JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(8), 307–317
https://doi.org/10.12911/22998993/204215
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.04.02
Accepted: 2025.05.26
Published: 2025.06.10

Impact of selected logistic factors on the efficiency of municipal waste collection with use the advanced statistical tools

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ABSTRACT

This article presents the results of research over 12 months on municipal waste export, assessing the load capacity of the export fleet and taking into account the impact of selected logistic factors on the efficiency of waste transport. The service range covered an area with a population of over 100,000 inhabitants. The highest average net weight of collected waste of 8.72 Mg with a standard deviation of 3.60 Mg was characteristic of a vehicle with the highest capacity in the study. The analysis of deviations from the maximum payload was also significant, showing over 20% underutilisation of the vehicles' payload. A full correlation was present between the net weight and filling of separated waste. The developed a new model is considered an essential tool in designing and controlling waste disposal, which, through its adjustment, is determined by the filling variable through the variable net mass. Based on the analysis, the selection of vehicles with a specific capacity should take into account optimising municipal waste transport parameters using tools for intelligent waste logistics management.

Keywords: municipal waste, efficiency, municipal waste disposal, logistics, multiple regression.

INTRODUCTION

Increasing the efficiency of municipal solid waste (MSW) export is a component of sustainable development. In this context, Chioatto et al. (2023) analysed solid waste management methods in four European Union countries within 75 NUTS-2 regions (Italy, France, Germany and the Netherlands). The regional research allowed the authors to propose comprehensive regulatory actions to transition from traditional waste management to sustainable waste management. The results showed that regions in Germany and the Netherlands have moved away from landfilling towards higher recycling rates (Chioatto et al., 2023; Azevedo et al., 2021). The literature review showed that in developed countries the main emphasis of waste management falls on the organized system of municipal waste management (Ciechelska et al., 2022). The operation of these systems is regulated by legislation at international, national and local levels (Hassan et al., 2022). The European Union (EU) Waste Framework Directive (2008) established a 'waste hierarchy' that places strategies in descending order of priority: prevention, reuse, recycling, recovery and landfilling (Wang et al., 2022). To navigate these waste management strategies, we need support for waste management and recycling activities through the development of waste segregation (Niska and Serkkola, 2019).

Among the 17 Sustainable Development Goals (SDGs) adopted in 2015 by 193 United Nations countries are those aimed at reducing poverty, protecting the environment and ensuring the general well-being of all people in the world. These goals set out a shared vision for the future and an action plan for governments, industry, non-governmental organisations, and citizens to improve the quality of life (Ministerstwo Rozwoju, 2017). This quality is influenced in particular by measures to reduce municipal waste's negative environmental impact, transport and treatment (Peng et al., 2023; Pawnuk et al., 2023; Tauš et al., 2023; Nowakowski and Wala, 2023).

In accordance with the applicable EU and national regulations, efforts should be made to reduce the amount of waste generated and, thus, increase the level of recycling (Smol et al., 2020). To achieve these goals, selective collection is required at the municipal level, which includes the collection of a certain fraction of recyclable waste, such as paper, metal, glass, plastics, multi-material packaging and biodegradable municipal waste (Przydatek, 2016; Przydatek et al., 2017).

Municipal waste management and its effectiveness have been increasingly addressed by many authors in science and economic practice (Hogg, 2017). For instance, Ciechelska et al. (2022) showed that municipal waste management in Poland corresponds to a polycentric system. Ulfik and Nowak (2014) showed improvements in waste management in the light of changes in Polish legislation.

The literature on the subject contains many inspiring comparative analyses, which is the difference in waste management systems among cities (municipalities) and countries (Przydatek, 2023; Chioatto et al., 2023; Panainte-Lehadus et al., 2022; Urbańska et al., 2023; Nieves and Ramos GC, 2023). Contemporary researchers devote relatively much attention to the issue of municipal waste in the context of the circular economy (Lelicińska-Serafin et al., 2022; Marciniuk-Kluska and Kluska, 2023). The situation of Polish municipalities in this respect was described by Kotlińska and Żukowska (2023) and Kolak and Maj-Zajezierska (2023).

