Using multi-criteria decision making for selection of the optimal strategy for municipal solid waste management

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Using multi-criteria decision making for selection of the optimal strategy for municipal solid waste management

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Abstract

Multi-criteria decision making (MCDM) is a relatively new tool for decision makers who deal with numerous and often contradictory factors during their decision making process. This paper presents a procedure to choose the optimal municipal solid waste (MSW) management system for the area of the city of Kragujevac (Republic of Serbia) based on the MCDM method. Two methods of multiple attribute decision making, i.e. SAW (simple additive weighting method) and TOPSIS (technique for order preference by similarity to ideal solution), respectively, were used to compare the proposed waste management strategies (WMS). Each of the created strategies was simulated using the software package IWM2. Total values for eight chosen parameters were calculated for all the strategies. Contribution of each of the six waste treatment options was valorized. The SAW analysis was used to obtain the sum characteristics for all the waste management treatment strategies and they were ranked accordingly. The TOPSIS method was used to calculate the relative closeness factors to the ideal solution for all the alternatives. Then, the proposed strategies were ranked in form of tables and diagrams obtained based on both MCDM methods. As shown in this paper, the results were in good agreement, which additionally confirmed and facilitated the choice of the optimal MSW management strategy.

Keywords

MCDM, municipal solid waste management, choice of optimal management system, SAW, TOPSIS

Introduction

Most of the present waste management models developed to support decision making and selection of an optimal waste management strategy (WMS) can be classified as:

- Models based on the cost benefit analysis of the studied waste management system;
- Models that consider environmental, energetic and material aspects of the WMS;
- Multi-criteria decision making (MCDM) models for selection of the optimal WMS (Morrissey and Browne, 2004).

MCDM is a relatively new discipline aimed at providing support to decision makers and stake holders who deal with numerous and often contradictory impact factors. It belongs to decision making theory, which integrates many scientific disciplines: mathematics, statistics, economy, psychology, sociology, philosophy, organizational sciences, informational technologies, etc. The term 'multi-criteria decision making' was first used in the area of management sciences in the USA in 1972 (Bana e Costa and Pirlot, 1997). The European 'version' of this method is multi-criteria decision analysis (MCDA). These methods aim to reach optimal and compromise solutions and improve the quality of made decisions by satisfying multiple criteria. The result of the decision making process should be an explicit, rational and effective solution.

All MCDM(A) procedures involve several criteria that are often contradictory. This multi-dimensional approach yields a more sustained decision compared with decisions reached by one-dimensional procedures. The basic approach involves identification of a number of alternatives (such as different WMS), assessment based on the adopted criteria, and, finally, ranking of options. It is necessary to define objectives, form alternatives and compare different perspectives in order to distinguish acceptable from unacceptable possibilities (Marttunen, 2011).

The decision making process is realized in the steps given in Figure 1 (Mourits and Oude Lansink, 2006). The first step involves defining the scope and primary objectives that comprise the decision context. These objectives must be specific, realistic and measureable. The second phase involves identification of all

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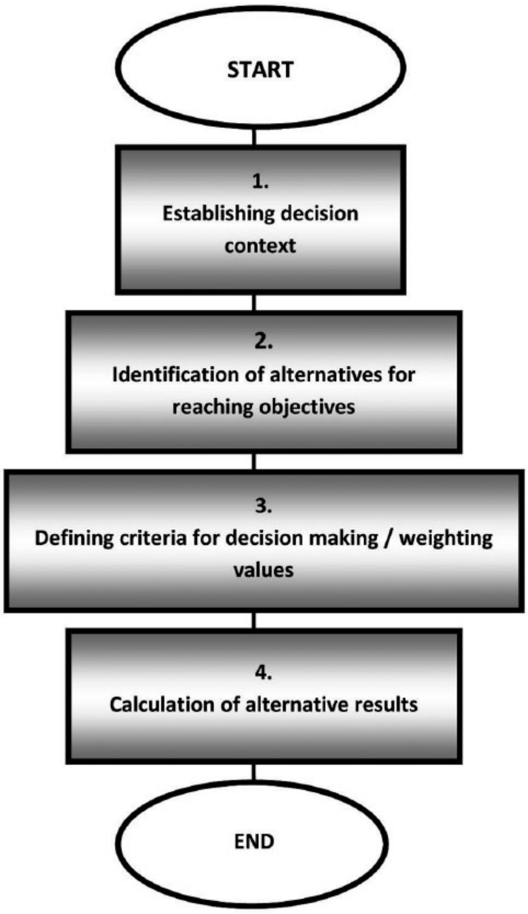

Figure 1. A basic multi-criteria decision making (MCDM) model.

possible alternatives to achieve the projected goals. In the third step, the decision makers define criteria for assessment of the performances that reflect the level to which the objectives have been realized. This phase involves assigning weighting coefficients and defining criteria priorities, if any. The last phase of the MCDM procedure includes assessment and ranking of the options in order to reach an optimal choice.

The most frequently used criteria include economic, environmental and energetic parameters. Recently, however, numerous analyses have also included various sociological and legal criteria (Ehrgott et al., 2010).

Materials and methods

These tasks are usually stated as the final results of the MCDM process (Bernardini et al., 2007):

- Obtaining an optimal solution – multi-criteria optimization;
- Ranking of the obtained results – alternatives;
- Distinguishing acceptable from unacceptable alternatives.

The final set of alternatives (options, potential solutions) is considered $A_i \in A$. Each alternative solution can be assessed based on several criteria $C_j \in C$. The alternatives (A_i) and criteria (C_j) and their mutual relations can be represented in a form of a matrix table or the so-called decision matrix. Each of the criteria (C_j) can be of maximization (max) or minimization (min) type.

