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# Waste management systems in the context of sustainability

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**Abstract**
The present paper deals with waste management systems in the context of sustainability in selected municipalities. The author's team aimed to find the key waste groups according to the classification groups that have a major impact on the volume of waste and the cost of the system, thus facilitating management decision-making. In order to optimise the management of the entire waste management system from the perspective of the statutory municipality, it was first necessary to reduce the original list of 53 waste items to a significantly smaller number. With the help of waste management experts, criteria for reducing the number of waste input items were defined, resulting in a reduced statistical sample of 27 items. Each item is quantified by the amount of waste per year and the cost of the system per year. The mathematical apparatus consisted primarily of calculating average values as well as marginal slopes of waste quantity and cost. The interrelationships between waste groups were graphically recorded in perceptual maps. The individual analyses were carried out primarily for a statutory city, with secondary comparisons of the results with smaller towns and small villages. The analytical procedures verified that the catalogue of basic components of mixed municipal waste can be significantly reduced for decision-making in secondary resource management. The amount of waste selected in each group significantly impacts the cost of the whole waste management system. Of the original 15 waste groups, only three groups appear to be the main ones. The municipal waste group even has a decisive influence on both the quantity of waste and the cost of the whole system. Thanks to these findings, from the point of view of both the manager and the management of the statutory city, it is possible to focus on this core group, which contains the 13 original catalogue items.

**Keywords**
municipal waste management, municipal solid waste, municipal waste, waste, group waste, volume, costs, marginal slope

## Introduction

Waste management and handling are a challenging and complex issue. Different municipalities and cities approach municipal waste management differently and with varying degrees of success. A fundamental change that we have seen in recent years, and one that is truly central, is the move away from landfilling municipal waste to sorting it and returning it to the economy in the form of sorted secondary raw materials. Given the fact that waste management usually places a huge financial burden on municipalities in relation to their budgets, it seems strategically important to proceed with waste management thoughtfully and predictably. Such an approach can bring huge savings. Efficiency in waste management is, therefore, one of the priority issues for every local authority.

The transition from linear economic chains to circular ones is not an easy issue, and each actor in the economic chain responds to it a little differently. Within the EU, waste management issues are being harmonised legislatively. In December 2015, the European Commission adopted a circular economy package with ambitious goals. This package was introduced to help businesses and consumers in the European Union move towards a stronger and more circular economy (EU, 2015a). Act No. 541/2020 Coll, the Waste Management Act, defines the legislative basis of waste issues in the Czech Republic. The purpose of this Act is to ensure a high level of environmental and health protection, sustainable use of natural resources, and prevention and management of waste (Zakon, 2020a).

There are many types of waste. Different types of waste need different solutions for collection, sorting, and subsequent recycling or recovery. Municipal waste management is a key issue for municipalities. Firstly, municipalities and cities are the owner of the mixed municipal waste (MSW) produced in their territory. It can be said that the collection of MSW and its subsequent treatment have already transformed MSW into secondary raw materials. This is a process that represents a relatively significant cost burden. It is, therefore, desirable to look for tools and solutions to manage this diverse waste more efficiently. The authors' team sees a research gap in the knowledge that the possibility of managing waste issues by reducing a large number of diverse waste types into a significantly smaller number of homogeneous groups according to selected classification characteristics has not yet been investigated. Therefore, using mathematical procedures, an attempt was made to determine selected characteristics of waste management in a selected statutory city and compare them with a smaller city and a small municipality. All the mentioned municipalities are located in a region long associated with coal mining. The aim of the authors' team was to identify the main waste groups that may appear to be essential for effective waste management and handling in different types of municipalities.

## Analysis of the problems

The European Commission's Action Plans are the cornerstone of the EU's waste management policy. They are strategic documents that set out the objectives and challenges to be achieved in the use of resources, among which waste plays an integral role. The EU's initial action plan for the previous decade on resource use and, thus, waste management was the 2011 Action Plan for the Resource Efficient Europe, which set waste management targets to be achieved by 2020 (EU, 2011). This document was subsequently followed by the EU Circular Economy Action Plan of 2015, which brought a vision of a transition of EU Member States from a linear product processing model, generally defined by the extract-make-use-dispose scheme, to a circular economy in which the value of products, materials and resources is preserved for as long as possible and in which waste generation is minimised (EU, 2015b). The new Circular Economy Action Plan (CEAP) of 2020 is the latest follow-up to the EU Action Plan, which brings a real transition to a circular economy and sets more ambitious challenges for recycling and reuse of waste. It is also one of the building blocks of the Green Deal - the European Green Deal - which sets out comprehensive assumptions for the EU's climate neutrality and low-carbon economy by 2050 (EU, 2020).

Directives, as acts of secondary EU law, have a decisive influence in shaping EU law in the field of waste management. The individual secondary legislative acts of European Union law can then be divided into the following headings, which are simplified to the act that is carried out with waste:

- Waste management - the legal framework for waste management within the European Union is set out in Directive 2008/98/EC on Waste (EU, 2008). It is the most important legal norm within European Union law, which forms the basis for waste management. Furthermore, it is mainly Regulation 1013/2006 of the European Parliament and of the Council, which regulates the shipment of waste within the European Union and between Member States and third countries (EU, 2006a).
- Waste generation - Directive 2012/19/EU regulates the management of electrical and electronic equipment waste, aiming to increase the collection of this waste and enable consumers to return the appliances to electrical shops (EU, 2012). Directive 2006/66/EC regulates the management of waste batteries and accumulators (EU, 2006b). Finally, Directive 94/62/EC regulates all packaging placed on the EU market and related packaging waste (EU, 2018b).

