route subjected to the optimization procedure assumed collection of municipal waste from companies and is a cyclical route, taking place every week on Friday. The route assumed the collection of waste from 68 collection points located in the city of Pruszków, and the total number of containers along the route was 82 of various sizes. The garbage truck brigade started work at 6:00 a.m. and, after a short briefing and receiving guidelines from the transportation department, started driving. The collection points along the route do not change, and the same brigade, with the same driver always completes the same route. The driver of a municipal vehicle is free to choose the collection route, the order of visiting all points is determined by himself, using his knowledge of the topography of the city. The tablet on which the waste collection points are marked does not have the function of displaying the optimal route, so the driver, at his discretion, chooses the best route according to him, the route he takes does not change significantly depending on the week. The route sent by the planners to the brigade's tablet with the 68 municipal waste collection points listed is presented in Table A in the appendix.

Although the route assumes the collection of municipal waste from companies, no time windows have been found (in the context of the availability of points) or the need to visit individual points as a priority. The only limitation was the working hours of garbage truck operators as defined by the Labor Code. On the analyzed day, the brigade left the company's headquarters at 6:26 a.m. and returned to the base at 11:30 a.m., determining a total working time of 304 minutes. During the brigade's working day, there was no need to return to the base to empty the garbage truck's body, unloading took place at the end of the shift at 11:30 a.m. The municipal vehicle almost always takes this route without unloading at the sorting plant. The garbage truck traveled 33 km that day, and the driving time, i.e. the period in which the wheels of the vehicle were in motion, was 98 minutes. This means that the average driving speed was rounded to 20 km/h, taking into account the average speed of the vehicle in terms of total working time, this value can be rounded to 6.5 km/h. The time of stops, loading of waste, service time at the base and other circumstances conditioning the stopping of the vehicle wheels amounted to 206 minutes on that day. The break from work due to the brigade was not taken into account, because the workers went on a break after returning to the base at 11:30 a.m. Because of the length and timing of the route, the brigade, after finishing the route, went to assist other brigades, ultimately finishing the job at 2:31 p.m. and driving 37 more kilometers. The value of the time of stops enables the determination of the average collection time of waste from the point. Assuming that the time of unloading waste at the base is 5 minutes, the equation for determining the average time of waste collection at the point can be presented using the following formula:

$$\text{Average waste collection time} = \\ = \frac{(Time\,of\ stop - service\,time\,at\,the\,base)}{number\,of\ collection\ points\,on\,the\,route} = \tag{7}$$

$$\frac{(206-5)}{68} = 2.95588 \approx 3\,min$$

All the most important route data on the analyzed day by brigade are summarized in Table 1.

Table 1. Selected variables for the route

Route length	Total route time	Average speed	Driving time	Average service time at the sorting plant	Average collection time at the point	Time windows
33 km	304 min	20 km/h	98 min	5 min	3 min	6:00-14:00

Source: Based on materials provided by the MZO.

Characteristics of the components

The first element that needs to be characterized is the base, i.e. the building of the waste sorting plant. The sorting plant is designed for the segregation of non-segregated waste and waste from selective collection. It was put into operation in 2005. Thanks to the modern infrastructure for waste processing, as well as well-equipped mechanical and biological units, this place can boast of being one of the newest sorting plants in Poland, which is why it received the status of the Regional Municipal Waste Treatment Plant (RIPOK). This unit hires about 100 workers who, depending on the unit of the plant, work 5 days a week in a two- or three-shift system. The capacity of the mechanical unit for mixed waste is 60,000 [Mg/year], 26,000 [Mg/year] in the biological unit and 15,000 [Mg/year] in the mechanical unit for selectively collected waste. By 2024, it is planned to almost double the capacity of the mechanical unit for selectively collected waste. Assuming that the waste sorting plant operates on average for 250 days a year, the daily capacity of this plant can be estimated at 240 [Mg/day]. The article assumes that this is where the vehicle starts and ends its route, and if it is full, the garbage truck comes to unload here. Before leaving the waste at the sorting plant, the vehicle is weighed to check the weight of the collected waste on a given day. Unloading is done by lifting the body and, including weighing, takes an average of 5 minutes. The left waste left is then distributed by the excavator-bulldozers for further processing inside the sorting plant building.