The simple additive weighting (SAW) method (Fishburn, 1967) is one of the best known, relatively simple and most widely used procedures, which gives results similar to the ones obtained using more complex MCDM methods. Each of the criteria is added a weighting coefficient determined by a decision maker or obtained by a method for determination of the criteria weighting coefficients. For each of the studied alternatives, the sum characteristics, i.e. the sum value of the products of relative weighting factors and normalized values of the performances per all the criteria, are calculated. The alternative with the highest value of the sum characteristics is the best of all the proposed solutions:

$$A^* = \left\{ A_i \middle| \max_i \sum_{j=1}^{n} W'_j r_{ij} \right\}. \quad (1)$$

The technique for order preference by similarity to ideal solution (TOPSIS) method is used to assess and rank the alternatives based on their distance in relation to the so-called ‘ideal’ alternative (‘ideal’ solution) and ‘anti-ideal’ alternative (‘anti-ideal’ solution). The solution at the least distance from the ideal and at the greatest distance from the anti-ideal option is chosen as the best. The relative closeness coefficient – RC_i of the ith alternative to the ideal solution – is calculated based on the following expression:

$$RC_i = \frac{D_i^-}{D_i^- + D_i^+} \quad (2)$$

where D_i^+ stands for the distance of the ith alternative from the ideal solution and D_i^- from the anti-ideal solution.

According to the official results of the 2011 census, the City of Kragujevac has a population of 179 417 inhabitants. Average generation rate of municipal waste per capita is 280 kg per year. Waste composition used in this paper is taken from experimental research conducted for the City of Kragujevac (Vujic et al., 2010). Waste fractions are adapted to requirements of IWM2 software package. The amount and composition of the generated municipal waste for the City of Kragujevac are given in Table 1.

As seen in Table 1, organic waste (about 40%) and recyclable materials (about 50 %) account for the greatest part of the waste. Hence, the future local municipal waste management system should have a facility for biological treatment of organic waste as well as a recycling facility.

If there is a landfill gas collection system installed, an optimum distribution of organic waste to be treated and disposed to landfill should be reached. As there is a large amount of recyclable materials, a significant amount of waste is sent to the recycling facility.

The six chosen municipal solid waste (MSW) management strategies were modelled using the software package IWM2 (Jovanovic, 2015). The input parameters were obtained from the studies on the quantity and composition of the generated MSW in Kragujevac conducted over several years (Vujic et al., 2010).

Table 1. The amount and composition of the generated municipal waste for the City of Kragujevac.

	Waste fractions								
	Paper	Glass	Ferrous metal	Non-Fe metal	Film plastic	Rigid plastic	Textiles	Organics	Other
Amount per year (tonnes)	11 419	3297	2832	595	4565	4565	1217	21 708	5961
% by weight	20.3	5.9	5.0	1.1	8.1	8.1	2.2	38.7	10.6

The first strategy (1KG) is characterized by a complete disposal (100%) of the generated and collected waste to landfill. In this case, the landfill is not equipped with a landfill gas collection system. According to the second strategy (2KG), about 10% of the generated waste is separated, while 90% of it is disposed to landfill. Unlike the first strategy, the landfill is equipped with a system for landfill gas collection and its utilization. In the third strategy (3KG), a larger amount of waste is to be recycled (21.66%), which requires installation of a secondary separation system. The rest of the waste is treated as in the 2KG strategy. The fourth strategy (4KG) involves treatment of biological waste (16.35%). A by-product of about 4250 tonnes (about 7.6%) of biologically treated waste is incinerated, while 1.2% of it is disposed to landfill. The amount of recycled waste reaches up to 30% in this strategy, while the total amount to be disposed to landfill is 35 494 tonnes or about 63% (i.e. 10.9% from the waste separation process, 1.2% residues from the biological treatment and 51.1% of the waste directly disposed to landfill). With the fifth strategy (5KG), the amount of waste to be incinerated is significantly increased (31.79%). The amount of waste to be biologically treated is the same as with the 4KG strategy. The percentage of the recycled waste is also almost identical to the one in the previous strategy (29.28%), while the percentage of the waste disposed to land fill decreases below 40%. The disposed waste is treated in the same way as in the second, third and fourth strategy. With the sixth strategy (6KG), the amount of waste to be incinerated is further increased (55.6%). The percentage of the recycled waste is about 27.4%, which is slightly smaller compared with the two previous strategies. Due to significant changes in the municipal waste management system, the amount of waste to be disposed to landfill reaches only 17%. The landfill treatment concerning the landfill gas and leachate collection system remains the same.

Figure 2 shows the waste treatment process including mass balance for the 6KG strategy. This alternative solution has the most complicated waste distribution and process of all the proposed strategies.

For each of the chosen strategies, the comparative analysis of the values of the following eight parameters was performed:

- Methane (CH_4) emissions;
- Carbon dioxide (CO_2) emissions;
- Global warming potential (GWP) factor;
- Dinitrogen oxide (N_2O) emissions;
- Particulate matter emissions (PM);
- Fuel consumption for the system operation (FC);
- Total operating costs (TOC);
- Volume of the remaining solid waste disposed to landfill (VW).

Results and discussion

Greenhouse gases and particulate matter emissions into the atmosphere

The diagram in Figure 3 shows extremely high CH_4 emission for the strategy 1KG of more than 3600 tonnes a year. In the 2KG strategy, although the amount of the disposed waste is decreased by only 9%, gas emissions are decreases more than 10-fold, but this is due to the installed landfill gas collection and utilization system. In both strategies, landfill CH_4 emissions are predominant, but the waste collection process also contributes to gas emissions. The recycling process yields positive results concerning the impact on the environment for all the strategies. The overall CH_4 emission decreases from the first to the last strategy. In the 6KG strategy (characterized with a large amount of incinerated waste and significantly decreased amount of disposed waste), CH_4 emissions reach negative values and enter the savings zone, with no adverse impact on the environment. Primary and secondary separation processes and biological treatment have little influence on the overall value of this parameter. The influence of the sorting process increases with the increase in the amount of recycled waste. The incineration process is characterized with the complete absence of CH_4 gas emissions.

