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Rationalisation of Costs in the Collection, Segregation and Transport of Municipal Waste

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Abstract: The article contains answers to three "why" questions: - why the waste management system still does not bring the expected results, and the Polish state is one of the lowest-ranking in the European score regarding the amount of segregated waste; - why the sale of selected secondary raw materials and their material reuse in production processes do not cover the costs related to waste management; - why it does not bring additional profits. The article is based on research conducted in Wroclaw from 1998 to 2018. There is a cost model that can be adapted to similar cases. The article deals with removing organisational and/or technical reasons causing the stagnation of selective waste collection.

Keywords: waste, mixed, sorting, fee, management

1. Introduction

Tasks related to the waste management system (with an appropriately adopted standard of service) and compliance with environmental (Chamier-Gliszczyński 2011) and sanitary normative requirements are absolute in nature – included in the objective function or the form of restrictions adopted in the optimisation model. Other determinants of the effectiveness of the system operation, if they are not adopted in the form of arbitrary recommendations, become a category of calculation (assessments of the type: inputs – benefits) and therefore require consideration in conjunction with the costs (economic efficiency, environmental efficiency (Lenort et al. 2019)) of the system's operation.

Waste management system plans are dual:

1) statistical – taking into account the description of the system only for a specific moment,
2) dynamic – considering the expected changes in input (and output) parameters and system status in specific time intervals.

The latter model – a dynamic model taking into account:

– the dynamics of changes in waste generation as a function of time, spatial development of the region, demographic development,
– stage possibilities of locating buildings along with determining transport routes to them from the source collection areas,
– limitations on the throughput and absorptivity of facilities and limitations on the composition and properties of the waste delivered to them,
– planning the launch of new recirculation processes in facilities or anticipating changes in their occurrence in the system as a result of liquidation or modernisation of old facilities,
– anticipation of changes in treatment processes based on the forecast of the development of processing and waste disposal in the global technology,
– affluence and availability of land for the location of new system facilities, specifying its area and absorptive capacity,

has a broader application in waste logistics (Zajac & Poznanski 2021, Zajac et al. 2020, Zajac et al. 2022, Gabryelewicz et al. 2022).

The article contains two irreplaceable elements: research results (carried out in Wroclaw in 1998-2018) integrated with mathematical relationships that build the cost calculation model. The authors did not build a case for the city of Wroclaw but a universal, scalable model in similar cases (e.g., Slovenia and Croatia). Exemplary comments have been added to the research results shown in the graphs, illustrating how the presented content is integrated with people's lives in a given area. The course of the graphs is a reflection of the life of the inhabitants. The reader should treat mathematical relationships and research results as a pair. The model considers several parameters, including, for example, profits from the sale of sorted raw materials and the intensity of social migration of citizens. Most often, the management staff in enterprises uses a typical Microsoft Office suite in decision support; hence, the derived mathematical relationships have been saved to be useful to calculate and optimise with software available in offices. It is obvious that computer simulation tools such as Matlab-Simulink are available in research centres and universities. Still, companies relatively rarely have not only licenses but also appropriate libraries for Matlab-Simulink.

The next section contains an analysis – "state of the art" in the area of the article. The following section presents research on municipal waste in Wroclaw.

2. Literature Review

For many years, changes in the operation of waste management have been observed in Poland. Despite several amendments to legal regulations, the management system still does not bring the expected results. In the European ranking regarding the amount of segregated waste, Poland is in one of the last places. The "Act on maintaining cleanliness and order in municipalities" was a very important element of the changes in 1996. Some of the provisions of this document were the same as those in the EU. Thanks to this, the society and gradually the entire waste management system in Poland were slowly being prepared for EU accession, e.g. automotive recycling (Chamier-Gliszczynski & Krzyzynski 2005, Czwajda et al. 2019, Deng et al. 2018, Dia et al. 2018).

The "state of the art" consists of three basic groups of documents: 1 – scientific papers/books; 2 – European Union regulations; 3 – regulations in force in Poland. Since not all documents have been published in English, in justified (selected) cases, such citations have been discussed in more detail so the reader can understand the authors' intentions. Legislation is available for free online (ISAP 2023).

The Act on Waste primarily introduced the obligation to segregate municipal waste to increase the volume of waste: stored in landfills, get rid of hazardous substances from the waste stream; in particular, save energy and recover valuable raw materials suitable for reuse (Chamier-Gliszczyński 2011a). The implementation of the Act on Waste required a change in the awareness of society (Den Boer 2009) and undertaking appropriate logistic activities to build a waste management system (Bilitewski et al. 2003, d'Obyrn & Szalińska 2005). To some extent, a reference to Polish regulations can be found in (Bendkowski & Wengierek 2012).

The sale of selected secondary raw materials and their reuse in manufacturing processes should cover the costs related to waste management and additionally bring profits and promotional and educational activities. Unfortunately, this is not the case in Poland (Gabryelewicz et al. 2021). Therefore, a fee is charged for managing municipal waste in the EU (European Parliament and Council Directive 94/62/ec). Despite this, the disposal of sorted waste is still not much cheaper than the disposal of mixed waste. Fees for placing waste in landfills are increasing yearly, and waste processing systems are being built with great reluctance and even social protests. Low prices of raw materials make waste segregation and recycling less and less profitable. The situation in Poland is such that it is more profitable for an individual to sell segregated waste for a profit to the collection point of secondary raw materials than for a company that does so on a larger scale (SNAGA).

The sharp increase in the waste fee in Wroclaw and Lubiana from EUR 1 to nearly EUR 10 in 2009-2019 per person in a family did not increase the volume of waste collected selectively or reduce waste stored in landfills. The amount of waste collected selectively increased by 6.5%, while the amount of municipal waste sent to landfills decreased by 4%. The amount of generated waste has not changed. The observed situation in Ljubljana, Zagreb, and Wroclaw gives grounds to conclude that the increasing waste fee does not significantly impact changes in waste management. This fee directly affects the operating costs of waste recycling, sorting and storage.

Calculating the waste fee – the most common interpretation, also used by the Ministry of the Environment, means that to calculate the fee rate, one should use data on the number of inhabitants, the amount of waste generated in the commune and the costs of operating the system. With this interpretation, the rate is calculated in PLN/person for the municipality's average amount of waste/person.

The Act requires a lower rate to be set when waste is picked up and collected selectively (Article 6k.3). At the same time, the collected fees must cover the system operation costs (collection, transport, pick up, recovery, disposal, creation and maintenance of selective collection points and administrative services – Article 6r.2). These provisions are contradictory because selective collection (especially 6 fractions separately) generates higher costs than non-selective collection or fewer fractions. It is, therefore, impossible to determine a lower fee rate for selectively collected waste based on the system's operating costs. The solution to this situation is to assume that the difference between the rate for selectively collected and mixed waste is the cost of possible penalties for failure to meet the quantitative objectives of waste management. It seems that this is the only way, consistent with the condition of basing the calculation on the system's actual costs. Any other calculations (e.g. calculation of system costs assuming that 100% of waste is collected selectively, and based on this, the basic rate for mixed waste is calculated) allow for balancing the system on a municipal scale but do not meet the condition of basing the fee on costs (Boer 2009).