- Waste treatment and disposal - The Landfill Directive (1999/31/EC) was also another of the amended Directives under the 2018 Circular Economy Measures (Directive 2018/850/EC), which set a binding target to reduce landfilling to a maximum of 10% of municipal waste by 2035 (EU, 2018a).

Since many of the EU's secondary legislative acts are in the form of directives, they need to be transposed into national law in order to have direct legal effect. This is also the case in the Czech Republic, where the EU legislation is incorporated into domestic law. Until the end of 2020, the key law in the field of waste management was Act No. 185/2001 Coll., on Waste, which was the basic legislation dealing with waste management in the Czech Republic for more than 15 years (Zakon, 2001). Due to the wide amendment of the European Union directives concerning waste management, there was a need to introduce a conceptual change in the national legislation. It was not appropriate to do this in the form of an amendment to the aforementioned Act No. 185/2001 Coll., on Waste, and therefore, the way of creating a completely new legal norm was chosen. This legal norm became Act No. 541/2020 Coll. on Waste (Zakon, 2020a). At the same time, the area of waste management was no longer to be regulated comprehensively by only one legal norm. Therefore, in addition to this law, a separate law, Act No. 542/2020 Coll., on selected end-of-life products (Zakon, 2020b) was created.

When studying published expert sources on efficient waste management in cities, the article's authors came across several recurring themes, most often the use of advanced technologies or smart solutions. The author team of Ali et al. (2020) proposed an IoT-based smart bin monitoring and municipal solid waste management system. This system helps solve problems related to waste material management and waste collection based on IoT for smart cities. The proposed system is able to efficiently collect waste, detect fire in waste material and predict future waste generation. Automatic identification and data collection of the process of emptying municipal waste containers can provide very useful information. Therefore, Svub et al. (2017) used the "RFID" technology to identify the time and location of municipal waste container emptying. Plastics tend to be a major problem in waste management. The circular economy can help reduce the impact of plastic waste through responsive, resilient and digital approaches. In addition, it can facilitate the reduction of plastic consumption. In this regard, consumer behaviour and digitalisation are considered two major factors that play a major role in implementing a circular economy of plastic waste, as Khatami et al. (2023) argued.

The second large thematic group was energetic waste treatment. There are many methods to exploit waste's raw material and energy potential in economically and environmentally acceptable ways. Therefore, Taus et al. (2023) focused their research on reducing the proportion of waste going to landfills, with the goal of zero waste to landfills to increase recycling and the amount of energy recovered from waste. Varjani et al. (2022) noted that the increasing production of municipal solid waste and environmental concerns have sparked a global interest in waste recovery through various waste-to-energy (WtE) methods to produce renewable energy and reduce dependence on fossil fuel-derived fuels and chemicals. Ozturk and Dincer (2020) discussed waste management systems with municipal waste incineration. A thermodynamic analysis of such a system then demonstrated the amount of electricity and heat for district heating that can be obtained by burning municipal solid waste. It is not only the waste composition that is important in achieving the desired energy efficiency. Therefore, Butt et al. (2022) investigated the feasibility of hydrogen as the primary combustion fuel for municipal solid waste incineration.

A third typical theme was the cost-effectiveness of waste management systems. As documented by Khan et al. (2022), economic evaluation of MSW through cost-benefit analysis (CBA) determines the most appropriate treatment/disposal strategy and is often a major concern of solid waste policymakers. For cost optimisation reasons, Valizadeh et al. (2022) proposed a new model to solve the problems of routing municipal waste collection vehicles with time windows and energy generated from waste. According to Di Foggia et al. (2023), municipal solid waste management fees are of great importance for successful waste management. When introducing unit-priced charging schemes, environmental performance improves significantly while per capita costs decrease slightly.

A special fourth problem area of the articles studied was the examples and experiences from the Czech Republic and Slovakia. A comprehensive analysis of the municipal waste management process in cities in the Slovak Republic was carried out by Klobučník (2021). Three main indicators were chosen for the multicriteria analysis: the amount of separated waste, the amount of landfilled waste, and the total current basic expenditure on waste management. The study by Struk and Bodi (2022) presents research on the factors affecting performance in municipal solid waste (MSW) management at the level of individual municipalities in the Czech Republic. It shows that performance in MSW improves with the availability of recycling consolidation facilities, but programs that encourage waste separation or green waste collection do not have the expected effect. Municipal waste management in the Czech Republic and Slovakia has also been subjected to research by Meričková et al. (2022), which concluded that contractual cooperation with external entities dominates. The experts interviewed almost unanimously agreed on three critical limitations related to the issue of inter-municipal cooperation in the supply of MSW - transaction costs of different types, lack of regular comparison of best solutions, and limited motivation to choose optimal service provision schemes.

Taušová et al. (2023) have tried to realistically assess the achievability of the EU recycling and landfilling targets. The situation in this area, not only in Slovakia, is not optimistic.