The municipal vehicle moving along the optimized route is a SCANIA P320 truck tractor. The garbage truck is intended for urban driving and performs well in medium traffic conditions. The vehicle performs best on good-quality asphalt roads and flat terrain. This truck tractor uses a P-series cab, which works well for transportation tasks that require a lot of stops. It is a day cab with a lowered roof that increases the load capacity of the vehicle. The vehicle was characterized by a single-chamber body with rear loading. The body is operated by a hydraulic system and additional levers to ensure the operation of the device in case of system failure. In addition, the garbage truck is equipped with a device for disinfecting and washing containers. The washing takes place in a closed system, i.e. all dirty water is pumped out to a separate tank. The estimated cost of driving 1 km on the discussed route is PLN 47.76 net, (fuel costs, but also, among other things: salary costs, or administrative costs). The exact proportions and how the ratio is calculated is a company secret. In connection with waste collection, an important component is the issue of garbage truck capacity, which is 18 m^3. On the analyzed day, the garbage truck came to the base at 11:30 a.m. with 4.36 tons of waste. The weighing of the vehicle takes place each time the garbage truck arrives at the base, it is the only moment when the amount of waste entering the MZO in Pruszków is registered. Due to the lack of volumetric measurement of the amount of waste collected from the route, in the article it was decided to adopt the conversion rate of 1 m^3 of mixed municipal waste being equal to 250 kg of this waste fraction. This result indicates that the garbage truck arrived at the MZO shortly before it was completely full, so it did not exceed the permissible capacity of the vehicle.

Table 2 shows a summary of all containers on the route and their capacity. The data on their number enabled the calculation of the maximum potential volume of waste stored in them, which amounted to 64.09 m^3. The main type of container used by companies for waste collection was SM-1100. Companies used it in 61% of cases, it is also the largest container in terms of volume.

Table 2. Detailed list of containers on the route along with their capacity

Type of container	Capacity of one container [in m³]	Number of containers on the route	Average filling of containers on the route [in m³]
BAG 120	0.12	1	0.032
SM-120	0.12	8	0.032
MGB-120	0.12	1	0.032
MGB-240(W)	0.24	1	0.065
MGB-240	0.24	8	0.065
SM-240	0.24	7	0.065
SM-360	0.36	1	0.098
MGB-360	0.36	2	0.098
SM-770	0.77	1	0.209
SM-1100	1.1	50	0.299
SM-1100(W)	1.1	2	0.299

Source: Based on materials provided by the MZO.

Due to the impossibility of estimating in detail what amount of waste was in each container during collection, in the study it was assumed that each container was filled to the same level in proportion to its volume. This percentage was calculated by substituting individual data into the following formula:

Average filling of containers on the route =

$$= \frac{Volume\ of\ waste\ collected\ on\ the\ route}{Maximum\ capacity\ of\ containers\ on\ the\ route} = \tag{8}$$

$$\frac{17.44\,m^3}{64.09\,m^3} \times 100\% = 27.21173..\ \% \approx 27.21\ \%$$

According to the calculations, the containers on the route were filled in 27.21% on average. Table 2 shows the average filling of each type of container.

Optimized route

Due to the nature of the optimization, the data held and the functions of Routimo, it was necessary to impose the bounds mentioned in the methodological part. The objective function minimizes the distance of the route with the accepted bounds, related to the collection points, the base and the vehicle. It was decided to use time windows 6:00 a.m.-2:00 p.m. It was the route length that was used as an optimization criterion. It was decided to choose the option with an average visit time at the point lasting 3 minutes.

The starting, ending and unloading points were the base, i.e. the sorting plant. In order to increase the accuracy of the locations of generated points, the pins with individual collection points have been moved to places where the brigade actually stops to collect. In some cases, these points were garbage sheds or containers, the location of which slightly differed from the location of the client. All mixed municipal waste collection points have been marked on the map (Figure 1).