Selective collection of waste fractions such as paper, metal, plastics, glass, multi-material packaging and biodegradable waste implies quite high costs of preparation for collection, provision of containers, securing space and, as noted in the further part of the article, transport costs: by separate cars or with specially separated space for individual fractions. Which is not always technologically justified (sorting systems). The research results indicate that in some cases, it would be more cost-effective to collect selectively, in compliance with the regulations, but broken down into 2 or 3 fractions: dry, wet, green and kitchen waste.

Scientific soundness demands, including the literature review of the methodology of conducting waste research in Poland, especially in Wroclaw, where the SWA (Solid Waste Analysis Data) was used – modified, i.e. extended.

The result of a thorough analysis of the available results of reports developed by individual countries (cities in individual countries) – versus – methods is the conclusion that individual countries using the same method get different results. It is best illustrated by an example: Poland, in the reporting procedure according to (Municipal Waste) uses method 2, and the country whose waste management (legal and technological solutions) is analogous to Poland, e.g. Slovenia: method 4. If we substitute the data for Slovenia (SNAGA) for method 2 and method 4, the recycling rate is approximately 30% (method 2) and 49 (method 40), respectively. It is due to the inclusion of bio and other recycled waste. It only proves that comparing different countries and/or individual cities using an indicator requires thorough validation, e.g. (Municipal Waste Statistics 2023, Guidoni et al. 2018).

3. Studies of Municipal Waste in Wroclaw

Studies of the waste management system were conducted in Wroclaw in the years 1998-2018. The study of the technological properties of the waste produced in urban development and the vicinity of detached houses considered the differences in waste composition. More and more often in suburban areas, a composter is used, which reduces the volume of collected biodegradable waste. In the city centre, in multi-family buildings, composters are not used (items such as (Lewicki 2014, Małacka 2006, Krzyśków 2012) are available, and advertisements for composters dedicated to balconies with a course on how to "feed" the composter), which means that organic waste ends up in a garbage container. The composition of waste varies over time and depends, among others, on the place of generation, the nature of the inhabitants who generate waste or the equipment of the buildings they live in (this statement is made more probable by the further part of the article). Therefore, they were divided into: W1 – household waste; W2 – waste from public utility facilities (administration, economic activity, education, etc.); W3 – bulky waste (electronic equipment, furniture, etc.); W4 – street waste (coming from the cleaning of streets, squares and sidewalks, cemeteries, street bins, etc.); W5 – waste from urban green areas - mainly biodegradable waste (created during cleaning parks, squares, etc.); W – demolition and construction waste (mainly bricks, ceramic waste, wooden elements, i.e. door frames, doors, etc.).

According to the Waste Act, each type of waste has an identification number. They were divided into 20 groups, where municipal waste was classified into a group. In (War on Science, 2015), the author writes that in 2015, in countries such as Poland, waste labelling should be implemented following (Kozłowski, 2002). In Poland, since 1997, based on (ALBA, 2015) and following the EU document (Municipal Waste, 2021) – this fact is additionally documented in the work (SNAGA) – identification was carried out.

3.1. Quantitative scope of waste research

Quantitative research was carried out to determine the necessary means of transport (Zajac et al. 2019, Zajac 2010), the frequency of removal and the size of landfills or waste processing facilities. The research was carried out on samples of at least a weekly amount of collected waste because the daily amount was unreliable due to the large variation. The research was carried out in separate areas (zones) with similar parameters, e.g., similar nature and character of buildings and presence of service and commercial facilities. The weight of the waste was determined based on the difference in the weight of the cars before and after emptying the waste. The volume, however, was determined based on the number and volume of waste containers. It is assumed that there are (1) weeks in a month to estimate the annual accumulation:

$$Q_a = \left(\sum_1^{12} Q_{tyg}\right) \text{[Mg/year]} \quad (1)$$

The tests were carried out every two weeks for a more detailed analysis, thus obtaining 26 results. Substituting them into the formula:

$$Q_a = 2\left(\sum_1^{26} Q_{tyg}\right) \text{[Mg/year]} \quad (2)$$

The calculated amount of waste accumulated during the whole year enables the calculation of indicators where:
Q_j – annual unit mass indicator of waste accumulation [kg/M year],
V_j – annual unit volume indicator of waste accumulation [m^3/M year],
k – coefficient of non-uniformity of waste accumulation,
ρ – waste bulk density [kg/m^3].

Since the amount of generated waste is affected by season/month and weather conditions – it was assumed that the distribution of the volume of waste is random. Let's compare the amount of waste generated over a short period. Significant fluctuations can be observed – further analysing the trend over a longer period, we may notice that it can be described quantitatively and qualitatively. The basis for such considerations is the coefficient of uneven accumulation of waste expressed as the ratio of the monthly value of the waste mass to the monthly average value calculated yearly. If a specific period is analysed, there are "peaks" defined by the unevenness of accumulated waste. The trend of generated municipal waste in particular periods oscillates around a certain fixed level. The indicator allows capturing and searching for the causes, e.g. in September 2018, one of the causes was the green mass of biodegradable waste produced by nature more intensively than in other years (additionally, e.g. leaves and branches).

Another analysed indicator is the volume indicator of municipal waste accumulation, i.e. the volume of collected waste per unit of time in a container. It is about loosely thrown waste, i.e. without mechanical compaction, which we deal with, for example, in cars adapted to collect waste from containers. This indicator is given in a unit of volume [m^3/inhabitant]. The average values of the volume indicators of waste accumulated in Wroclaw for three types of buildings are R1 – high buildings (2.17 [m^3/inhabitant/year]); R2 – old and new compact buildings in the city centre (2.10 [m^3/inhabitant/year]); R3 – scattered single and multi-family housing (1.61 [m^3/inhabitant/year]). The greatest accumulation occurs in R1, while the lowest is in R3 and R2.

The last indicator is the bulk density of waste given in [kg/m^3], which is the basis for the logistics and transport departments in the correct planning of the transport system and the number of waste containers. To illustrate, the average bulk density value during the year for a specific type of building is: R1 = 327.29, R2 = 334.71, R3 = 328.52, R4 = 330.17 [kg/m^3].

3.2. Scope of qualitative research on waste

Qualitative, three-stage tests were carried out to determine the possibility of utilisation by an appropriate method.

Stage-1. Fractional (sieve) analysis is used for the preliminary breakdown of waste into 4 grain fractions according to their size. For this purpose, a set of sieves is used, e.g. a vibrating sieve or a rotating drum, thanks to which the successively sieved layers remain in the appropriate sieves, forming the following fractions: fine < 10; average 10-40; thick 40-100; remaining >100 [mm].

Fractional analysis was carried out in the next step to determine the possibility of selecting and using some components and to go to the next step, which is the pre-treatment of waste, i.e. sorting, separation, and shredding. Another advantage of subjecting waste to this procedure is separating the fine fraction, e.g., ash, which is a ballast substance whose fertilising properties deteriorate. On the other hand, once separated, ash can be used to produce concrete, roads, etc.