The effectiveness of municipal waste management in Poland compared to other EU countries was presented by Poniatowska et al. (2022). The authors compared the methods and installations used for waste processing in Poland and Europe, i.e. recycling, composting, thermal transformation and waste disposal. According to Smol et al. (2020), in Poland, despite the gradual reduction in the amount of waste sent to landfill sites and the increase in the amount of waste recovered and recycled, intensifying activities within the circular economy (CE) is advised. Cheng et al. (2019) considered one advantage of CE to be its ability to break the link between environmental sensitivity and economic poverty. According to Saeed et al. (2024), the impact of rapid industrialisation and massive waste generation worsens the global climate situation. An important element of waste management is monitoring the amount of waste (Brunner and Helmut, 2015), which provides evidence that forms the basis for decision-making and improvement actions, such as the waste transfer card (Starkowski and Bardziński, 2017).

Asefi et al. (2019) discussed the need to develop an effective logistics system for the transport of MSW. In this context, increasing efficiency and optimising waste collection routes become essential (Dixit et al., 2019; Del Carmen-Niño et al., 2023). The vehicle routing problem (VRP) involves many decision-making elements, including those related to transport, distribution and outsourcing. The main tasks of the VRP include searching for and planning the optimal route on the map from the starting point to the destination. For example, GIS-based transport systems are being created to provide the easiest, fastest and shortest route to reach a junction.

Some authors (Oliskevych and Danchuk, 2023; Villanueva, 2020) proposed a pragmatic approach to improving the efficiency of a waste management system using big data, heuristics and open-source VRP solutions for waste collection in Stockholm. For optimisation purposes, various route planning algorithms are used in practice, e.g. Dijkstra's shortest path algorithm (Sahu et al., 2023). The literature also includes publications on decision-making models useful in the processes of organising municipal waste collection, factors influencing the amount of this waste (Jonek-Kowalska, 2022), and the inter-municipal cooperation in the field of waste management (Kołsut, 2016).

Routing models for capacity vehicles for solid waste collection and route optimisation using the PSO (particle swarm optimisation) algorithm are also described in the literature (Hannan et al., 2018). Similarly, Sasikumar et al. (2020) proposed the use of the analytic hierarchy process (AHP) for the evaluation of solid waste collection and transportation. Models for designing service networks for the multimodal transport of municipal waste were also suggested for some enterprises providing municipal services (Inghels et al., 2016).

For waste management processes, including planning waste collection routes, intelligent municipal waste management systems based on deep learning and the Internet of Things (IoT) are being increasingly recommended (Wang et al., 2021; Erçin et al., 2021; Martikkala et al., 2023). Unconventional solutions have also been proposed, including the use of archival aerial photos and images obtained using unmanned aerial vehicles (UAVs) to reconstruct changes in the annual load on landfill sites. For instance, a case study of a suburban landfill using UAV tools was described by Hajdukiewicz (2022).

In addition, many available analyses address the problem of optimising municipal waste transport parameters in the context of environmental protection (Malinowski and Wozniak, 2011). Algorithms for waste collection routes in cities are being developed, taking into account the level of container filling. For instance, Oliskevychi and Danchuk (2023) proposed, as part of optimisation, applying vehicle carrying capacity limits and searching for the shortest routes for means of transport.

This article aims to assess the impact of selected logistical factors on the efficiency of the export of collected municipal waste and the load capacity of the export fleet, along with developing an example model for a selected waste removal company serving an area inhabited by over 100 000 inhabitants.

MATERIALS AND METHODS

This work used four variables – the vehicle performing the removal task, code for the municipal waste collected, the net weight of waste collected and vehicle fill level – based on data for January–December 2022. These weight data were recorded based on the readings of an on-road scale (with an accuracy of 0.2 Mg) using licensed software. The study included ten vehicles used for waste collection over two shifts for the work week from Monday to Friday (sometimes Saturdays). In general, the number of data for individual vehicles ranged from 202 to 733, which resulted from two vehicles being replaced with newer ones with larger capacities in August 2022 (during the year, eight vehicles were on the route every day). These data involved the disposal of municipal waste carried out by a selected economic entity in southwestern Poland (Lower Silesian Voivodeship). This work takes into account the net weight of collected waste divided into five types based on the following codes (Regulation, 2020): 15 01 01 – paper and cardboard packaging; 15 01 02 – plastic packaging; 15 01 06 – mixed packaging waste; 15 01 07 – glass packaging; 20 03 01 – mixed municipal waste.