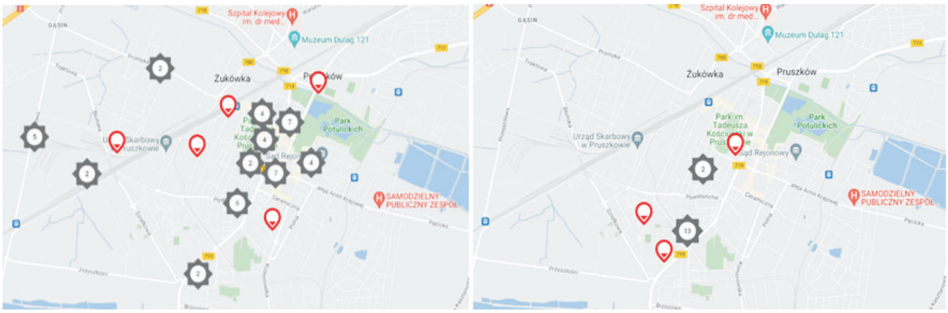

Fig. 1. Distribution of waste collection points
Source: Based on materials provided by the MZO

Performing all of the above actions allowed the route to be generated. The Routimo software proposed a route of 22.54 km, assuming the collection of waste from all 68 companies, without any necessary unloading during the route. The planned route is presented in Figure 2, the numbers in red circles indicate the total number of points in a given area. The location of the base has been additionally marked with a green circle.

Fig. 2. Generated optimal route
Source: Based on materials provided by the MZO

A summary with the order of visiting each point was developed and presented in Table 3. To clearly present the order, a column was added with an ordinal number corresponding to the respective ordinal numbers of the collection points in Table A (Appendix).

Table 3. List of municipal waste collection points by order of visiting

Order	No.	Distance increment	Weight of shipment	Weight of cargo
1	BASE	0.00		0
2	36.	1.27	16,300	0
3	35.	1.33	16,300	16,300
4	34.	1.54	149,600	32,600
5	33.	1.62	32,600	182,200
6	32.	1.67	74,800	214,800
7	41.	4.07	24,500	289,600
8	7.	5.08	74,800	314,100
9	6.	5.22	16,300	388,900
10	5.	5.27	74,800	405,200
11	4.	5.87	74,800	480,000
12	12.	6.17	8200	554,800

cd. tab. 3

13	23.	6.59	74,800	563,000
14	14.	6.90	74,800	637,800
15	13.	7.05	8200	712,600
16	47.	7.44	74,800	720,800
17	1.	7.89	8200	795,600
18	28.	8.52	74,800	803,800
19	46.	9.67	149,600	878,600
20	44.	10.17	8200	1,028,200
21	48.	10.38	8200	1,036,400
22	49.	10.38	8200	1,044,600
23	20.	10.67	74,800	1,052,800
24	19.	10.72	74,800	1,127,600
25	37.	10.87	74,800	1,202,400
26	40.	11.04	74,800	1,277,200
27	8.	11.15	149,600	1,352,000
28	22.	11.38	149,600	1,501,600
29	51.	11.68	224,400	1,651,200
30	21.	11.75	48,900	1,875,600
31	16.	12.34	163,00	1,924,500
32	15.	12.35	74,800	1,940,800
33	17.	12.52	16,300	2,015,600
34	18.	12.57	149,600	2,031,900
35	39.	12.86	74,800	2,181,500
36	38.	12.86	8200	2,256,300
37	11.	13.24	74,800	2,264,500
38	10.	13.39	74,800	2339,300
39	29.	13.78	16,300	2,414,100
40	50.	13.96	74,800	2,430,400
41	30.	14.60	74,800	2,505,200
42	43.	15.06	8200	2,580,000
43	52.	15.59	74800	2,588,200
44	24.	15.97	74,800	2,663,000
45	25.	16.04	74,800	2,737,800
46	53.	16.31	74,800	2,812,600
47	54.	16.46	8200	2,887,400

cd. tab. 3

48	58.	16.75	74,800	2,895,600
49	57.	16.81	16,300	2,970,400
50	56.	16.93	149,600	2,986,700
51	55.	16.93	224,400	3,136,300
52	59.	17.19	16,300	3,360,700
53	60.	17.19	16,300	3,377,000
54	62.	17.20	74,800	3,393,300
55	61.	17.21	16,300	3,468,100
56	45.	17.23	74,800	3,484,400
57	64.	17.23	74,800	3,559,200
58	67.	17.24	74,800	3,634,000
59	65.	17.28	16,300	3,708,800
60	66.	17.28	52,400	3,725,100
61	63.	17.32	8200	3,777,500
62	31.	17.83	149,600	3,785,700
63	68.	18.06	24,500	3,935,300
64	9.	18.59	74,800	3,9598,00
65	42.	19.87	74,800	4,034,600
66	27.	20.95	24,500	4,109,400
67	26.	20.95	74,800	4,133,900
68	2.	22.41	74,800	4,208,700
69	3.	22.41	74,800	4,283,500
70	BASE	22.54		4,358,300
Sum		22.54		4,358,300