Stage-2. Physico-chemical analysis. Susceptibility to biochemical and thermal processes makes it possible to determine the fertilising and fuel properties of waste based on the content of organic matter (% dm), organic carbon (% dm), organic nitrogen (% N dm), organic phosphorus (% P_2O_5 sm), organic potassium (% K_2O sm). Based on the results of these tests, it was determined whether waste from a given area is susceptible to biochemical transformations. Good fuel properties are possessed by such municipal waste, which is characterised by low humidity and low content of non-combustible elements. The recommended calorific value is >7000 [kJ/kg]. The greater the amount of paper and plastics, and at the same time, the smaller the amount of mineral fraction, the higher the calorific value of the waste.

Stage-3. Morphological analysis. Waste is divided into individual streams – types of waste. Such testing is essential because it carries information about the possibility of recycling, the suitability for particular processing methods, and returning raw materials to production. These tests are performed manually on a sorting table.

The following morphological components of waste, i.e. fractions, are distinguished: F1 – paper and cardboard; F2 – plastics; F3 – textiles; F4 – glass; F5 – organic waste; F6 – metals; F7 – hazardous waste; F8 – wood; F9 – composite; F10 – inert waste.

The computerised waste database enables reliable formulation of a waste management plan, selection of the best waste disposal methods and is conducive to designing an effective process of selective collection. For this purpose, quantitative and qualitative tests shall follow standards on how the samples are prepared and taken and how the composition and individual components are determined. In addition, knowledge of waste's quantity, properties and morphology allows for a reliable valuation of waste management services. Research can be the basis for developing reliable, long-term forecasts regarding the amount and type of waste generated in a given area (zone). Forecasts are a very important factor when it comes to city development projects or the implementation of an effective waste disposal system, e.g. the introduction of the EU law (The Single-Use Plastics Directive, effective since 19-07-2021) could be predicted, but the waste that appeared due to the covid pandemic could not.

4. Wroclaw Waste Study

The Wroclaw Waste Study resulted in the collection of a large amount of municipal waste management data in 1998-2018 (Figure 1).

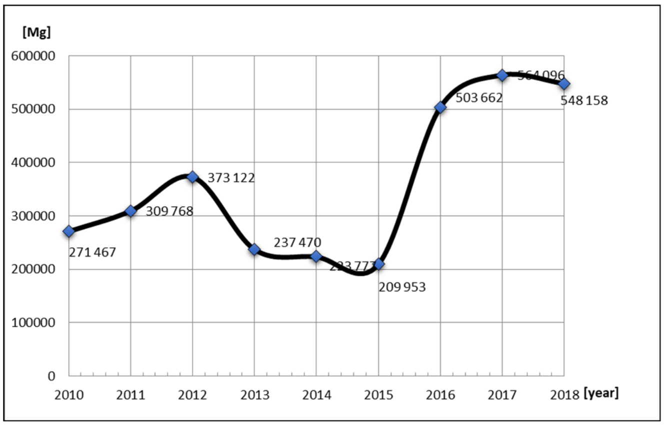

Fig. 1. Amount of municipal waste generated in Wroclaw

A substantial amount of waste was recorded in Wroclaw during the research period. The annual amount was around 540,000 [Mg]. In the 1998 timeline, this gigantic amount of waste was caused by the millennium flood that hit parts of Poland, including Wroclaw. The scale of the damage is indicated by the fact that it was estimated at PLN 12 billion (flood of 1000 years). After the flood subsided, the population began slowly removing the damaged things. Heaps of garbage were piled up in the streets, squares or the interiors between blocks of flats. The research results document that it took about 2.5 years to remove/dispose of this waste. Moreover, incidentally, waste collection at that time was suspended for technological reasons involving the operation of RIPOK, MPSZOK (landfills). PSZOK is a Point of Selective Collection of Municipal Waste. RIPOK is a Regional Installation for Processing Municipal Waste – these acronyms are found later in the article.

A characteristic point on the chart is 2005. At that time, a sharp increase in waste amount was recorded. It was "built" by high economic growth – approximately 5.3% – caused by Poland's accession to the EU in May 2004. The improvement of the market situation also contributed to the increase in income. At that time, many Wroclaw residents took advantage of a housing/consumer loan –confirmed by the data of the Statistical Office in Wroclaw: an increase of 19% in nominal terms in 2005. At the same time, the prices of consumer goods and services fell to a very low level during this period. Summing up, 2005 was a year of consumption – that's why there was more municipal waste than usual.

An increase in the municipal waste amount has been recorded again for several years, and last year, it was a fairly large jump – comparable to the apogee that occurred in 2005. Perhaps this is due to the general improvement of the economy, a higher standard of living, and, as a result, a gradual increase in consumer lifestyle. The promotion of newer and newer products and the principles of marketing even impose the use of unusual packaging to attract the customer's attention. This packaging is often a waste of raw material – it consists of several layers that are often heavily folded, have futuristic shapes and are oversized to give the impression that they contain more product. There are more and more products on the market that are designed for a short life cycle and those that are only disposable. The pace of people's lives, especially those living in large cities, definitely discourages the avoidance of waste generation or its segregation. It is conducive to the trend of increasing the amount of waste.

The number of inhabitants (not growing as intensively as the amount of waste) in a given period concerning the appropriate amount of municipal waste generated allows us to estimate the amount per inhabitant (Figure 2).

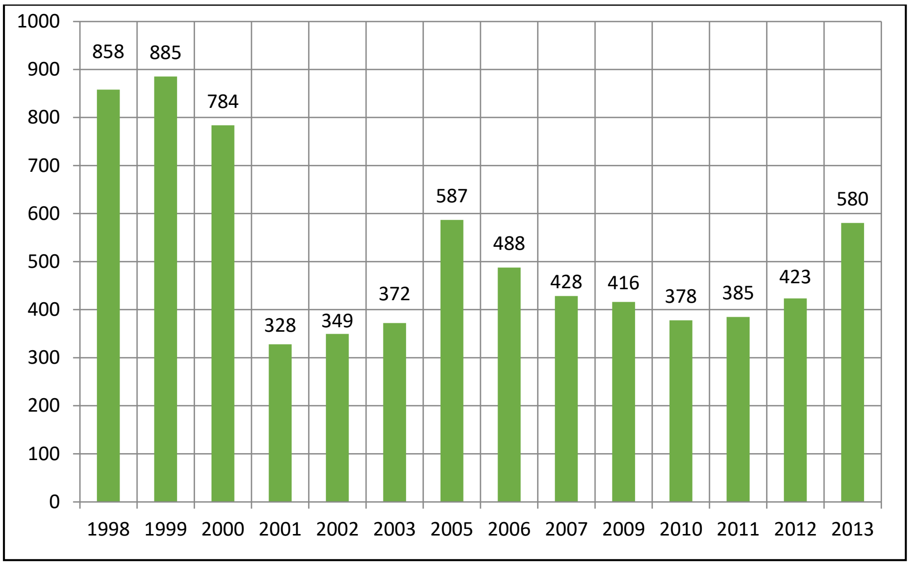

Fig. 2. The amount of municipal waste generated per capita in Wroclaw in the years 1998-2013

The study of the morphology of municipal waste showed the possibility of obtaining and processing fractions suitable for recycling, reducing the amount of waste generated and proposing the most advantageous place to build a landfill and installation. The results of the first research conducted in Wroclaw (Figure 3).