The Statutory City of Havířov, for which all the analyses in this article will be carried out, is located in Těšín Silesia, in the Karviná District of the Moravian-Silesian Region. It is located in the Ostrava agglomeration 11 km Southeast of Ostrava on the Lučina River. More than 70 thousand inhabitants live here. It is, therefore, the largest Czech town, not a regional or district town. In the Statutory City of Havířov, two companies are currently dealing with the issue of WEEE management - Technical Services Havířov a.s. and CEVYKO a.s.

The new legislation forces municipalities to take major measures to manage WEEE. Due to changes in legislation, which increases the pressure on waste sorting and recycling, the following measures have been taken in the Statutory City of Havířov in recent years (Technické služby Havířov, 2023):

- Opening a new collection yard for Havířov's citizens enables efficient and controlled transfer of waste from citizens closer to their homes.
- Improving the efficiency of the operation of collection yards in the area of waste sorting when collecting waste from citizens.
- Expanding the network of collection containers for sorted waste in container sites. The aim is that all sites should be equipped with all types of containers so that citizens can sort and dispose of their waste in one place.
- Introduction and expansion of separate collection of bio-waste in residential buildings. Containers for bio-waste are placed at container sites. It forms a significant part of mixed municipal waste, and its separation has significant environmental and economic benefits.
- Introduction of separate collection of edible oils and fats at container sites. Educational activities for residents in the form of informative brochures, reports and awareness-raising at events organised by the municipal company.
- However, the main measure is the CEVYKO a.s. project, which aims to ensure long-term and efficient treatment of municipal waste in accordance with the principles of the waste management hierarchy.

## Material and methods

The aim of the authors' team was to identify the key waste groups according to the classification groups that have a major impact on the volume of waste and the cost of the system. Thus, they appear to be crucial for effective waste management in different types of municipalities. Therefore, the authors' team repeatedly met with waste treatment experts from the Statutory City of Havířov, who provided the authors with appropriate data, especially on the amount of total waste and its individual components and the costs of individual waste components, which formed the basic statistical set (Technické služby Havířov, 2023). On the basis of repeated consultations, the criteria for reducing the number of waste input components were gradually defined, resulting in a statistical sample. In a further step, these meetings defined the classification of a small number of waste groups that can replace the original large number of waste components for the purposes of efficient waste management and treatment. The final outcome of the meetings was the formulation of the main research questions:

1. The catalogue of the basic components of mixed municipal waste contains 53 individual items. Can this number be reduced for decision-making regarding the management of secondary raw materials?
2. Is it possible to define the waste groups that have a major impact on the amount of waste and the cost of the waste management system for municipalities of different sizes?
3. Do any of the groups thus form a fundamental effect on the waste management system for different-sized municipalities?

The article's authors agreed with the experts from the Statutory City of Havířov that in answer to the first question, it can be assumed that there is a way to reduce the number of items in the MSW catalogue from 53 items to a set of smaller items. This implies that WEEE items are marginal in terms of volume and cost to the waste management system. In answer to the second question, it can be assumed that there will be a group of basic items of WEEE that will have a major impact on waste volumes and costs and that such a group or groups will be the same for municipalities of different sizes. In response to the third question, it can be assumed that if a group/groups of waste have a major impact on system quantities and costs, it will show similar growth/decline trends across the municipalities of different sizes under consideration.

The basic dataset consists of 53 waste types, each identified by its catalogue number and name. The main data monitored for each type is the amount of waste collected (in tonnes per year) for three different sizes of municipalities:

- Statutory City (hereinafter SC)
- City (hereinafter C)
- Municipality (hereinafter M)

Specifically, it was the statutory town of Havířov, the smaller town of Rychvald and the smallest municipality of Pustějov. All municipalities are located close to each other in a region associated with coal mining for decades. Data (waste quantities) are available from 2016 to 2021 for the statutory town of SC. Other data available in the base file are average unit costs for waste disposal and collection, mostly converted to CZK per 1 tonne of waste (excluding VAT). All waste types are classified according to 5 criteria, and in each case, they are assigned to one of three groups (categories):

Classification WASTE:
- municipal waste (WAS1)
- hazardous waste (WAS2),
- other waste (WAS3);

Classification RECYCLING:
- 100% recyclable (REC1),
- partially recyclable (REC2),
- non-recyclable (REC3);

Classification ENERGETICS:
- partial use (ENE1),
- energy potential (ENE2),
- other waste (ENE3);

Classification TRANSPORTATION:
- collection vehicles (TRA1),
- container collection (TRA2),
- other transport (TRA3);

Classification PRICE (= cost):
- permanently negative price (PRI1),
- permanently positive price (PRI2),
- variable price (PRI3).

For the purpose of further analyses and validation of the research questions, the core dataset was reduced from the original 53 items to the resulting 27 items. The following two rules were established for the reduction:
- average amount of waste in at least one municipality size (SC, C, M) above 1 t per year;
- The available unit cost of waste in CZK is per tonne of waste (excluding VAT).