The highest CO_2 emissions (above 28 000 tonnes per year) are registered with the 6KG strategy, which is mainly due to incineration (Figure 4). The 5KG strategy with the annual emission of 18 000 tonnes is the second worst ranked. The lowest overall emission of this greenhouse gas is recorded for the 4KG strategy.

With all the strategies, and especially with the first three where the amount of waste disposed to landfill is the largest, high CO_2 emissions are recorded. Recycling significantly decreases CO_2 emissions for all the strategies. This is particularly obvious when large quantities of waste are recycled. Collection of waste has relatively similar levels of CO_2 emissions for each variant, while sorting and biological treatment have negligible impact on these emissions.

In general, emissions of N_2O are not significantly high for the presented strategies (Figure 5). The highest emissions are

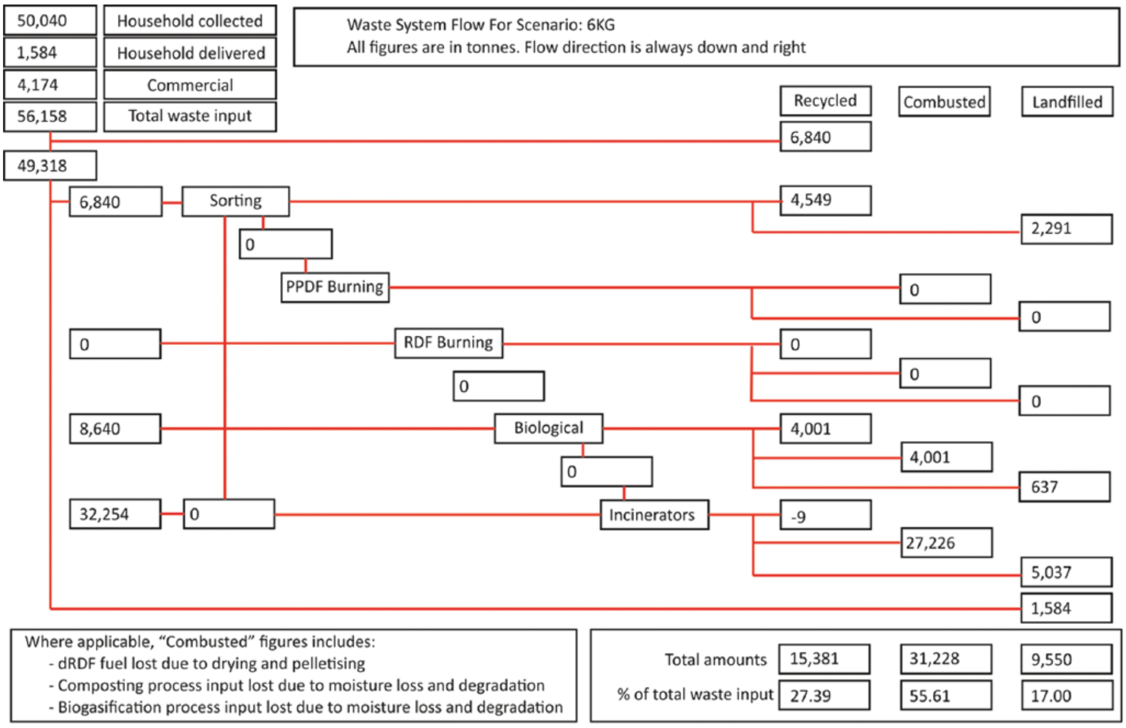

Figure 2. Waste management flow chart for the 6KG strategy (in tonnes per year).

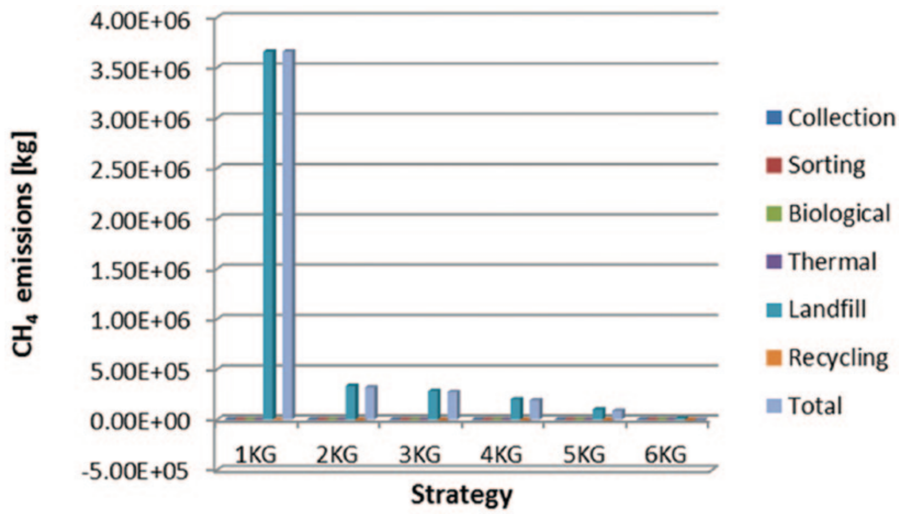

Figure 3. Methane (CH_4) emissions for the proposed strategies [kg].

recorded for the 3KG strategy, where they are mainly the result of recycling. The other strategies have mostly negative emissions (2KG, 4KG, 5KG and 6KG) or negligible positive values (1KG). The diagram in Figure 6 shows that incineration has the greatest impact on the levels of PM emissions – the larger the amount of incinerated waste, the higher the levels of PM emissions. The rest of the strategies have little influence on this parameter.