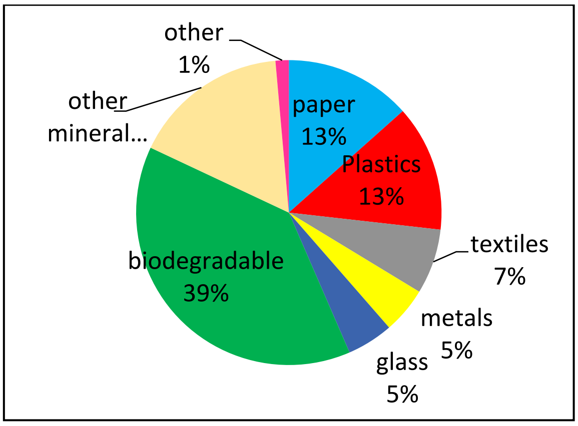

Fig. 3. Research results of the raw material composition of waste from Wroclaw. Data in % by weight

Biodegradable waste generates the largest mass of waste. The largest amounts of this fraction can be expected in spring and autumn, as it is caused, among others, by active work in the gardens (mowing grass or collecting leaves). As can be seen, the results of the first morphological analysis from the period 1998-2005 were narrowed down to the main fractions. In subsequent studies, they were extended to other waste streams. Waste was broken down into fractions and sub-fractions because, over time, the requirements of RIPOK increased, it was necessary to plan well where and what facility to create and what waste processing techniques should be used.

Conducting the research met with great, kind interest of the inhabitants of Wroclaw. Conducting the research met with the friendly attitude of the inhabitants of Wroclaw, and the idea was born to involve people who would supervise the collection of waste daily.

These people have become known in Wroclaw as "Eco-Keepers". An Eco-Keeper helps residents segregate waste, and thanks to them, more recyclables are recovered, and less waste ends up in landfills. An Eco-Keeper in a recognisable outfit moves around on a bicycle (green transport) between 41 points – courtyards in the Old Town, visiting selected locations 2-3 times a day.

The bicycle shortens the distance between people, enabling education (residents ask: how to classify waste) based on open personality, ease of establishing contact with residents. The Eco-Keeper often helps older people with problems taking out the garbage. Eco-Keepers become attached to their areas, and residents to Eco-Keepers.

The tasks of the Eco-Keeper include visiting places with bins (boxes, courtyards), checking whether all raw materials have been placed in the appropriate containers, verifying incorrect insertion and placement of bins, looking for bin placement scenarios that favour segregation, adjusting the number of bins and the frequency of emptying to actual needs of the residents. It increased the number of segregated waste containers concerning mixed waste containers. Further conclusions from our surveys from 2016-2019 indicate that older people are most willing to segregate, while young people care less about order and ecology. Perhaps this is not the effect of the so-called difficult age and renting apartments to students who do not treat their temporary residence respectfully. Twice as much plastic, fine metals, and tetra-packs were collected from the area where the Eco-Keeper worked as in other parts of the city.

In Poland, Eco-Keepers are only found in Wroclaw – like a man in a cloak lighting historic gas street lamps or a bugle caller on the Market Square in Kraków.

The "When does the truck arrive" smartphone app provides information on the date of collecting waste containers and unusual waste pick-ups and supports selective waste collection.

The introduction of assessment of waste sorting by residents and collection of waste from zones 1-4; from residents who are exemplary – 3, average – 2, sufficient – 1 and linkage to fee-reducing vouchers.

Subsequent studies were carried out in the years 2003-2018 in 4 cycles, taking into account the seasons, heating periods, and the type of buildings in which the waste was generated. In each of the four series (spring, summer, autumn, winter), waste from 3 environments was examined, which differed in their surroundings, buildings and urbanisation. Sorting was done on manual screens. Fractions were separated according to their size, then grouped into 34 subcategories and 11 categories, and each was weighed separately. Figure 4 shows the detailed results of the average composition of waste.

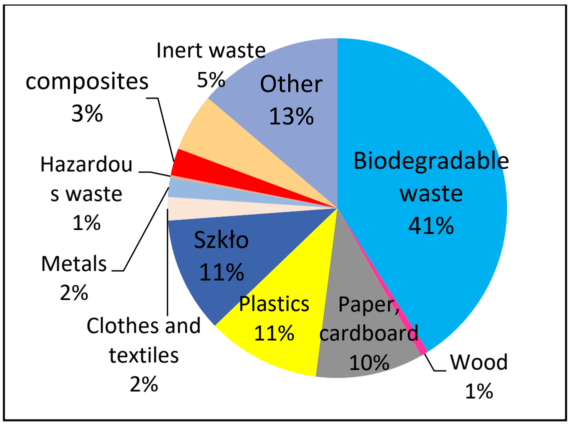

Fig. 4. Fractions, annual average of four batches (% of total waste weight)

41% was by the fraction of biodegradable waste. On the other hand, paper, plastics and glass occurred in similar amounts – approx. 11%. Studies of mixed waste have shown that since 1998, little has changed in the material composition of mixed municipal waste since the first studies. Among other things, this was due to the small scope and low efficiency of waste segregation in households at that time. It should be noted, however, that there was a significant increase in the content of glass (from 4.5% to 11%) and plastics. It is mainly due to the introduction of more glass and plastic packaging (including disposable packaging) to the consumer market.

Until mid-2013, most of the collected municipal waste was deposited in landfills. It resulted from the regulations in Poland. Entrepreneurs competed mainly in terms of the price of their services; however, after the amendment to the regulations, they introduced a mandatory fee for municipal waste management (Figure 5).