The basic statistics used in this analysis included minimum, maximum, sum and average

Figure 1. Localisation the lower Silesian voivodeship (red) in southwestern Poland (Middle – East Europe)

values, as well as the standard deviation of the transported waste. In addition, we determined the average vehicle fill level. Pearson's *r* linear correlation coefficient (net mass of waste and vehicle filling) was calculated based on a normal distribution, and linear regression models were determined (occupancy as a function of net mass). In these studies, the significance level was set at $p < 0.05$. We employed Statistica 12 program (StatSoft Poland, StatSoft, Inc., USA) for statistical analysis.

Logistics and waste transportation

The waste collection area of study included about 100 000 inhabitants in the Lower Silesian Voivodeship (Middle – East Europe) (Figure 1).

The waste collection system included 16 routes, which are served during the week by eight vehicles over two shifts. The export fleet consisted of vehicles with capacities of 7–8 m^3 (4 vehicles) and 21 m^3 (6 vehicles). Waste was collected selectively (codes 15 01 01, 15 01 02, 15 01 06 and 15 01 07) and non-selectively (code 20 03 01) from about 22 000 plastic in bins and containers with a capacity of 120, 240 and 1 100 dm^3, respectively. The vehicles were equipped with GPSs (global positioning systems) to monitor the location and routes of waste transport vehicles.

Ten vehicles with a capacity of 7–21 m^3 collected municipal waste from bins at low-rise buildings (dispersed) and from containers at high-rise buildings. The collected waste in a selective and non-selective form was weighed by the analysed carrier and then transported to the waste management plant. At this stage, various waste was recovered to recycle raw and other materials (e.g. organic waste). The leftover waste from the recovery process was sent to the landfill site per the final waste management hierarchy shown in Figure 2 (Pires and Martinho, 2019).

RESULTS

Master data analysis

The largest share in the rolling stock, 60%, were vehicles with a capacity of 21 m^3, while the remaining vehicles accounted for 40% (7 m^3 – 20%, 8 m^3 – 20%) with an average weight capacity of 15.6 Mg. Table 1 lists the maximum