Global warming potential factor

CH_4, CO_2 and N_2O are the most significant greenhouse gases produced in the waste treatment sector. This part of the paper will give a short analysis of the impact of the GWP factor (Figure 7) in the given strategies. CH_4 from landfill is considered the greenhouse gas with the highest impact on global warming.

Figures 3, 4 and 5 show significant congruence of distributions of CH_4 emissions and GWP factor values for different strategies. The 1KG strategy has the highest GWP that reaches up to 85 000 tonnes per year. For this strategy, the contribution of landfill processes is much higher than the contribution of the waste collection and transport processes. In the strategies 2KG, 3KG and 4KG, the amount of the waste disposed to landfill is relatively high, but the landfill gas and leachate collection and treatment system significantly decreases landfill gas emissions. Installation and operation of these collection systems brings

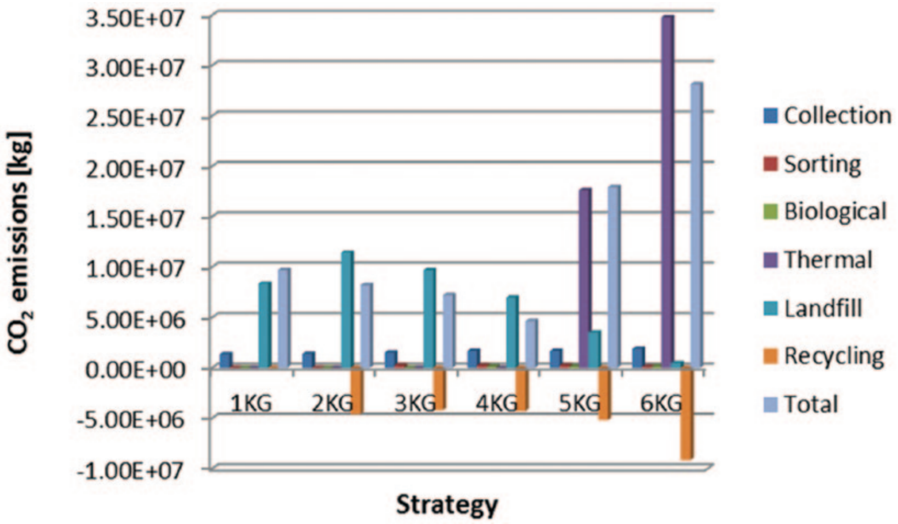

Figure 4. Carbon dioxide (CO_2) emissions for the proposed strategies [kg].

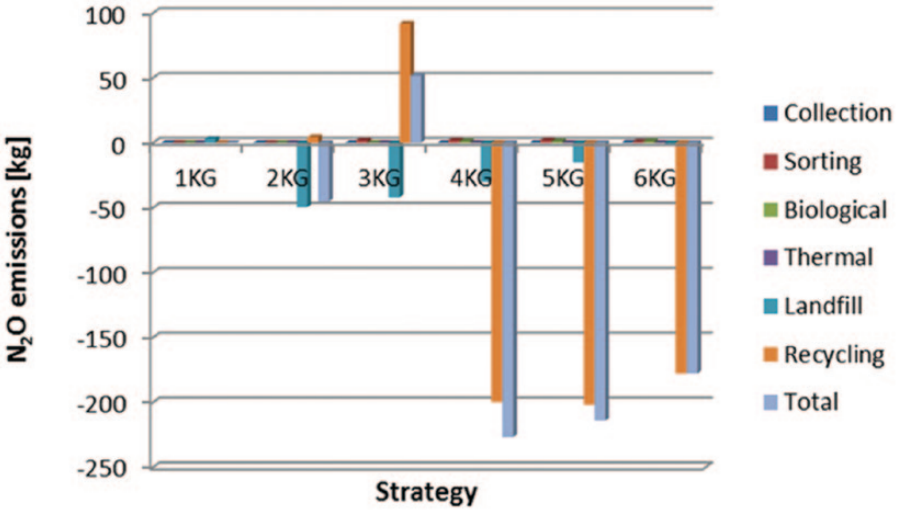

Figure 5. Dinitrogen oxide (N_2O) emissions for the proposed strategies [kg].

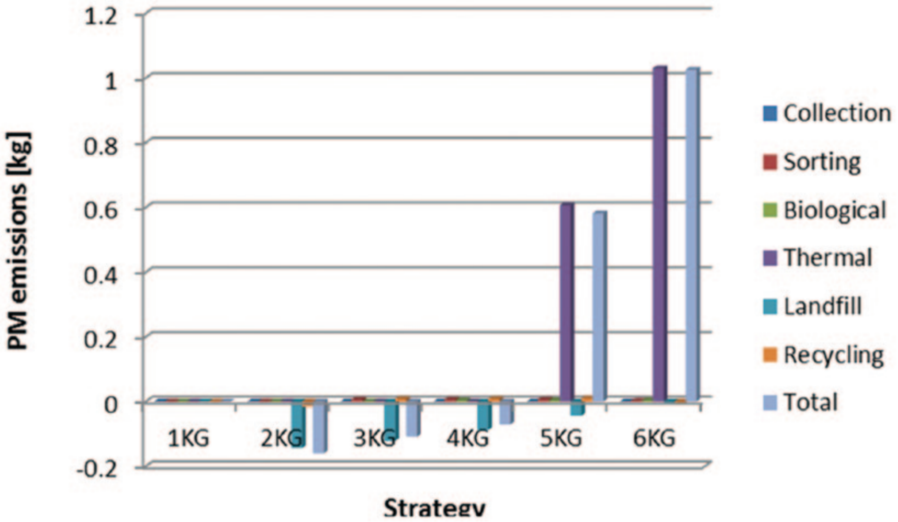

Figure 6. Particulate matter (PM) emissions for the proposed strategies [kg].