The average waste quantity$\bar{Q}$ was obtained as the arithmetic average of these values for 2016 to 2021. The unit cost of $AC$ waste was obtained by simply summing the waste price $P_q$ and the collection price $P_{tr}$ (excluding VAT):

$$AC = P_q + P_{tr} \quad (1)$$

As it turned out, except for one item, both criteria led to the same data reduction. That is to say, the missing data on unit costs of waste is related mostly to items with an average waste quantity below 1 t/year in all three municipalities of all sizes. Table 1 shows the selected 27 items of the reduced sample, including the classification of the items according to the above 5 criteria. The items are listed in order of increasing catalogue number.

*Tab. 1. The obtained sample of 27 items (waste types)*

| Number | Type |
|---|---|
| 150102 | Plastic packaging |
| 150105 | Composite packaging |
| 150110 | Packaging containing or contaminated with NL residues |
| 160103 | Tyres |
| 170101 | Concrete |
| 170102 | Bricks |
| 170203 | Plastics |
| 170405 | Iron and steel |
| 170409 | Metal waste contaminated with NL |
| 170504 | Soil and stones other than those mentioned in 17 05 03 |
| 170604 | Insulation materials other than those mentioned in 17 06 01 and 17 06 03 |
| 170605 | Building materials containing asbestos |

| Number | Type |
|---|---|
| 170904 | Mixed construction and demolition waste not listed under |
| 190805 | Sludges from municipal wastewater treatment |
| 200101 | Paper and cardboard |
| 200102 | Glass |
| 200110 | Clothing |
| 200125 | Edible oil and fat |
| 200127 | Paints, printing paints, adhesives and resins containing NL |
| 200138 | Wood other than those mentioned in 20 01 37 |
| 200139 | Plastics |
| 200140 | Metals |
| 200201 | Biodegradable waste |
| 200203 | Other non-biodegradable waste |
| 200301 | Mixed municipal waste |
| 200303 | Street rubbish |
| 200307 | Bulky waste |

*Source: katalogodpadu.cz*

In order to compare the development (dynamics) of waste volumes Q and the total costs of waste disposal TC, the total costs of TC (in CZK per year) were calculated for each item (type of waste), each size of municipality and each year:

$$TC = Q \cdot AC \tag{2}$$

*where Q is the quantity of waste (in tonnes per year), and AC is the unit cost of waste (in CZK per tonne).*

The resulting sample dataset contains data on waste volumes Q and waste costs TC for individual items, municipality sizes (SC, C and M), and years (2016 to 2021). In the next step, the authors calculated two summary characteristics (Friedrich et al., 2020):

- average (annual) value of waste volume $\bar{Q}$ (mathematically expressed as $\bar{x}$)

$$\bar{x} = \frac{x_{16}+x_{17}+x_{18}+x_{19}+x_{20}+x_{21}}{6} \tag{3}$$

- the marginal slope of the waste volume $\Delta Q$ (mathematically expressed as $\Delta x$), which determines the rate of change of the indicator over the time period under consideration.

$$\Delta x = \frac{x_{21}-x_{15}}{5\bar{x}} \tag{4}$$

In this way, 45 indicators and corresponding statistics are obtained for the quantity of waste and 45 indicators for the cost of waste. The interrelationships between the groups according to the proposed classification (Waste, Recycling, Energy, Transportation, and Price) can be graphically expressed by a two-dimensional perceptual map (Gigauri, 2019), which on the horizontal axis shows the magnitude, i.e. the average value of the indicator $\bar{x}$ (waste volume or cost) for the period under study, on the vertical axis, its dynamics, i.e. the marginal trend of growth or decline$\Delta x$. Items that are located near the centre (intersection of the axes) in the four-field matrix do not have a distinct profile. Conversely, the deeper the items are within a quadrant (away from both axes), the more pronounced their profile, as expressed by the properties of that quadrant.

The individual quadrants can be characterised as follows (see Figure 1):

- Quadrant I - high proportion, rather increasing (high load and still strengthening).
- Quadrant II - low proportion, rather increasing (low burden, but may strengthen).
- Quadrant III - low proportion, rather decreasing (lowest load, uninteresting).
- Quadrant IV - high proportion but rather declining (high burden but weakening).

| | low proportion | high proportion |
|---|---|---|
| rather increasing | **II.** | **I.** |
| rather decreasing | **IV.** | **III.** |

*Fig. 1. Perceptual map with four quadrants*
*Source: own source*

## Results

### Slope analysis

The waste volume slope analysis compares the observed waste volume slopes to determine which group and by which classification shows the largest increase in waste volume. As shown in Table 2, most groups in the City have a positive waste volume slope, indicating that waste volumes are predominantly increasing year by year. Hazardous waste, other modes, and consistently positive prices are the groups with the largest increases. Plastics are mostly found in SC groups with negligible or small increases in waste volumes.