Source: Own research

Routimo set the beginning of the working day at 6:00 a.m. and the end at 10:26 a.m., giving priority to the start time. The total driving time according to the software is 58 minutes, which gives a total speed on the route of 23.36 km/h. The working time on that day was 4 hours 26 minutes. The system speed of the route covered is close to the real speed of the garbage truck, which is 20 km/h. Due to the need to start the work of the brigade at 6:26 a.m. (it was assumed that the departure from the MZO will take place as on the analyzed day), it was decided to perform own calculations related to the route completion time. This decision was also influenced by the desire to achieve greater accuracy in the calculations. The formulas for the individual parameters related to working time are presented below:

$$\text{Garbage truck driving time} = \frac{Route\,length}{Average\,vehicle\,speed} = \frac{22,54\,km}{20\,km/h} = 1\,hour\,7\,\text{min}\,37\,s \approx 1\,hour\,8\,min \tag{9}$$

$$\begin{gathered}\text{Total working time} = Garbage\,truck\,driving\,time + \\ + Number\,of\,\,points\,on\,the\,route \times Average\,waste\,collection\,time + \\ + Service\,time\,at\,the\,base = 1\,hour\,8\,\text{min} + 68 \times 3\,\text{min} + 5\,min = \\ = 4\,hours\,37\,min\end{gathered} \tag{10}$$

Therefore, assuming that the vehicle leaves the MZO at 6:26 a.m., it will finish the course at 11:03 a.m., i.e. 27 minutes faster than on the comparable date, when the vehicle finished the route at 11:30 a.m. According to the following formula, the brigade's working time was reduced by 8.9%:

Turning to the optimization criterion – the route length – the value has decreased significantly. Compared to the data from the analyzed day, the route length was shortened by 10.46 km (from 33 km to 22.54 km). Given the relatively short route, this result should be considered positive. The formula below shows that the route length has been reduced by 31.7%. The maximum use of the vehicle's load capacity, which on the generated route amounted to as much as 96%. The performed optimization gave very good results, and the generated route should be considered optimal (Table 3).

Table 4. Comparison of the route before and after optimization

Parameter	Before optimization	After optimization	Effect
Route length	33 km	22.54 km	- 31.7%
Truck driving time	304 min	277 min	- 8.9%

Source: Own research

In addition to the effects indicated above, the optimization also brought environmental benefits, such as the reduction of greenhouse gases emitted during the transportation of waste. Another advantage may be the reduction of noise in the city, or the reduction of congestion on the roads of Pruszków, created by a municipal vehicle stopping to collect waste on the way of other vehicles moving. An important aspect for the company is the reduction of fuel costs, such a significant shortening of the route will significantly contribute to reducing fuel expenses. The second saving is the cost of manpower, which results from shortening the working time of the brigade by 27 minutes. As far as costs are concerned, it is also important to use the ratio provided by the MZO for the cost of a garbage truck traveling 1 km on the analyzed route. The cost of driving on the old route was PLN 1,576.08, while after optimization it was PLN 1,076.51.

Discussion

The obtained route optimization results are in line with the assumptions. Moreover, they are similar to other studies (Apaydin,Gonullu, 2007; Jakubiak, Hanczar, 2016). For example, Swapan Das and Bidyut Kr. Bhattacharyya (2015) showed that the proposed waste collection optimization system in the city of Kalkota is able to reduce the total length of paths by more than 30%. In turn, Hailin Wu et al. (2020) proved that the proposed new waste collection model can reduce waste collection costs by about 40%. The obtained research results should be considered as filling the research gap in terms of the methodology used and the actual case study. On the other hand, they also contribute to further research on introducing additional improvements to IT programs, e.g. related to adding variables related to the road situation and traffic history.