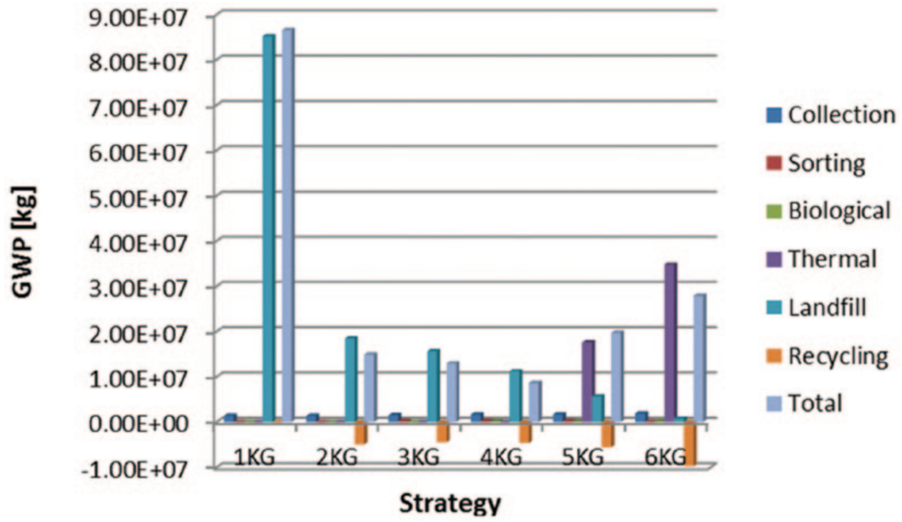

Figure 7. Global warming potential (GWP) factor for the proposed strategies [kg], GWP.

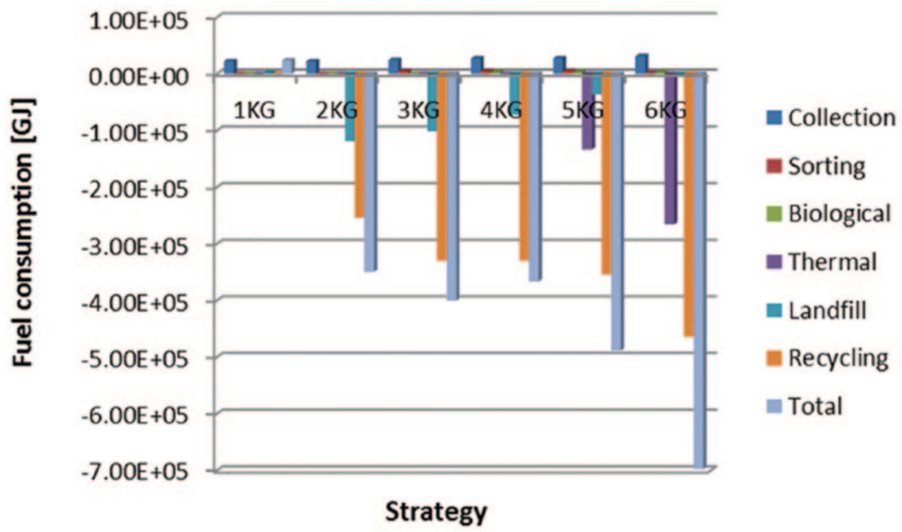

Figure 8. Comparative fuel consumption (FC) for the proposed strategies [GJ].

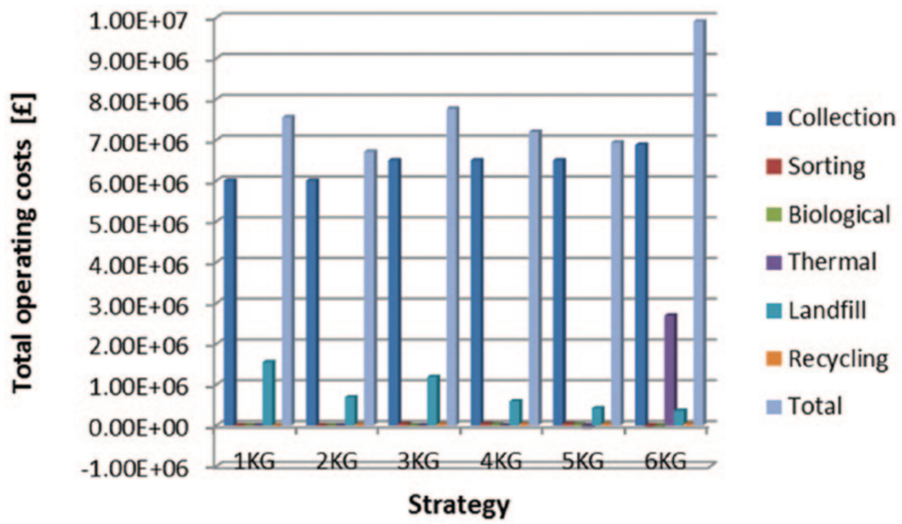

Figure 9. Comparison of the total operating costs (TOC) for the proposed strategies [£].

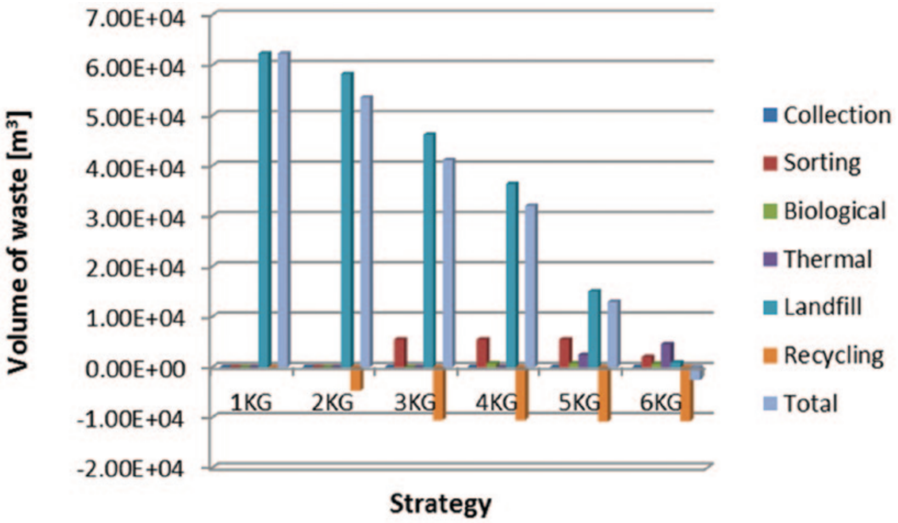

Figure 10. Volume of the remaining solid waste (VW) for the proposed strategies [m^3].