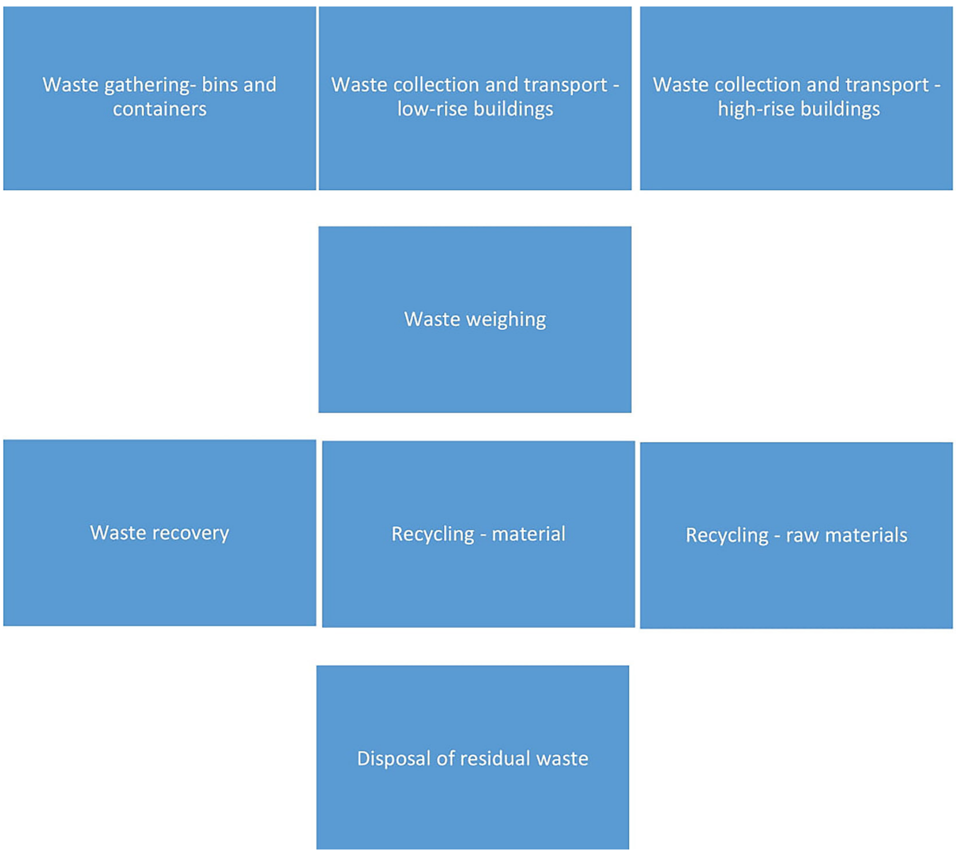

Figure 2. Hierarchy of logistics processes in a waste disposal company

Table 1. Maximum collected waste per transport depending on type

Vehicle no.	Trailer capacity [m^3]	15 01 01 Paper [Mg]	15 01 02 Plastic [Mg]	15 01 06 Packaging [Mg]	15 01 07 Glass [Mg]	20 03 01 Mixed [Mg]	Dates of collection
1	21	3.5	3.5	4	11	11	1 Jan 2022 to 31 Dec 2022
2	21	3.5	3.5	4	11	11	
3	21	2.5	2.5	3.5	5	9	
4	21	3.5	3.5	4	11	11	
5	21	3.5	3.5	4	11	11	
6	21	2.5	2.5	3.5	5	8	
7	7	2	2	2.5	2.5	2.5	
8	7	2	2	2.5	2.5	2.5	
9	8	2	2	3	3.5	3.5	26 Aug 2022 to 31 Dec 2022
10	8	2	2	3	3.5	3.5	
Max	21	3.5	3.5	4	11	11	1 Jan 2022 to 31 Dec 2022
Min	7	2	2	2.5	2.5	2.5	
Average	15.6	2.7	2.7	3.4	6.6	7.3	

mass of each waste type collected by each vehicle per transport. The largest mass of selective waste collected and transported was for code 15 01 07 (glass), which was recorded in Vehicles 1, 2, 4 and 5. The most non-selectively collected waste was coded as 20 03 01 (mixed waste), collected by these same vehicles, and characterised by the highest average mass of 7.3 Mg. Differently, the lowest mass of waste among the maximum collected was 2 Mg for 15 01 01 (paper) and 15 01 02 (plastic). Similarly, the lowest average was 2.7 Mg for these types. Waste was generally collected on five working days (Monday to Friday and on Saturdays if there was a holiday during the week) over two shifts operated by eight vehicles. On 26 August 2022, Vehicles 7 and 8 were replaced with Vehicles 9 and 10 (with greater capacity).

STATISTICS OF RESULTS

Table 2 shows the statistics for the net mass of collected waste. The largest total net mass of 6 368.10 Mg was collected by Vehicle 3, while the smallest net mass of 383.2 Mg was collected by Vehicle 9. The maximum collected net mass of 16.10 Mg occurred in Vehicle 3, and the minimum was 0 Mg in Vehicle 2. Vehicle 6 exhibited the highest standard deviation of collected waste mass, 0.36 Mg, while the lowest standard deviation was 0.24 Mg in Vehicle 3. The lowest net mass standard deviation of 0.74 Mg was recorded by Vehicle 1, and the highest value of 3.60 Mg was for Vehicle 4. Vehicle 8 had the highest level of waste (95.39%), while Vehicle 9 had the lowest level (57.12%), with an average of 77% for all vehicles.

Table 2. Basic statistics of the net weight of collected waste, where SD is the standard deviation

Vehicle	Descriptive statistics					Average vehicle occupancy level [%]
	Nimportant	Sum [Mg]	Min [Mg]	Max [Mg]	SD [Mg]	
1	241	418.310	0.08	4.14	0.74	69.61
2	328	509.44	0	3.52	0.82	62.72
3	730	6 368.10	1.4	16.10	2.70	79.69
4	428	3 718.16	0.62	15.26	3.60	92.13
5	483	2 742.16	0.36	14.56	2.77	93.12
6	557	1 281.43	0.18	9.52	1.11	76.98
7	483	2 742.16	0.36	14.56	2.77	82.14
8	674	3 992.95	0.56	14.92	3.37	95.39
9	202	383.2	0.14	4.3	0.99	57.12
10	233	499.8	0.14	8.4	0.91	62

Figure 3 displays the average net weight per transport to the landfill. The highest average net weight of 8.72 Mg was found for Vehicle 3, and the lowest at 1.55 Mg for Vehicle 2.