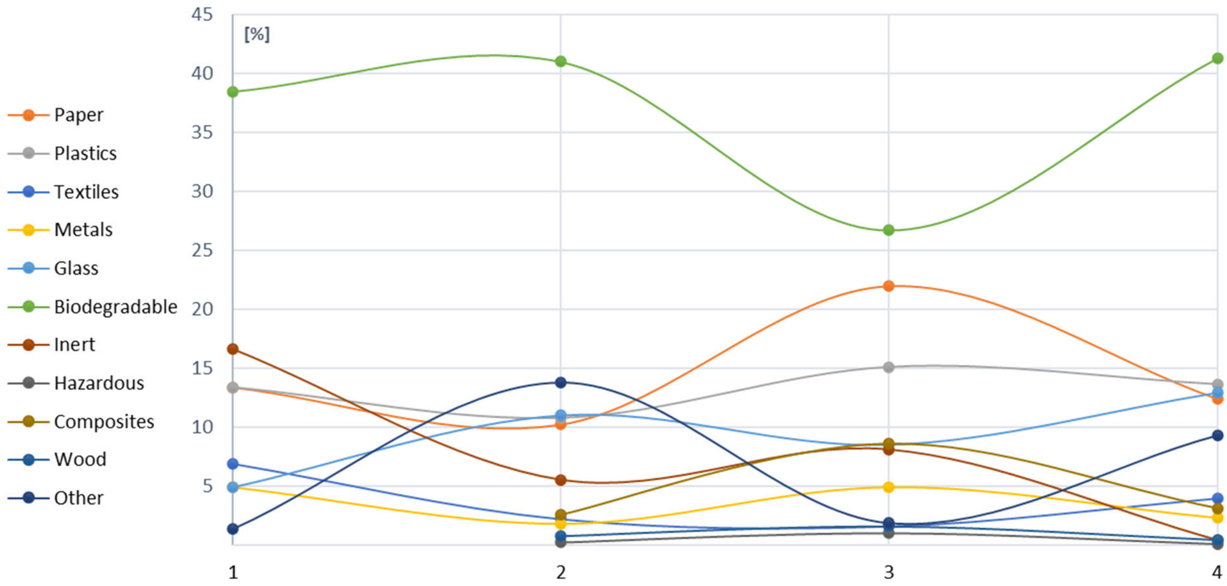

Fig. 5. Morphological composition of mixed waste

Organic waste constitutes the largest part of municipal waste and has been at a comparable level for several years. The relatively large amounts of paper, plastics and glass are generated in old and new buildings in the city centre. It is related to the saturation of the surroundings with service facilities, infrastructure and increased tourist traffic. On the other hand, the percentage of the remaining fractions decreased accordingly over several years. Therefore, selective collection is slowly starting to achieve small successes, but it is worth noting that the waste segregation system is heading in the right direction.

5. Assumptions, Boundary Conditions of the Model

According to EUROSTAT, in the EU-27, around 25% of the mass of municipal waste is recycled, 15% is composted, 22% is incinerated to recover energy, and 38% is still landfilled. In Wroclaw, on the other hand, 18% of municipal waste is recycled, 8% is composted, and only 1% is subject to energy recovery (there is only 18 wastes incineration plant in Poland. Currently, in Wroclaw, residents are protesting against the construction of an incinerator in Wroclaw (Incinerator Wroclaw protests, 15-05-2021)), and 73% is landfilled.

In Wroclaw, almost twice as much garbage is deposited in landfills as on average in EU countries. It is certainly the cheapest but least desirable form of waste management. If the 27 EU countries were compared in terms of the smallest amount of landfilled waste, Wroclaw would take a distant 18th place. For comparison, 38% of waste in Germany is incinerated, and 62% is recycled or composted. In both Germany and the Netherlands, municipal waste is not landfilled at all.

An important reason (one of many) is the costs of transport to sorting and storage locations: collection – handling – transport in the share of costs are 30-40%. In addition to transport costs, there are significant waste treatment and disposal costs. Large amounts of landfilled waste are also affected by the low quality of segregation or its lack, mainly due to the lack of awareness of the importance of waste management, which significantly reduces the adverse impact on the environment.

In the process of waste recovery, we obtain substances, materials or energy (Chamier-Gliszczyński 2010), while in recycling, we obtain a primary product with the same or very similar composition (Chamier-Gliszczyński 2011b).

The selective waste collection system in Wroclaw started in the 1990s. At that time, Wroclaw received an EU grant to purchase 200 containers with a capacity of 20 and 40 FT and self-dumping trucks adapted to collect and empty these containers. In 1998, these containers, used for selective waste collection, were placed in the city, and, through a tender, companies that comprehensively dealt with the selective waste collection system were selected. The first selected fractions were plastics and glass, 44.4 [t] and 298.6 [t], respectively. Considering the total amount of municipal waste, 1% of plastic and 7% of glass were recovered.

First of all, it is worth focusing on recovering those raw materials whose processing pays off in a given period: metal scrap, waste paper and glass cullet (white/coloured separately). Most of the waste is contaminated and requires cleaning in the sorting plant, packaging, pressing, baling, etc. In enrichment processes, e.g., purification, removing as many elements as possible that could reduce the selling price of the raw material is important. These raw materials are then sold and processed according to their usefulness.

Pursuant to the applicable regulations, Wroclaw was obliged to achieve min. 12% recycling rate and preparation for reuse of metal, paper, plastic and glass fractions. According to the data, it achieved a recycling rate of 16.4%. Similarly, according to the Regulation of the Minister of the Environment (European Parliament and Council Directive 94/62/ec), the permissible mass of biodegradable waste transferred to the landfill could not be greater than 50% of the mass delivered in 1998. In Wroclaw, in 2013, 10.24% of the mass was transferred to the landfill in biodegradable waste. Required level of recycling achieved.

Collection and transport of waste are elements of the economic system that play a very important role, often even underestimated (Izdebski & Jacyna 2018). They are estimated to be approx. 60-80% of the waste disposal costs. It is a very large proportion; based on this, it can be concluded that any improvement in collection and transport in the areas of organisation or implementation would reduce costs, which equals increased savings (Woźniak et al. 2016).

The waste collection system can be modified by combining elements such as container type, schedule for issuing containers and planning collection routes (e.g. by combining collection from exemplary customers), type of collecting vehicle (single-family houses), etc. Strict reporting in the acceptance system allowed for the analysis and optimisation of the system in search of the most effective version of the system. It is worth noting that the elements of the waste management system should be adapted to the given area (e.g. the size and parameters of the car and the type of building or the collection of waste from rural-urban areas was based on a different system than the one operating in large cities). It is mainly dependent on the amount and morphology of waste. The optimal system must meet the needs and spatial conditions. In some cases, the best solution could be the introduction of a three-container system: wet fraction – i.e. bio-waste; dry fraction – i.e. secondary raw materials; the remaining fraction – i.e. mixed (of course, there are also medicines, chemicals, electrical waste, furniture, etc., but this is a PSZOK's matter).

PSZOK is a Point of Selective Collection of Municipal Waste. RIPOK is a Regional Installation for Processing Municipal Waste – these acronyms are found later in the article. The state administration's regulations define municipal waste management regions, indicating RIPOK in individual regions. RIPOK for Wroclaw has the following RIPOK addresses (Figure 6-map and calculate the distances): RIPOK-1 mechanical-biological processing; Rudna Wielka, 56-210 Wąsosz, Kryniczno 93, 55-300 Środa Śląska, Rusko 66, 58-120 Jaroszów. RIPOK-2 Composting; Rudna Wielka, 56-210 Wąsosz, ul. Jerzmanowska 4-6, 54-519 Wroclaw, ul. Janowska 51, 54-067 Wroclaw. RIPOK-3 landfill; Rudna Wielka, 56-210 Wąsosz, Rusko 66, 58-120 Jaroszów. RIPOKs are operated by many entities that must participate in tenders, which is also due to their operational capabilities.