about a remarkable decrease in the GWP. In the 5KG and 6KG strategies, a gradual increase of this factor is noticed due to significant amounts of CO_2 emitted during the incineration process. However, as CO_2 has a 25 times lower GWP compared with CH_4 (Forster et al., 2007), the GWP values in these two strategies are not too high, regardless of relatively high CO_2 emissions. In all the strategies except 1KG, recycling has a positive environmental impact because GWP is significantly reduced. Similar to gas emissions, collection and transport processes have some adverse impacts, but not substantial. In this case, sorting and biological treatment have negligible influence on this factor.

Fuel consumption and total operating costs

Collection and transport of MSW account for the greatest part of FC in each of the proposed systems. Sorting and biological treatment also account for some FC (Figure 8). Still, FC needed for operation of the studied systems is lower than energetic savings (expressed through the FC parameter) achieved by landfill gas utilization, thermal waste treatment and recycling. In relation to the used technology and the amount of collected gas, the landfill waste treatments that involve landfill gas collection and utilization have positive effects. Therefore, the 2KG and 3KG strategies, with relatively small amounts of waste disposed to landfill, yield greatest energetic savings. Note that in both these strategies, advanced technology for collection and utilization of landfill gas is used.

Among the alternative solutions, only the 1KG strategy has a negative energy balance concerning the FC. Here, the FC refers to the fuel needed for waste collection and transport, as well as for the waste treatment. Due to the absence of the landfill gas collection and utilization system and other waste treatment options, this strategy does not offer any energetic benefits.

TOC are pretty much the same for all the variants (Figure 9), although slightly higher costs are seen with the 6KG strategy (20–35% higher compared with other strategies). In all the variants, waste collection and transport account for the greatest part of the total costs. In most strategies, these costs comprise less than 80% of the total monetary costs. Collection and transport costs increase with the increase in the number of treatment options. They reach the highest values for the strategies that include incineration of larger amounts of waste. In general, sorting and biological treatment costs are not high and they do not comprise a big part of the total system operating costs (less than 1% of the total costs for each strategy). In the 6KG strategy, sorting and biological treatment give financial benefits. Landfill treatment costs are considered in all the strategies, especially in the case of the 1KG strategy (where machinery is used for handling of large amounts of waste). Thermal treatment in the 6KG strategy also requires substantial finances.

It is obvious that considerable financial investments are needed in order to achieve high ecological, energetic and spatial performances (Figure 10) of the MSW management systems. In addition, waste collection and transport costs are also important issues influencing the total costs of all these systems. However, there are many possibilities to cut down on costs and reduce investments.

The VW that ends up at the landfill depends on the applied treatment technologies and, as expected, it is the highest in the strategy 1KG (Fig 10). This volume is reduced with the increase in the amount of alternative waste treatment. Thermal waste treatment and particularly recycling significantly reduce the amount of the remaining waste. This waste (VW) has to be disposed to landfill and its amount determines the capacity (airspace volume) of the landfill. Therefore, a crucial objective of sustainable waste management is to reduce the amount of the remaining waste in all treatment phases.

Table 2. Values of the parameter (x_{ij}) per strategies.

	Parameters (criteria)							
	CH_4	CO_2	GWP	N_2O	PM	FC	TOC	VW
1KG	3660886419	9702095390	86580721178	35	0	24479	7549600	62330
2KG	322379185	8195270649	14951191400	−45297	−160	−349143	6708008	53579
3KG	275549875	7204401627	13006978099	51707	−109	−399987	7760535	41147
4KG	195373325	4645014256	8677579260	−226693	−71	−366249	7190784	32058
5KG	89847396	17931207137	19751628200	−214110	581	−488276	6934515	12968
6KG	−8941934	28161489424	27918594552	−177788	1026	−697531	9902157	−2557

CH_4, methane; CO_2, carbon dioxide; GWP, global warming potential; N_2O, dinitrogen oxide; PM, particulate matter; FC, fuel consumption for the system operation; TOC, total operating costs; VW, volume of the remaining solid waste disposed to landfill.

Multi-criteria decision making

A combined application of MCDM and life cycle assessment (LCA) method provides decision makers with a highly flexible strategy (Hertwich and Hammitt, 2001; Huang et al., 2011; Linkov and Seager, 2011). The proposed strategies were ranked using MCDM based on the parametric values obtained by LCA calculations (IWM2 software package).

The six proposed strategies (1KG–6KG) were ranked using two methods of MCDM (i.e. SAW and TOPSIS), and the obtained results were compared. Based on the values for the eight different parameters used for the analysed strategies, given in diagrams in Figures 3–10, it is not easy to single out the best waste management option and rank the strategies. Here, MCDM was used for the two above-mentioned methods. At the very beginning, a basic matrix table was defined, in which the proposed strategies are the alternatives ($A_i,\ i = 1 \div 6$), while the analysed parameters are the criteria ($C_j,\ j = 1 \div 8$).

Table 2 shows obtained values for the x_{ij} parameter for each of the six proposed strategies.