Correlation analysis of the net weight of waste and the degree of vehicle filling

Analysing the data according to the waste code in relation to two variables – net weight and fill level – shows that most types of waste are characterised by very high correlation coefficients of 0.91–1. Full correlation corresponds to waste codes 15 01 02 and 15 01 07 concerning these two variables, as shown in Table 3. Waste code 20 03 01 corresponds to a correlation of a lower value of 0.70 between net weight and fill level.

Linear regression models: occupancy as a function of net weight

The regression coefficients for two vehicles are statistically significant: Vehicle 9 has a correlation coefficient r of 0.99, which indicates a very good linear correlation, while the coefficient of determination R^2 explains 98% of the variability of the filling variable with the variability of net mass. Similarly, for Vehicle 10, the correlation coefficient of 0.97 indicates a very good linear correlation, while the coefficient of determination is 95%. The p-value of zero for two cases indicates that the linear correlation coefficient is statistically significant. These results are detailed in Table 4. The relationship between the fill level of Vehicles 9 and 10 and the net weight is written as the following:

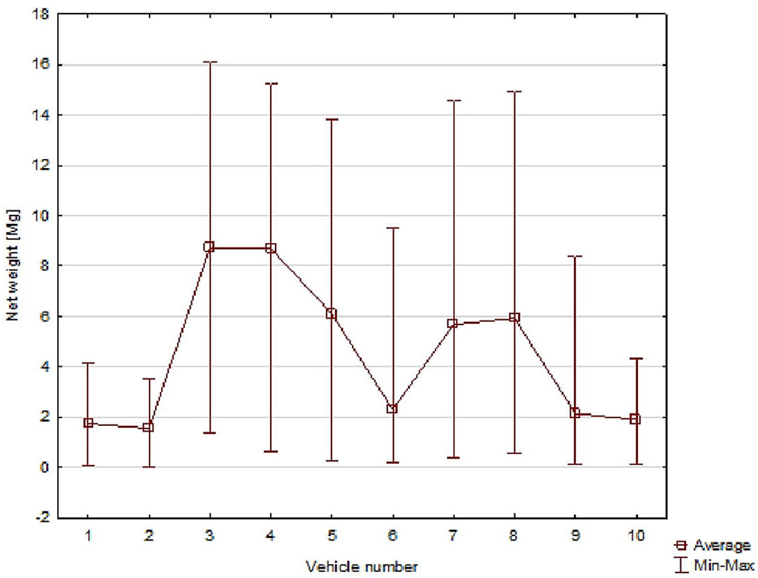

Figure 3. Average net weight per vehicle

Table 3. Correlation in groups by waste code

Waste code	Results aggregated correlations		
	Variable	Net weight	Filling
20 03 01	Net weight	1	0.70
	Fill level	0.70	1
15 01 01	Net weight	1	0.91
	Fill level	0.91	1
15 01 02	Net weight	1	0.95
	Fill level	0.95	1
15 01 06	Net weight	1	0.99
	Fill level	0.99	1
15 01 07	Net weight	1	1
	Fill level	1	1

Table 4. Linear regression results for vehicles

Indicator	Vehicle	Value	Vehicle	Value
R multiple	9	0.99	10	0.97
Multiple R^2		0.99		0.95
Corrected R^2		0.99		0.95
F(1.200)		20 605.36		3 532.97
p		0		0
Statistical error of estimation		0.03		0.06

$$\text{Vehicle 9 fill level} = 0.282645 \times \text{net weight} + 0.013725 \quad (1)$$

$$\text{Vehicle 10 fill level} = 0.258832 \times \text{net weight} + 0.080205 \quad (2)$$

These equations presented above fit the linear regression model well to the data, confirming the high reliability of the forecasts returned by the model. These are the same models for which high Pearson r correlation coefficients were demonstrated.

DISCUSSION

Annually, 2.01 billion tonnes of municipal waste is produced worldwide, of which at least 33% is not disposed of in an environmentally friendly manner. By 2050, the global amount of waste is expected to reach 3.40 billion tonnes, more than doubling the population during this period (Kaza et al., 2018). The area of waste collection services under study is currently inhabited by more than 100 000, which, according to Stoeva and Alriksson (2017), and changes in this number affect the quality and quantity of municipal waste collected.

Waste management systems based on collection and transport to landfills are becoming obsolete (Jouhara et al., 2017). In contrast, Bing et al. (2016) identified municipal waste logistics management (MWLM) as essential to addressing the growing waste stream and the need to reuse non-renewable resources. Li et al. (2011) showed that the MSW depends on various factors, such as standard of living, degree of commercial activity, and eating habits.