It should be noted that there are numerous problems arising from waste collection: high costs, the degree of use of vehicles, the degree of fullness of containers, negative environmental effects. Thus, it is important to notice the directions of development in waste collection: the use of optimization software, smart containers, improved segregation or ecological vehicles. If different optimization software and methods are used, then a detailed review of the studies was carried out by Alhassan Suleman et al. (2018). In turn, smart containers, using sensors, transmit information about their filling in real time to IT systems located at the entity responsible for waste collection in a given location. In Zamość, for example, a decision was made to set up 20 waste collection points, each of which consisted of five containers for waste: mixed, plastic and metal, paper, glass and bio-waste. Real estate managers provided their residents with special stickers with QR codes, which residents placed on bags with waste. When a one-time QR code was brought close to the reader, the lid of the container opened and waste could be thrown inside. This solution was to prevent situations in which people from outside the housing estate throw garbage into smart containers, as well as to control whether the segregation process is proceeding correctly. The use of QR codes eliminated anonymity among residents of the housing estate, each tenant became responsible for what he or she threw away, and improperly sorted waste risked receiving a fine. A mobile application has been made available to residents, thanks to which they can track the level of segregation and the weight of individual waste fractions produced in their households. The connection of all containers with IT systems made it possible to control their filling in real time, as well as the possibility of getting acquainted with the forecasts of waste accumulation in individual containers (T-MASTER 2023). Smart waste management using sensors is discussed, among others, by Olga Rybnytska et al. (2018) or Andre Lundin Castro et al. (2017). Another important solution significantly reducing the negative environmental effects are garbage trucks powered by green fuel. Dariusz Piernikarki (2021) described an example of the use of electric garbage trucks. However, it is important to keep in mind the challenges and constraints related to the development of infrastructure for vehicles powered by other green fuels, such as hydrogen (Greene et al., 2020).

Conclusions

The article confronts the problem of municipal waste collection and transportation, which arises when planning an effective waste management system in a city. In particular, we investigated the problem of waste collection, where the points are dispersed in a heterogeneous manner and the filling of the containers is only known at the collection stage. For this purpose, at the beginning, the waste collection route was described in accordance with GPS readings, then the components important for planning the route were described. Then, the municipal waste collection route was optimized using the traveling salesman problem and the Routimo software. All the objectives set in the article were achieved. Furthermore, the study hypothesis that the use of IT software allowed to reduce the route length and the time of waste collection was confirmed. The route length was reduced by nearly 32%,

However, it is important to mention the constraints of the study carried out. The waste collection was optimized for one region (one route). In order to obtain more accurate effects of the application of the IT software, studies should be carried out for all waste collection points in Pruszków. Nevertheless, only the best effects of optimizing the costs of waste collection would be achieved when the company would use IT software, but also smart containers. Such an algorithm for optimizing routes with simultaneous monitoring of the filling of containers on the example of a city was described in their study, for example, by Myroslav Oliskevych and Victor Danchuk (2023). In that case, one would expect even greater cost reductions, but on the other hand, it would require more frequent route changes for drivers. In view of the above, the issue of waste route optimization is still relevant, and future studies could deal precisely with the analysis of routes taking into account smart containers, or comparing the cost of waste collection using garbage trucks powered by different fuels.

BIBLIOGRAPHY

[1] Amal, L., Son, L.H., Chabchoub, H., 2018. SGA: spatial GIS-based genetic algorithm for route optimization of municipal solid waste collection. Environ Sci Pollut Res 25, 27569–27582. https://doi.org/10.1007/s11356-018-2826-0.

[2] Amponsah, S.K, Salhi, S., 2004. The investigation of a class of capacitated arc routing problems: the collection of garbage in developing countries. Waste Management, 24(7) 711-721. https://doi.org/10.1016/j.wasman.2004.01.008.

[3] Apaydin, O., Gonullu, M.T., 2007. Route Optimization for Solid Waste Collection: Trabzon (Turkey) Case Study. Global NEST Journal, 9 (1), 6-11.

[4] Boskovic, G., Jovicic, N., Jovanovic, S., Simovic, V., 2016. Calculating the costs of waste collection: A methodological proposal. Waste Management & Research, 34(8):775-783. 10.1177/0734242X16654980.

[5] Bui, T-D., Tseng, J-W., Tseng, M-L., Wu, K-J., Lim, M.K. 2023. Municipal solid waste management technological barriers: A hierarchical structure approach in Taiwan. Resources, Conservation and Recycling, 190, 106842. https://doi.org/10.1016/j.resconrec.2022.106842.