*Tab. 2. Comparison of volume slopes for the Statutory City*

| Waste Group (SC) | Slope of Volumes |
|---|---|
| WAS 2 – hazardous waste | 0.4684 |
| TRA 3 – other transport | 0.3013 |
| PRI 1 - permanently positive price | 0.1483 |
| ENE 2 - energy potential | 0.0872 |
| PRI 2 - variable price | 0.0755 |
| REC 1 - 100% recyclable | 0.0605 |
| REC 2 - partially recyclable | 0.0409 |
| WAS 1 - municipal waste | 0.0218 |
| ENE 1 - partial use | 0.0199 |
| TRA 2 - container collection | 0.0187 |
| TRA 1 - collection vehicles | 0.0142 |
| PRI 3 - permanently negative price | 0.0074 |
| ENE 3 - other waste | 0.0013 |
| REC 3 - non-recyclable | -0.0031 |
| WAS 3 - other waste | -0.0245 |

*Source: own source*

When compared with other municipalities, it was found that the waste groups with other forms of transport and with consistently positive prices showed the highest relative increase in waste volumes in the City. Conversely, partially recycled waste and hazardous waste (which were among the groups with the largest increase in waste volumes in SC showed a significant year-by-year decrease in waste volumes. As with the Statutory City, Plastics for the City were mostly in groups with negligible or small waste volume increases. The groups with the largest increases in waste volumes in the Municipality include Other Waste, Variable Price Waste, and those with consistently positive prices. Groups with decreasing waste volumes include wastes with energy potential, partially recycled wastes, and hazardous wastes, similar to those in the city. The groups containing plastic in the Municipality, similar to the Statutory City and the City, are those with negligible or positive growth in waste volumes. Compared to the City, the slope of these groups is higher, indicating a greater year-by-year increase in volumes.

*Tab. 3. Comparison of cost slopes for the Statutory City*

| Waste Group (SC) | Slope of Costs |
|---|---|
| TRA 3 – other transport | 0.2355 |
| PRI 1 - permanently positive price | 0.1498 |
| ENE 2 - energy potential | 0.1149 |
| REC 1 - 100% recyclable | 0.1049 |

| | |
|---|---|
| REC 2 - partially recyclable | 0.0894 |
| PRI 2 - variable price | 0.0821 |
| ENE 1 - partial use | 0.0780 |
| WAS 1 - municipal waste | 0.0773 |
| TRA 1 - collection vehicles | 0.0749 |
| TRA 2 - container collection | 0.0718 |
| PRI 3 - permanently negative price | 0.0584 |
| REC 3 - non-recyclable | 0.0494 |
| ENE 3 - other waste | 0.0437 |
| Waste Group (SC) | Slope of Costs |
| WAS 3 - other waste | 0.0330 |
| WAS 2 – hazardous waste | -0.0889 |

*Source: own source*

Similarly to the comparison of waste volume slopes in each group according to the size of the municipality, the slopes of waste treatment and disposal costs were also compared. For the Statutory City, the groups with a slight increase in waste costs predominate; see Table 3. The waste groups with the highest slope (year-by-year increase) are those with other forms of transport, with consistently positive prices and energy potential. On the other hand, the only group with a negative (decreasing) slope in waste costs is the WAS2 group with hazardous waste. The groups, including Plastics, are among the groups with a slight to moderate increase in waste costs. Compared to waste volume, there is, therefore, a shift towards a higher slope (faster increase in costs than waste volume).

For the City, similar to the Statutory City, the groups with a positive waste cost slope predominate. Waste groups with other forms of transportation, consistently positive prices, and 100% recycled also show the largest cost increases. In contrast, hazardous waste (WAS2) is the group with a significant average decrease in annual waste costs. Also, for the City, groups including Plastics are among the groups with a slight to moderate increase in waste costs. Also, for the Municipality, groups with a positive slope in waste costs are predominant, but groups with a negative slope are also more represented. With one exception (ENE3), the groups expressing stagnation in average costs, i.e. a negligible marginal waste cost slope, have disappeared. For the Municipality, the largest increases in waste costs are observed in the WAS3 group, along with other waste types, containerised waste and variable waste. Conversely, the largest year-by-year decreases in waste costs are in the groups of waste with energy potential, partially recycled waste, and waste with other types of transport. Hazardous waste (WAS2) is still one of the groups with a significant decrease in costs, but no longer in the first place. Groups including Plastics are among the groups with a slight and medium positive slope in waste costs. This is similar to the City, but the slope values are higher (larger relative year-on-year cost increases than for the City).

**Analysis of volumes and costs in groups**

This analysis compares the average waste volumes and disposal costs for the period under review on a relative basis (in %) for each group. The aim of the analysis is to see how the volume of waste from each waste group affects the costs of waste treatment and disposal. The cost-effectiveness of *the NA* of a given group can be expressed as the difference between the percentage of waste volumes in that group and the cost of disposal:

$$NA_i = pQ_i - pC_i \qquad (5)$$

*where pQ is the percentage share of the group in the waste volume, and pC is the percentage share of the cost of waste treatment and disposal.*

NA cost-effectiveness values are colour-coded in the Table 4 according to their sign:

- red = cost-intensive group (positive sign) - the share of waste costs exceeds the share of waste,
- blue = cost advantage group (negative sign) - the share of waste exceeds the share of waste costs,
- white = cost neutral group - the share of waste and waste costs is comparable.