Multi-criteria decision making – the SAW method

Once the maximum and minimum values have been chosen in each column (for each jth criterion), normalized values are obtained using the expression (3), which applies to the criteria of the *min* type:

$$r_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}}. \tag{3}$$

In order for the strategies to be assessed and ranked using the SAW method, weighted normalized values of the weighting coefficients per all the criteria have to be determined:

$$W'_j = \frac{W_j}{\sum_{j=1}^{8} W_j} \tag{4}$$

where W_j stands for the weighting coefficient per the jth criterion (parameter). Thus calculated values (in the expressions 3 and 4) are used to rank the alternatives by comparison of the products obtained using the following expression:

$$A^* = \left\{ A_i \,\middle|\, \max_i \sum_{j=1}^{8} W'_j r_{ij} \right\}. \tag{5}$$

During the SAW analysis, five variations of the weighting coefficients (I, II, III, IV and V) for eight given criteria were made and consequently five rankings of the proposed strategies were performed. Based on the values of the weighting coefficients W_j, based on the expression (4), normalized values of the weight W'_j were calculated for five different variants.

The strategies are ranked by comparing the sums of the normalized values of the parameters r_{ij} multiplied by normalized weighting coefficients W'_j (expression 5). The ranking was performed for each of the five variants of the weights added to the criteria.

Figure 11 shows the diagrams of sum characteristics of the strategies obtained using the SAW method. In all five variants of weighting coefficients distribution, it is obvious that the 4KG strategy has the best sum characteristics; therefore, this strategy is the optimal solution. On the other hand, the currently used WMS – 1KG – has the worst sum characteristics in all the cases. Note that the ranking of the six strategies remains the same for all the variations. The sum characteristics of the proposed alternatives (A_i) are not significantly sensitive to the change of the normalized weighting coefficients. Table 3 shows the mean (average) values (A_{iavr}) of the sum characteristics of all the proposed strategies in five simulation variants.

Multi-criteria decision making – the TOPSIS method

Multi-criteria ranking of the proposed strategies was performed based on parameters determined by the IWM2 software and in accordance with the algorithms of the TOPSIS method. This method is used to assess the alternative strategies based on their distance (Euclidean distance) from the ideal and 'anti-ideal'

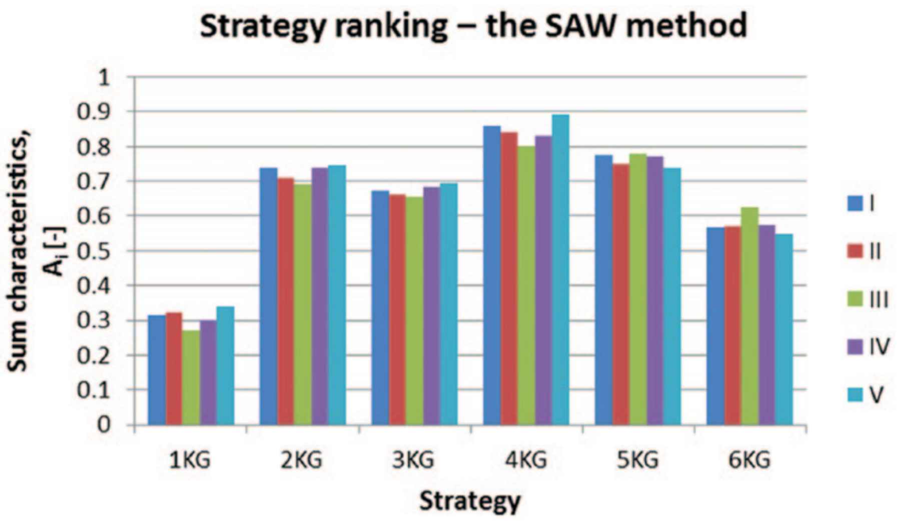

Figure 11. Strategy ranking for different weighting coefficients variants (*I* ÷ *V*) – SAW (simple additive weighting method) method.

Table 3. Mean sum characteristics and strategy ranking (simple additive weighting method, SAW, method).

	Waste management strategies					
	1KG	2KG	3KG	4KG	5KG	6KG
A_{iavr}	0.309274	0.724988	0.6736	0.844127	0.762805	0.577978
Rank	6	3	4	1	2	5

Table 4. The criteria weighting coefficients and normalized values.

	Parameters (criteria) for comparative analysis							
	CH_4	CO_2	GWP	N_2O	PM	FC	TOC	VW
W_j	80	80	100	80	50	80	100	50
W'_j	0.12903	0.12903	0.16129	0.12903	0.08064	0.12903	0.16129	0.08064

Abbreviations as in Table 2.

Table 5. Weighted normalized values of the parameter (v_{ij}) per strategies (TOPSIS, technique for order preference by similarity to ideal solution).

	Parameters (criteria) for comparative analysis							
	CH_4	CO_2	GWP	N_2O	PM	FC	TOC	VW
1KG	0.12796	0.03408	0.14612	1.24E–05	0	0.00296	0.06417	0.05117
2KG	0.01127	0.02879	0.02523	–0.01599	–0.01078	–0.04216	0.05702	0.04398
3KG	0.00963	0.02531	0.02195	0.018256	–0.00734	–0.0483	0.06596	0.03378
4KG	0.00683	0.01632	0.01464	–0.08004	–0.00478	–0.04423	0.06112	0.02631
5KG	0.00314	0.06299	0.03333	–0.07559	0.039144	–0.05897	0.05894	0.01064
6KG	–0.00031	0.09892	0.04712	–0.06277	0.069126	–0.08424	0.08417	–0.0021

Abbreviations as in Table 2.

solution. In the first step, the x_{ij} values from the start matrix (Table 2) are normalized based on the following equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{6} x_{ij}^2}}. \tag{6}$$

The criteria weighting coefficients and their normalized values are presented in Table 4.