The practised conventional waste collection is based on the collection and transport of waste with the help of rolling stock, which usually allows the use of containers of different sizes (Melakessou et al. 2020) that are typically located close to the waste source, which affects efficiency. In general, waste in the study area was collected selectively and non-selectively by eight vehicles, divided into five fractions, using the door-to-door method or from the kerb for processing and recycling. Rodrigues et al. (2016) showed that the type of waste collection system, including the number of vehicles used, has an impact on the quantity and quality of recyclables intended for use (Guerrero et al. 2013).

Collecting and managing MSW in an environmentally friendly way can lead to sustainable solutions for the medium and long term (Council 2007). According to Passarini et al. (2011), each collection system is unique and designed to achieve specific waste collection and environmental goals, limited to location conditions, such as an area with a varied distribution of waste containers. In waste transport, the technical parameters of vehicles are critical, such as the effective fill level adapting to the amount of waste collected (Ferrer and Alba 2019). Of note, the highest average fill level was 95.39%, and a vehicle with a low capacity (8 m^3) has an average fill level of 77%.

On the contrary, the highest average net weight of 8.72 Mg and standard deviation of net weight of 3.60 Mg were characteristic of vehicles with the highest capacity. Collecting partially filled containers is disadvantageous because it increases collection costs and air pollution and reduces collection efficiency (McLeod et al. 2013). This indicates the need to optimise activities to increase the efficiency of waste disposal. One solution to optimise waste disposal is the introduction of intelligent containers. Other researchers (Vishnu et al. 2021) showed that hybrid network architecture can be used to optimise and monitor household and public waste bins. Proper planning of the route remains important (Erdem 2022).

The highest total net weight of transported municipal waste amounted to 6 368.10 Mg for a vehicle with the largest capacity of 21 m^3. A maximum net weight of 16.1 Mg was recorded for this vehicle. Kinobe et al. (2015) found that collection and transport in the case of improper management generates additional costs.

Ibáñez et al. (2011) investigated socioeconomic and logistic covariates using a linear regression model. On this basis, a full correlation between the variables net weight and filling capacity is present for waste code 15. On the other hand, for mixed waste, the indicator was lower by 0.21. Similarly, lower values of this indicator were shown by Meijer et al. (2021).

Teixeira et al. (2014) used statistical analysis to manage selected waste management partners more effectively. In this study, the statistically significant regression coefficient with the highest correlation index was 0.99, indicating a very good linear correlation, while the coefficient of determination showed 98% of the variability of the filling variable with the variability of net mass for a vehicle with the lowest capacity. This confirms that the occupancy models included in this study fit the linear regression model well to the data, confirming the high reliability of the forecasts returned by the model. Similar results were achieved by Jahandideh et al. (2009), who confirmed a very good fit of the regression model to the data. Moreover, Bányai et al. (2019) showed that mathematical models and algorithms are essential tools in waste collection management and in the selection of solutions to achieve the expected process optimization. In summary, resource and waste management will require sustainable management, and waste management will require a more systemic approach to address the root causes of problems (Singh et al., 2014).

CONCLUSIONS

Based on the analysis of the results of municipal waste collection by vehicles of various capacities over 12 months, the following conclusions were formulated:

1. The highest total net weight of transported municipal waste, 6 68.10 Mg, was allocated to one of the vehicles with the largest capacity of 21 m^3. The highest average fill level (95.39%) and the lowest (57.12%) were with low-capacity vehicles.
2. The highest average net weight of 8.72 Mg and standard deviation of net weight of 3.60 Mg were characteristic of a vehicle with the highest capacity.
3. An average fill level of 80% with waste indicates the need to optimise activities to increase the efficiency of waste collection. A full correlation is present between net weight and fill level, associated with code 15, which should be considered favourable.
4. The regression coefficients are statistically significant, including the R^2 coefficients of determination of 0.98 and 0.95, confirming that the occupancy variable was explained by the net weight variable.
5. Based on the relationship between the fill level of vehicles with 8 m^2 capacity and net weight of waste, models were developed that achieve a good fit of the linear regression model to the data, which means high reliability of the forecasts returned by the optimisation model.

Acknowledgement

The authors of this study would like to thank the authorities of the municipal company for providing the necessary materials, which were very helpful in preparing the article.

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