Due to the obligation to document the collection and return of municipal waste (the act imposes the obligation), waste collection vehicles are equipped with GPS. After collecting the waste directly from the owner, it is transported to reloading stations, storage and transport bases or directly to RIPOK.

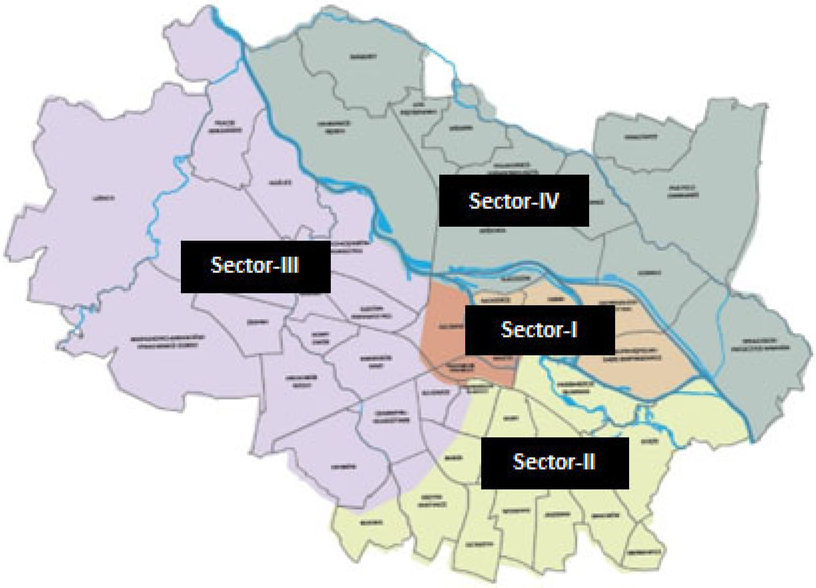

Fig. 6. Division of Wroclaw into municipal waste collection sectors

6. Cost Model of the Municipal Waste Management System

Managing municipal waste following the law requires a lot of effort and money. Apart from striving to obtain the highest possible recovery as a priority, several requirements must be met, such as protecting human health and the environment against the effects of waste management. All this makes waste management in an environmentally friendly manner very costly.

6.1. Cost model – mixed municipal waste

At the beginning, the following constants were assumed: cost of fuel used by vehicles 45 [l/100 km]; fuel price PLN 5 (PLN 4.7≅1 Euro); monthly gross remuneration of a garbage truck crew member PLN 3,500; unit cost of car depreciation 4.80 [PLN/km]; cost of repairs, insurance, etc. of cars 2 [PLN/km]; government fee 116.25 [PLN/Mg]; average price for waste storage 317 [PLN/Mg]. These data were used in the calculations.

Wroclaw has been broken down into 4 sectors. Characteristic points are determined for waste collection points and the distance to RIPOK. Moreover, the number of inhabitants in each sector is calculated (Table 1).

Table 1. Morphological composition in % of mixed municipal waste in Wroclaw

Fraction	Average content			
	1998-2003	2005-2010	2015	2018
Paper	13.4%	10.25%	22.0%	12.43%
Plastics	13.4%	10,815	15.1%	13.64%
Textiles	6.9%	2.21%	1.6%	3.97%
Metals	4.9%	1.84%	4.9%	2.33%
Glass	4.9%	11.00%	8.5%	12.91%
Biodegradable	38.5%	41.02%	26.7%	41.34%
Inert	16.6%	5.53%	8.1%	0.42%
Hazardous	n/d	0.24%	1%	0.11%
Composites	n/d	2.57%	8.6%	3.12%
Wood	n/d	0.75%	1.60%	0.41%
Other	1.4%	13.78%	1.9%	9.32%
Total	100.00%	100.00%	100.00%	100.00%

Due to the varied mass of materials contained in the mixed waste, their density is divided into individual streams. Therefore, the morphology of waste is needed to estimate the density of mixed waste. Table 2 breaks down waste according to the fractions specified in the scope of their selection in Wroclaw. The percentage content of fractions in solid waste separated in this way was determined based on morphological tests.

Table 2. Waste density by fraction

Fraction	kg/m^3 for multi-family and single-family housing	%
Mixed misc	200	19.68%
Plastics	30	13.64%
Paper	140	12.43%
Glass	310	12.91%
Bio	300	41.34%

Taking into account the percentage of the population in sectors I_{m1}, the number of people per sector I_m was calculated by multiplying the percentage share and the number of all inhabitants of Wroclaw P_1 – as for sector I (eq. 3). Percentage shares of inhabitants in sectors and the number of people are presented in Table 3.

$$I_{m1} = P_1 \cdot I_m \tag{3}$$

Table 3. Number of people living in particular sectors

Sector	Percentage share of inhabitants	Number of inhabitants of Wroclaw	Number of inhabitants in sectors
1	28%	631,263	176,753
2	15%		94,689
3	31%		195,691
4	26%		164,128

It is possible to calculate how much was generated in each sector by knowing the amount of mixed and segregated municipal waste generated in 2018. Inhabited and uninhabited properties are included in the calculations (as mentioned in this section, only mixed municipal waste is estimated). Research shows that in 2018, about 201976 [Mg] of mixed municipal waste Z_w was generated in Wroclaw. Dividing their number by the number of inhabitants I_m we reach the amount of mixed waste per capita Z_o (eq. 4). It is then multiplied by the percentage share of the population in each sector I_{m1}, and we get the potential amount of mixed waste generated in these sectors Z_{m1} (eq. 5). The amount of mixed waste per capita and per sector is presented in Table 4.

$$Z_o = \frac{z_w}{I_m} \tag{4}$$

$$Z_{m1} = I_{m1} \cdot Z_o \tag{5}$$

Table 4. Amount of mixed municipal waste generated in individual sectors, 2018

segregated	mixed	total
164,398.40	201,976.10	366,374.50
Number of inhabitants of Wroclaw as of 2014		
631,263		
Amount of mixed waste per person in Mg in Wroclaw		
0.320		
Sector	number of inhabitants in the sector	amount of mixed waste generated in the sector in Mg
1	176,753	56,553
2	94,689	30,296
3	195,691	62,612
4	164,128	52,514

Then, in Table 5, the parameters regarding the density of individual fractions, the garbage truck's capabilities and other information necessary for further calculations are presented.

Table 5. Data on waste parameters

Itemisation	Unit	Plastics	Glass	Paper	Bio	Other mixed	Average
Average density of waste thrown into containers	Mg/m^3	0.03	0.31	0.14	0.3	0.2	x
Degree of filling the container/bag with waste	%	80%	80%	80%	50%	80%	74%
Car crush indicator	%	30%	100%	40%	75%	40%	57%
Capacity of trucks transporting waste	m^3	20					
The number of people in the crew per vehicle	ppl	3					

It is possible to calculate the necessary number of trips for vehicles transporting waste during a month Z_{i1}, using the above data and previous information on the morphology of mixed waste.