[6] Das, S., Bhattacharyya B. Kr., 2015. Optimization of municipal solid waste collection and transportation routes. Waste Management. 43, 9-18. https://doi.org/10.1016/j.wasman.2015.06.033.

[7] Dumitrescu, A., Toth, C.D., 2016. The Traveling Salesman Problem for Lines, Balls, and Planes. ACM Transactions on Algorithms, 12, 325, 1–29. https://doi.org/10.1145/2850418.

[8] Ghiani, G., Manni, A., Manni, E., Moretto, V., 2021. Optimizing a waste collection system with solid waste transfer stations. Computers & Industrial Engineering, 161, 107618, https://doi.org/10.1016/j.cie.2021.107618.

[9] Greco, G., Allegrini, M., Lungo, C.D., Savellini, P.G., Gabellini, L. 2015. Drivers of solid waste collection costs. Empirical evidence from Italy. Journal of Cleaner Production, 106, 364-371. https://doi.org/10.1016/j.jclepro.2014.07.011.

[10] Greene, D.L., Ogden, J.M., Lin, Z., 2020. Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. eTransportation. 6, 100086, https://doi.org/10.1016/j.etran.2020.100086.

[11] Han, H., Ponce-Cueto, E., 2015. Waste Collection Vehicle Routing Problem: Literature Review. Promet, 27, 4, 345-358.

[12] Hanczar, P., Michniewska, K., 2006. Modelowanie sieci selektywnej zbiórki odpadów w aglomeracji miejskiej. Logistyka, 6, 34-36.

[13] Jakubiak, M., Hanczar, P., 2016. Optymalizacja tras zbiórki odpadów komunalnych na przykładzie MPO Kraków. Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu, nr 446, 83-92.

[14] Jędrczak, A. (Eds.). 2021. Analiza kosztów gospodarki odpadami komunalnymi. Warsaw: Instytut Ochrony Środowiska – Państwowy Instytut Badawczy.

[15] Kanh, Y. O. Kang, Yabar, H., Mizunoya, T., Higano, Y., 2023. Environmental and economic performances of municipal solid waste management strategies based on LCA method: A case study of Kinshasa. Heliyon, 9 (3). https://doi.org/10.1016/j.heliyon.2023.e14372.

[16] Kinobe, J.R., Bosona, T., Gebresenbet. G., Niwagaba, C.B., Vinnerås, B., 2015. Optimization of waste collection and disposal in Kampala city. Habitat International, 49, 126-137.

[17] Khan, D., Samadder, S.R., 2014. Municipal solid waste management using Geographical Information System aided methods: A mini review. Waste Management & Research, 32(11),1049-1062. doi:10.1177/0734242X14554644.

[18] Khanh, N-T., Anh, N-T-N., Doanh, N-N., Van, D-T-H., 2017. Optimization of municipal solid waste transportation by integrating GIS analysis, equation-based, and agent-based model. Waste Management, 59, 14 – 22. 10.1016/j.wasman.2016.10.048.

[19] Castro, A. L., Özkil, A. G., Schuldt-Jensen, J., 2017. Smart cities: A case study in waste monitoring and management. In Proceedings of the 50th Hawaii International Conference on System Sciences (HICSS 2017). (pp. 1392-1401) https://doi.org/10.24251/HICSS.2017.167.

[20] Malakahmad, A., Bakri, P.M., Mokhtar, M.R.M., Khalil, N., 2014. Solid waste collection routes optimization via GIS techniques in Ipoh City, Malaysia. Procedia Engineering, 77, 20–27.

[21] Mrówczyńska, B., Nowakowski, P., 2015. Optymalizacja tras przejazdu przy zbiórce zużytego sprzętu elektrycznego i elektronicznego dla zadanych lokalizacji punktów zbiórki. Logistyka, 2, 593-604.

[22] Munir, M.T., Li, B., Naqvi, M., 2023. Revolutionizing municipal solid waste management (MSWM) with machine learning as a clean resource: Opportunities, challenges and solutions.

[23] Oliskevych, M., Danchuk, V., 2023. An Algorithm for Garbage Truck Routing in Cities with a Fixation on Container Filling Level. Transport Problems: an International Scientific Journal, 18 (1), 75-87.