*Tab. 4. Cost-effectiveness of groups for the Statutory City*

| Waste Group (SC) | Waste Volume | | Costs | | Difference |
|---|---|---|---|---|---|
| | t | % | CZK | % | % |
| REC 1 - 100% recyclable | 5201.56 | 18.47 | 16791560.09 | 32.36 | 13.89 |
| PRI 2 - variable price | 597.59 | 2.12 | 7443598.80 | 14.35 | 12.23 |

| | | | | | |
|---|---|---|---|---|---|
| TRA 1 - collection vehicles | 17237.79 | 61.21 | 37811512.46 | 72.88 | 11.67 |
| PRI 1 - permanently positive price | 1815.87 | 6.45 | 7451129.15 | 14.36 | 7.91 |
| WAS1 - municipal waste | 25788.28 | 91.57 | 49164884.53 | 94.76 | 3.19 |
| ENE 1 - partial use | 25119.02 | 89.19 | 47009342.68 | 90.60 | 1.41 |
| ENE 2 - energy potential | 18.30 | 0.06 | 120022.77 | 0.23 | 0.17 |
| WAS 2 – hazardous waste | 4.75 | 0.02 | 17794.39 | 0.03 | 0.01 |
| TRA 3 – other transport | 195.11 | 0.69 | 275589.49 | 0.53 | -0.16 |
| ENE 3 - other waste | 3026.31 | 10.75 | 4755043.78 | 9.16 | -1.59 |
| REC2 - partially recyclable | 5962.72 | 21.17 | 9801705.70 | 18.89 | -2.28 |
| Waste Group (SC) | Waste Volume | | Costs | | Difference |
| | t | % | CZK | % | % |
| WAS 3 - other waste | 2370.59 | 8.42 | 2701730.30 | 5.21 | -3.21 |
| TRA 2 - container collection | 10730.73 | 38.10 | 13797307.27 | 26.59 | -11.51 |
| REC 3 - non-recyclable | 16999.35 | 60.36 | 25291143.43 | 48.75 | -11.61 |
| PRI 3 - permanently negative price | 25750.17 | 91.43 | 36989681.28 | 71.29 | -20.14 |

*Source: own source*

The most cost-intensive waste groups in the City appear to be 100% recycled waste, waste with variable prices and waste transported by collection vehicles. The least cost-intensive (most cost-effective) waste groups are consistently negatively priced, non-recycled and containerised waste. Comparison with the City shows that the same waste groups are the most and least costly in the City, just in a different order. Also, in the Municipality, the most cost-intensive and least cost-intensive waste groups are the same as in the Statutory City and the City (except for their order). Therefore, the conclusions presented in this section for the Statutory City can be extended to a municipality of any size.

An item-by-item analysis was also performed to more finely differentiate the cost-effectiveness results. Only 27 items, forming a reduced sample, are included in this analysis. However, Table 5 shows only those items that achieved significant positive or negative results. In the case of the Statutory City, Plastics (cat. no. 200139) has the highest cost intensity; the next high-intensity items are Paper and Cardboard (cat. no. 200101) and Glass (cat. no. 200102). In contrast, the highest cost-efficiency items are Mixed municipal waste (cat. No 200301), Biodegradable waste (cat. No 200201) and Bulky waste (cat. No 200307).

*Tab. 5. Cost-effectiveness of items for the Statutory City*

| No. | Waste Type (SC) | Waste Volume | | Costs | | Difference |
|---|---|---|---|---|---|---|
| | | t | % | CZK | % | % |
| 200139 | Plastics | 590.45 | 2.10 | 7438107.66 | 14.34 | 12.24 |
| 200101 | Paper and cardboard | 937.06 | 3.33 | 5182927.28 | 9.99 | 6.66 |
| 200102 | Glass | 670.20 | 2.38 | 2115493.46 | 4.08 | 1.70 |
| … | … | … | … | … | … | |
| 170504 | Soil and stones other than 170503 | 527.21 | 1.87 | 232732.13 | 0.45 | -1.42 |
| 170904 | Mixed construction and demolition waste not listed | 1782.44 | 6.33 | 2391897.66 | 4.61 | -1.72 |
| 200307 | Bulky waste | 5951.93 | 21.13 | 9790587.49 | 18.87 | -2.26 |
| 200201 | Biodegradable waste | 2406.13 | 8.54 | 1304989.48 | 2.52 | -6.03 |
| 200301 | Mixed municipal waste | 14659.50 | 52.05 | 22542688.56 | 43.45 | -8.60 |

*Source: own source*

Also in the City, the highest cost-intensity item is Plastics (cat. no. 200139), followed by Paper and Cardboard (cat. no. 200101) and Glass (cat. no. 200102). Therefore, the highest cost intensity items are the same for the Statutory City and the City, even with the same ranking. The items with the highest cost-effectiveness are Biodegradable waste (Cat. No. 200201), Mixed municipal waste (Cat. No. 200301) and Mixed construction and demolition waste not listed (Cat. No. 170904). Except for the latter, these are again the same items as for the Statutory City, only in a different order. Plastics (cat. no. 200139) also dominate the cost-intensive items in the Municipality, followed by Plastic packaging (cat. no. 150102) and Paper and cardboard (cat. no. 200101). Conversely, cost-effective items include Biodegradable waste (cat. No 200201), Mixed municipal waste (cat. No 200301) and Sludge from municipal wastewater treatment (cat. No 190805). It is clear that some items are cost-effective or ineffective regardless of the size of the municipality in which the waste is generated. For example, Plastics is the least efficient item in all three types of municipalities studied.

**Analysis of perceptual maps**

In order to assess the relationships in a multidimensional space, graphical descriptions using perceptual maps were used. The economic requirements of each waste group are expressed in the form of a perceptual map, separately for waste volumes and costs. The perceptual map shows the average value of waste volumes and costs over the period under consideration on the horizontal axis and the trend of growth and decline on the vertical axis. In the case of waste volume (Figure 2), it is clear that the groups in the first quadrant, which represent the greatest burden, are not present in the City. The vast majority belong to the third and fourth quadrants, which are the groups with the lowest growth and the highest marginal decrease, respectively.