The above amount of waste can be divided into potential fractions contained in mixed waste containers/bags, and their amount can be determined using the results of the morphological composition of mixed municipal waste. Then, knowing how much Mg will fit in 1000 l of a given fraction (because materials have different densities), you can calculate how many liters are needed to fit a given waste stream for each fraction. After adding up the capacity of individual streams, we will determine the total capacity of monthly mixed municipal waste. Then, knowing that the average compaction rate of waste mixed in a garbage truck is 57%, the actual capacity to be transported by the garbage truck was calculated. The average garbage truck's capacity is 20000 l. By dividing the capacity of all waste by the garbage truck capacity, we will get the number of cars/courses needed to transport the monthly amount of mixed municipal waste. The values calculated based on formula (eq. 6) and formula (eq. 7) are presented in Table 6. (I_k – number of courses, Pi – percentage shares of individual fractions in mixed waste; G_i – average density of individual fractions thrown into containers; Z_{i1} – Quantity of mixed municipal waste accumulated in the sector I per month; W_z –average car crushing index for mixed waste; $V_ś$ – garbage truck capacity; I_k – number of courses; P_i – percentage shares of individual fractions in mixed waste; G_i – average density of individual fractions thrown into containers; Z_{i1} – Quantity of mixed municipal waste accumulated in the sector I per month; W_z –average car crushing index for mixed waste; $V_ś$ – garbage truck capacity

$$I_k = \sum_{i=1}^{5} \frac{P_i}{G_i} \frac{Z_{i1} \cdot W_z \cdot 1000}{V_ś} \tag{6}$$

Table 6. The volume of fractions and the number of garbage truck trips

Fraction	Quantity in Mg	Capacity needed (in liters)	Capacity after compaction in the garbage truck	The number of trips needed to transport the waste
Plastics	643	2,1428,440	9,214,229	461
Paper	586	4,184,471	1,799,322	90
Glass	608	1,962,736	843,977	43
Bio	1,948	6,494,514	2,792,641	140
Remaining	928	4,637,592	1,994,165	100
Total	4,713	38,707,753	16,644,334	833

To transport all mixed municipal waste generated within a month in Sector I, 833 trips to the RIPOK are needed. By multiplying the number of trips and the doubled average distance from RIPOK, we will get the number of kilometres that must be covered to transport waste.

$$K_z = S \cdot P \cdot W + \frac{Ik \cdot O \cdot 2 \cdot B}{100} \cdot C + A \cdot I_k \cdot O \cdot 2 + I_n \tag{7}$$

where:
K_z – Cost of the waste collection order, Sector I,
S – number of cars,
P – number of employees per 1 car,
W – employee's monthly wage,

I_k – number of courses,
O – average distance to RIPOK,
B – fuel consumption per 100 [km],
C – fuel price,
A – amortisation,
I_n – monthly cost of intervention collections.

The costs of transporting mixed waste should also include the costs of storing mixed waste at the landfill – the amount of the administrative fee, maintenance costs of RIPOK, PSZOK (calculated to the percentage of inhabitants in a given sector), system administration costs, 5% profit margin for the waste collection company (eq. 8).

$$K_{fm} = K_z + K_z \cdot M_z + \left(\frac{S_r+B_o+S_k+O_g+A_d+P_s+P_w}{12}\right) \cdot P_1 \cdot P_z \; + \; M \cdot Z_{i1} \tag{8}$$

where:
K_{fm} – Monthly cost of managing mixed municipal waste – costs calculated for companies and residents, Sector I,
K_z – Cost of the waste collection order, Sector I,
M_z – profit margin percentage,
S_r – annual maintenance cost of the sorting plant,
B_o – annual cost of maintaining a BIO installation,
S_k – annual landfill maintenance cost,
O_g – annual overhead costs,
A_d – annual administrative costs,
P_s – annual cost of maintaining the PSZOK,
P_w – annual purchase cost of containers and bags,
P_1 – percentage share of Wroclaw residents in sector 1,
P_z – percentage share of mixed waste,
M – marshal's fee,
Z_{i1} – quantity of mixed municipal waste accumulated in the sector I per month.

The above calculations show that the monthly cost of K_1 waste management in Sector I is about PLN 4 million/inhabitant/month. In the research process, it was established that approx. 40% of municipal waste comes from economic activity, therefore, this part of the costs was transferred to companies as in formula (eq. 9). It was assumed that P_1 means the % share of Wroclaw residents in sector 1 and respectively: P_2 – in sector 2; P_3 – in sector 3; P_4 – in sector 4;

$$K_1 = K_{fm} \cdot P_m \tag{9}$$

K_{fm} is the monthly cost of managing mixed waste – costs calculated for companies and residents, Sector I; P_m is the percentage share of costs incurred by residents. Substituting the data into the formula above, we get the value: K_1 = 2397179 PLN. Knowing K_1 we can similarly convert costs in other sectors for individual months K_{cz} according to the dependence (eq. 10), which are PLN 1,284,203, P3 2,654,019 and P4 PLN 2,225,951, respectively.

$$K_{cz} = K_1 + \frac{K_1(P_2+P_3+P_4)}{P_1} \tag{10}$$

The total cost is approximately PLN 8,561,352. Ultimately, this amount should be divided by the number of inhabitants I_m who do not segregate waste P_z (eq. 11) and compared with the fee rates for mixed municipal waste management in Wroclaw.

$$K_o = \frac{K_{cz}}{I_m * P_z} \tag{11}$$

The fee rate per person is PLN 24.66, the average rate in Wroclaw is PLN 30.75 (there are 347,195 residents who do not segregate, and the cost of mixed waste management is approx. PLN 8,561,351.88). The above rate assumes 100% collection of the waste fee, which should be determined individually.

6.2. Cost model – segregated municipal waste

It is necessary to calculate the individual costs, as in the case of mixed waste, to estimate the management cost of selectively collected municipal waste. However, the difference will be that selected secondary raw materials can be sold to processors with profit. This section attempts to estimate such costs. Some data will be taken from previously presented or calculated factors in subsection 4.1.

According to the analysis of the state of municipal waste management in the Wroclaw commune, data from the Central Statistical Office and based on morphological studies (Table 7) presents the amounts of selected waste streams that were collected in 2013. In addition, the percentage rate of recovery of secondary raw materials is also given because one cannot rely on people to segregate waste perfectly. Most fractions are contaminated by incorrect selection. Therefore, it was assumed that a given % of the fraction is recovered as raw material, while the rest of the waste is transported to a landfill. By dividing the annual mass of a given fraction by 12 months, we will obtain the monthly amount of a given fraction. Then, by multiplying by the recovery %, we will find out what part is potentially recovered. The rest goes back to the landfill.