[24] Piernikarski, D., 2021. [online] Electric garbage trucks enter the streets. Available at: https://samochody-specjalne.pl/2021/02/26/elektryczne-smieciarki-wjezdzaja-na-ulice/ [Accessed: 30 June 2023].

[25] Rada, E.C., Ragazzi, M., Fedrizzi, P. 2013. Web-GIS oriented systems viability for municipal solid waste selective collection optimization in developed and transient economies. Waste Management. 33(4), 785-792. https://doi.org/10.1016/j.wasman.2013.01.002.

[26] Renaud, J., Boctor, F.F., Laporte, G. 2002. Perturbation heuristics for the pickup and delivery traveling salesman problem. Computers & Operations Research, 29 (9), 1129-1141. https://doi.org/10.1016/S0305-0548(00)00109-X.

[27] Rybnytska, O., Burstein, F., Rybin, A.V., Zaslavsky, A. 2018. Decision support for optimizing waste management, Journal of Decision Systems, 27:1, 68-78. 10.1080/12460125.2018.1464312

[28] STATISTA. 2023. [online] Generation of municipal waste worldwide as of 2021, by select country. Available at: https://www.statista.com/statistics/916749/global-generation-of-municipal-solid-waste-by-country/ [Accessed: 15 June 2023].

[29] Sulemana, A., Donkor, E.A., Forkuo, E.K., Oduro-Kwarteng, S., 2018. Optimal Routing of Solid Waste Collection Trucks: A Review of Methods. Journal of Engineering. 2018, 4586376, 1-12. https://doi.org/10.1155/2018/4586376

[30] T-MASTER. 2023. [online] O systemie. Available at: https://t-master.pl/produkty-t-master#inteligentnepojemniki. [Accessed: 30 June 2023].

[31] Weng, Y-Chi., Fujiwara, T., 2011. Examining the effectiveness of municipal solid waste management systems: An integrated cost–benefit analysis perspective with a financial cost modeling in Taiwan. Waste Management, 31 (6), 1393-1406. https://doi.org/10.1016/j.wasman.2011.01.016.

[32] Wu, H., Tao, F., Yang, B., 2020. Optimization of Vehicle Routing for Waste Collection and Transportation. Int J Environ Res Public Health. 9:17(14):4963. 10.3390/ijerph17144963.

[33] Zilka, M., Stieberova, B., Scholz, P., 2021. Sustainability evaluation of the use of cargo-trams for mixed municipal waste transport in Prague. Waste Management, 126, 97-105. https://doi.org/10.1016/j.wasman.2021.02.053.

APPENDIX

Table A. Characteristics of municipal waste collection points

No. waste collection point	Container type	Number of containers
1	BAG 120	1
2	SM-1100	1
3	SM-1100	1
4	SM-1100	1
5	SM-1100	1
6	SM-240	1
7	SM-1100	1
8	SM-1100	2
9	SM-1100	1
10	SM-1100	1
11	SM-1100	1
12	SM-120	1
13	MGB-120	1
14	SM-1100	1
15	SM-1100	1
16	SM-240	1
17	SM-240	1
18	SM-1100	2
19	SM-1100	1
20	SM-1100	1
21	SM-240	3
22	SM-1100	2
23	SM-1100	1
24	SM-1100	1
25	SM-1100	1
26	SM-1100	1
27	MGB-360	1
28	SM-1100	1
29	MGB-240	1
30	SM-1100	1
31	SM-1100(W)	2
32	SM-1100	1
33	MGB-240	2

cd. tab. A

34	SM-1100	2
35	MGB-240	1
36	MGB-240(W)	1
37	SM-1100	1
38	SM-120	1
39	SM-1100	1
40	SM-1100	1
41	SM-360	1
42	SM-1100	1
43	SM-120	1
44	SM-120	1
45	SM-1100	1
46	SM-1100	2
47	SM-1100	1
48	SM-120	1
49	SM-120	1
50	SM-1100	1
51	SM-1100	3
52	SM-1100	1
53	SM-1100	1
54	SM-120	1
55	SM-1100	3
56	SM-1100	2
57	MGB-240	1
58	SM-1100	1
59	SM-240	1
60	MGB-240	1
61	MGB-240	1
62	SM-1100	1
63	SM-120	1
64	SM-1100	1
65	MGB-240	1
66	SM-770	1
67	SM-1100	1
68	MGB-360	1

Source: Based on materials provided by the MZO