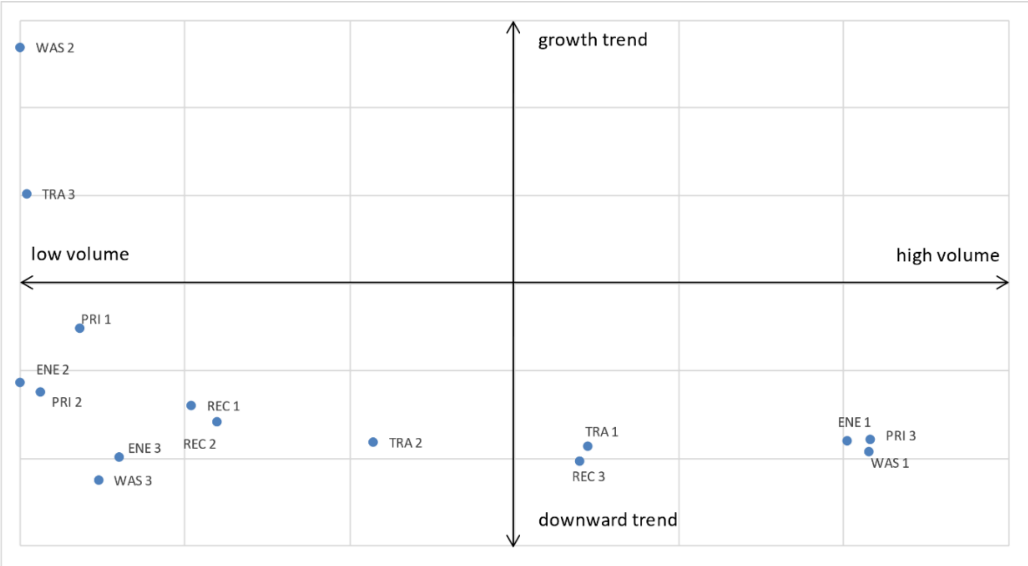


*Fig. 2. Perceptual map for the Statutory City - waste volume*
*Source: own source*

By comparing the perceptual maps for waste volumes and waste costs for the Statutory City (Figure 3), it is clear that some groups have moved from the 4th quadrant closer to the first quadrant, indicating a greater economic intensity of the groups and items. All these indicators show that the cost of waste disposal in the Statutory City is increasing faster than the volume of waste.

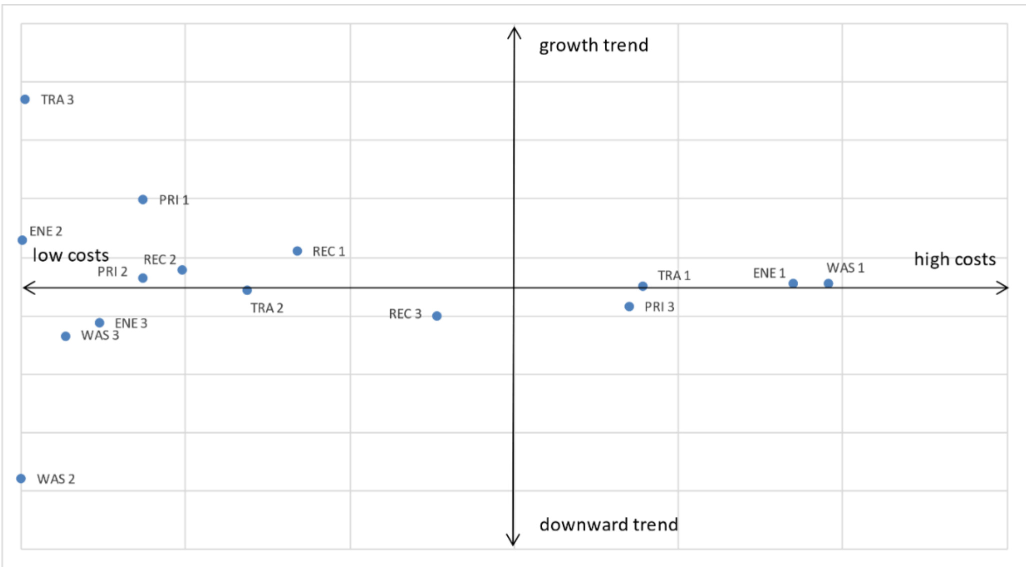


*Fig. 3. Perceptual map for the Statutory City - waste costs*
*Source: own source*

The most pronounced profiles in both maps are WAS2 - hazardous waste and TRA3 - waste transported by other means. Hazardous waste is classified in the second quadrant for waste quantities and in the third quadrant for waste costs. This means that although there is a small representation of this type of waste, an increase in the volume can be expected in the following years, but the costs are not significantly affected. In contrast, waste transported by other means (other than collection and container transport) tends to increase in both volume and cost. On the contrary, the significant profiles ENE1 - waste with partial energy recovery, WAS1 - municipal waste and PRI3 - waste with permanently negative price are located in quadrant 4 with volume, while costs for all these groups are on the borderline of quadrants 1 and 4. This means that these groups represent a relatively large amount of waste, and despite the decreasing trend in waste volume, the costs of disposal are not decreasing.