Table 7. Quantities of individual waste streams and their management

FRACTION	Quantity Mg/year	Quantity a month Mg	% recycling Raw materials	Quantity Raw material Recovered Mg/month	Number of fractions returning to the landfill Mg/month
Paper and cardboard	20,550	1,712	50%	856	856
Plastics	22,358	1,863	25%	466	1,397
Glass	23,673	1,973	88%	1736	237
Biodegradable	67,403	5,617	75%	4213	1,404
Other – metals, bulky items, rubble, etc.	30,414	2,534	70%	1774	760
Total	164,398	13,700			4,655

As mentioned earlier, the transport of waste is a significant cost. Therefore, at the beginning, an analysis should be carried out regarding the number of trips needed to transport the waste to the facility. It is necessary to calculate the volume of its monthly accumulation for each fraction separately to calculate the necessary and sufficient number of courses. Then, knowing the degree of compaction, multiply the result by a given percentage, giving us the actual capacity of the waste. Finally, the result should be divided by the garbage truck capacity to get the number of trips needed for a given fraction. We will get the final result by adding up the number of trips for all fractions.

$$I_{ks} = \frac{\sum_{i=1}^{4} \frac{I_{si} \cdot W_{si}}{G_{si}} \cdot 1000}{V_{ś}} \tag{12}$$

where:
I_{ks} – number of segregated waste collection trips,
I_{si} – individual amounts of fractions accumulated during the month,
W_{si} – individual car crush indicators,
G_{si} – average density of individual fractions thrown into containers,
$V_{ś}$ – garbage truck capacity.

As in the previous model, the number of trips must be converted into the amount of fuel needed, its cost, amortisation, insurance and employee wage costs (eq. 13). Table 7 does not contain an analysis of the management of waste such as rubble or bulky waste into prime factors – because they are transported differently. Their total development cost has already been presented as a monthly cost. Similarly, the rest of the packaging waste must be well prepared before it goes on sale as a secondary raw material, i.e. segregated and cleaned, which is associated with high costs of such preparation.

$$K_{zs} = \frac{I_{ks} \cdot O \cdot 2 \cdot B}{100} \cdot C + A \cdot I_{ks} \cdot O \cdot 2 + \frac{G_r}{12} + \\ + S_s \cdot P \cdot W + I_n + T + S_k + B_0 \cdot O_b \tag{13}$$

where:
K_{zs} – the cost of ordering the collection of segregated waste,
I_{ks} – number of trips needed to transport segregated waste,
O – average distance to RIPOK,
B – fuel consumption per 100 [km],

C – fuel price,
A – amortisation,
G_r – annual cost of managing waste such as rubble, etc.,
S_s – number of cars for selective collection,
P – number of employees per 1 car,
W – employee's monthly wage,
I_n – monthly cost of intervention collections,
T – monthly cost of treating plastics and waste paper,
S_k – monthly cost of glass preparation,
B_o – BIO waste management fee,
O_b – amount of recovered BIO fraction.

Some of the sorted waste will not be used as secondary raw material. Residues after sorting in the north-central region go to RIPOK-1. Waste is delivered to the installation and coded as 19 12 12, i.e., waste from mechanical treatment (e.g., sorting, crushing, granulating). The average cost of storing such waste is PLN 329.10 per Mg. The above cost of storing the rest of the waste, which can be calculated by multiplying the amount of residues from each fraction unsuitable for recycling times the rate for storing the sorted waste, should be added to the previously calculated costs. The profit margin must be added to this, as well as overhead costs and, similarly to mixed waste, 40% of the costs covered by the companies should be subtracted from this sum (14).

$$K_{cs} = (K_{zs} + K_{zs} \cdot M_z + \frac{S_r+B_o+S_k+O_g+A_d+P_s+P_w}{12} \cdot P_{se} + \frac{L+M\cdot R}{12}) \cdot P_m \quad (14)$$

where:
M_z – denotes the % profit margin,
P_{se} – % share of segregated waste,
M – administrative fee,
R – the amount of sorted waste going to the landfill and the costs of: S_r maintaining the sorting plant,
B_o – maintaining the BIO installation,
S_k – maintaining the landfill,
O_g – overhead,
A_d – administrative,
P_s – maintaining the PSZOK,
P_w – purchase of containers and bags,
L – collection of expired drugs,
P_m – % share of costs incurred by residents.

The calculated rate for the management of segregated waste Kos is given by the formula (eq. 15), where the number of inhabitants I_m segregating waste P_{se}. It is a similar situation assuming 100% collection of liabilities imposed on residents. Given that this situation will not happen, higher rates should be assumed than those calculated under the assumption of perfect collectability.

$$K_{os} = \frac{K_{cs}}{I_m \cdot P_{se}} \quad (15)$$

The fee rate calculated per person was PLN 17.16, with an average value of PLN 20.50 – the values were calculated for the number of residents who segregate, 284,068 PLN, and the cost of managing segregated waste PLN 4,873,891.

6.3. Sale of segregated municipal waste – secondary raw material

It is possible to sell segregated and treated fractions. After preparing fractions such as plastics, glass or paper – they are offered for sale to processors for recycling at a price individually set by the recovery company. To obtain the values, the reader should find the purchase prices of raw materials (examples are given in brackets): plastics (PLN 0.60/kg) 465794 kg, waste paper (PLN 0.26/kg) PLN 856240, scrap (PLN 0.70/kg) PLN 124189, glass (PLN 0.06/kg) PLN 1736043.

Summing up the product of the masses of each R_i fraction intended for recycling and the corresponding purchase price C_i, the profit Z is obtained:

$$Z = \sum_{i=1}^{4} C_i \cdot R_i \quad (16)$$

The final fee rate for managing segregated municipal waste K_{or} is obtained from the relationship (eq. 17). The comparison of the actual rate and the estimated rate after adding the profit is shown in Table 4.20, where Z is the total profit from the sale of recyclable materials, I_m is the number of inhabitants, and P_{se} is the percentage share of segregated waste.

$$K_{or} = \frac{K_{cs} - Z}{I_m \cdot P_{se}} \tag{17}$$

Ultimately, the balance of costs and profits, assuming 284,068, the cost of segregated waste management is PLN 4,180,698, and the calculated cost per person is PLN 14.72.

7. Conclusions

Analysing the results of the estimated garbage fee rates in Wroclaw and the municipal waste management existing in that city, one may conclude that the sorting of municipal waste is currently hardly profitable. The main reason for low profitability is the high cost resulting from high fuel prices or the maintenance of waste treatment facilities. Low profit is also connected with the fact that the preparation of sorted fractions for recycling is expensive. At the same time, the amounts of collected recyclables are also not high enough to cover most of the costs. Based on the estimated costs and profits of the management of sorted municipal waste, it may be seen that the profit from the sale of recyclables can cover only about 14.2% of the total costs of the management of sorted municipal waste. Based on analyses, studies and observations, it may also be concluded that as time passes, the sorting of municipal waste by residents may be at an increasingly higher level, which may significantly reduce the costs of preparing such waste for recycling. One of the factors that can lead to this is the continuous running of programmes promoting an ecological attitude, making the public aware of the significance of the garbage problem. It would be worth saying more about the fact that, on average, each of us produces about 320 kg of garbage per year and openly encouraging the reduction of this bulk value, which, if it were lower, could certainly reduce the rate of the garbage fee by reducing the number of garbage truck trips needed for their removal, reducing fuel consumption, the number of employees and the costs of maintaining the sorting plant, installations, etc., and thus the overall reduction of costs affecting the fee for municipal waste management in the municipality of Wroclaw.

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