When comparing the Statutory City with other municipalities, it was found that the perceptual map for waste volume for the City is similar to the map for the Statutory City. The perceptual map for waste costs for the City resembles the perceptual map for waste volume in the distribution of the different groups. Thus, unlike the City, there is no significant shift to the upper quadrants (1 and 2). It can be concluded that the development and structure of waste volume costs in the City are analogous to the development and structure of waste volumes. Thus, there is no faster growth in waste costs than in the City. The perceptual map for waste volumes in the Municipality is similar in shape (distribution of groups) to the map for the City. However, the individual points are shifted more towards the 1$^{st}$ and 2$^{nd}$ quadrants. This means that the Municipality has the fastest increase in waste volume compared to the other municipalities (SC and C). However, this increase is relative to the average values for a municipality of a given size. In fact, waste volumes are highest in the Statutory City and lowest in the Municipality. The distribution of the individual points (groups) in the perceptual map for waste costs for the Municipality is similar to the map for waste volumes, but the points are shifted lower in the 3$^{rd}$ and 4$^{th}$ quadrants. This fact means that in the Municipality the rate of growth of costs is relatively lagging behind the rate of growth of waste volumes. Thus, the largest economic burden is on the Statutory City, and this burden decreases as the size of the municipality decreases. Thus, the "cheapest" waste is in the Municipality, but the "most expensive" is in the Statutory City (calculated from the relationship between waste volumes and disposal costs).

## Discussion

In terms of the main topics of the studied scientific research, the author's team succeeded in:

- the situation in the Czech Republic and Slovakia - to build on the knowledge of the outputs of the abovementioned Czech and Slovak authors in the development of the methodology of the whole analytical procedure, especially regarding the important factors and criteria for effective management and waste management for different municipalities,
- energy treatment of waste - to be used for classification purposes, where a total of three groups had an energy subtext (ENE groups) and one of these groups (ENE1) even ranked among the three most important groups that have a major impact on the amount of waste and the cost of the WEEE management system for municipalities,
- cost efficiency - apply the issue in all analyses performed and especially in the analysis of volumes and costs in groups,
- use of advanced technologies - as a response to legislative requirements and partly to the findings of the author's team, the implementation of modern waste sorting and processing technology is being prepared in the Statutory City of Havířov.

Based on the analyses, it is now possible to comment on and verify the original expectations of the author's team, which were based on three research questions.

*1. The catalogue of the basic components of mixed municipal waste contains 53 individual items. Can this number be reduced for decision-making regarding the management of secondary raw materials?*

It can be concluded that there is a reduced set of basic items. This file contains a total of 27 items, compared to 53 items in the input data file. As verified by the analytical procedures, 26 items from the input dataset have a negligible impact on the total volume of waste collected and the total cost of the MSW management system.

*2. Is it possible to define the waste groups that have a major impact on the amount of waste and the cost of the waste management system for municipalities of different sizes?*

The amount of waste collected in each group has been shown to impact the cost of the entire waste management system significantly. The three main waste groups, WAS1, ENE 1, and PRI3, significantly influence the amount of waste and the cost of the municipal waste management system in all three municipalities studied. These three groups contain, on average, about 13 original components each and have common subsets of these basic components of WEEE. In particular, in the case of the WAS1 and ENE1 pairs, there are 10 common waste components.

*3. Do any of the groups thus formed affect the waste management system for municipalities of different sizes in the same or similar ways?*

Of the 15 pre-defined groups of basic waste groups, WAS group 1 was found to be the most influential cost driver of the whole waste management system for all municipalities studied. The results confirm that the WAS1 group significantly influences both parameters, i.e., waste quantity and waste costs for all three municipalities studied: SC, C, and M. The WAS1 waste group contains a total of 13 basic components of WEEE and influences both parameters studied by around 90%, showing that this group is crucial for the whole waste management system. It influences the total system costs for each municipality between 89.6% and 94.8%.

## Conclusions

The author's team aimed to help simplify the decision-making of managers and leaders of the statutory city in waste management and handling. To this end, the number of items in the waste catalogue was gradually reduced from 53 to 27. Subsequently, 15 classification groups were created from these 27 items. Of these, three significant groups were selected first. From these major groups, one major group was then selected, which contained the original 13 items. Such a significant reduction of input variables is successful from the viewpoint of the author team. In addition, the main classification group WAS1 municipal waste achieves the strongest position across all municipalities studied.

Each of these main groups is characterised by the original items of which it is composed. The original items bring with them their specificities to each group (see Plastics). The author team is aware that mere mathematical analysis of data cannot be sufficient for such a complex activity as the application of circular economy in practice. Therefore, the authors would like to focus on more sophisticated statistical analyses such as factor, cluster, or regression analysis in the next steps. They would like to try to reduce the number of input variables in this way and check whether the conclusions described here are correct and whether the resulting factors (clusters) will have similar characteristics to, for example, WAS1, ENE1 or PRI3 groups.

The main pitfall of mathematical-statistical analyses is the absence of other important factors, such as residents' motivation to sort, the amount of the waste collection fee, etc. These are often political decisions that are not always based on rational quantitative analysis.

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