In the second step the elements, the so-called weighting normalized matrices V, whose values are given in Table 5 are obtained using the expressions:

Table 6. 'Ideal' (A^+) and 'anti-ideal' (A^-) solution.

	Parameters (criteria) for comparative analysis							
	CH_4	CO_2	GWP	N_2O	PM	FC	TOC	VW
A^+	−0.00031	0.01632	0.01464	−0.08004	−0.01078	−0.08424	0.05702	−0.0021
A^-	0.12796	0.09892	0.14612	0.01826	0.06913	0.00296	0.08417	0.05117

Abbreviations as in Table 2.

Table 7. Distances of the alternatives from the 'ideal' and 'anti-ideal' solutions.

	Waste management strategies					
	1KG	2KG	3KG	4KG	5KG	6KG
D_i^+	0.225984	0.091635	0.112092	0.050118	0.076525	0.123686
D_i^-	0.098567	0.208641	0.209634	0.239332	0.213096	0.207989

Table 8. The factor of relative closeness of the alternative to the ideal solution and strategy ranking (TOPSIS method).

	Waste management strategies					
	1KG	2KG	3KG	4KG	5KG	6KG
RC_i	0.303702	0.69483	0.651593	0.826851	0.735775	0.627088
Rank	6	3	4	1	2	5

$$W'_j = \frac{W_j}{\sum_{j=1}^{8} W_j}$$

and

$$v_{ij} = W'_j r_{ij} \tag{7}$$

In the third step of the multi-criteria analysis by application of the TOPSIS method, the so-called 'ideal' and 'anti-ideal' solutions are formulated. The 'ideal' solution (A^+) has the best characteristics per all the criteria (parameters), all of which belong to the *min* type, and they are determined based on the expression:

$$\begin{aligned} A^+ &= \left\{ \left(\max_i v_{ij} \,\middle|\, j \in C' \right) \mathrm{U} \left(\min_i v_{ij} \,\middle|\, j \in C'' \right) \right\} \\ &= \left\{ v_1^+, v_2^+, ..., v_j^+, ..., v_8^+ \right\}, i = 1 \div 6 \end{aligned} \tag{8}$$

In contrast, the 'anti-ideal' solution (A^-) has all the worst characteristics per all the criteria (parameters) and it is determined using the equation:

$$\begin{aligned} A^- &= \left\{ \left(\min_i v_{ij} \,\middle|\, j \in C' \right) \mathrm{U} \left(\max_i v_{ij} \,\middle|\, j \in C'' \right) \right\} \\ &= \left\{ v_1^-, v_2^-, ..., v_j^-, ..., v_8^- \right\}, i = 1 \div 6 \end{aligned} \tag{9}$$

These two solutions are given in Table 6.

The fourth step involves determination of the distance (Euclidean distance) for each alternative (A_i) from the 'ideal' and 'anti-ideal' solution. The distance from the ideal solution is obtained using the expression:

$$D_i^+ = \sqrt{\sum_{j=1}^{8} (v_{ij} - v_j^+)^2} \tag{10}$$

while the distance from the 'anti-ideal' solution is obtained through the expression:

$$D_i^- = \sqrt{\sum_{j=1}^{8} (v_{ij} - v_j^-)^2} \tag{11}$$

The values of the distances D_i^+ and D_i^- for six studied alternatives are shown in Table 7.

In the fifth step of the analysis, values of the factor of relative closeness of each alternative to the 'ideal' solution (Eq. 2) are calculated.

In the sixth step, the proposed strategies are ranked based on the obtained values of the factor of relative closeness of the alternative to the 'ideal' solution RC_i ($i = 1 \div 6$). Table 8 shows values of this parameter, while Figure 12 gives diagrams.

The 4KG strategy is chosen as the best solution for the local waste management system based on the TOPSIS analysis and the relative closeness factor (RC_4= 0.8269). The current management system (1KG strategy) in which almost complete generated MSW is disposed to landfill has the lowest factor value RC_1= 0.3037. In addition to the fact that waste disposal to landfill is practically the only local waste management option, the reason for such a low value of this factor also lies in the fact that the city landfill has no landfill gas collection and utilization system installed. Based on the obtained values for the relative closeness factor for all the proposed strategies, installation and operation of such a system has the

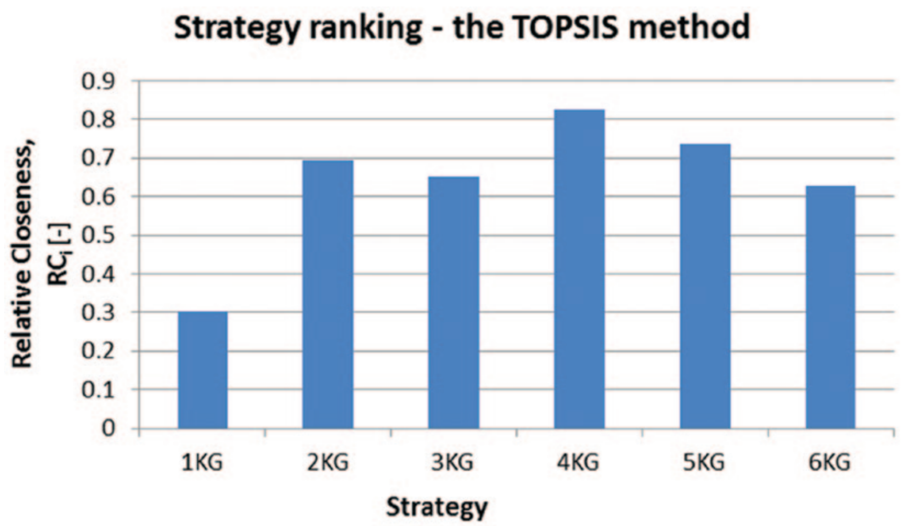

Figure 12. Values of the factor of relative closeness of the alternative to the 'ideal' solution for the proposed strategies.

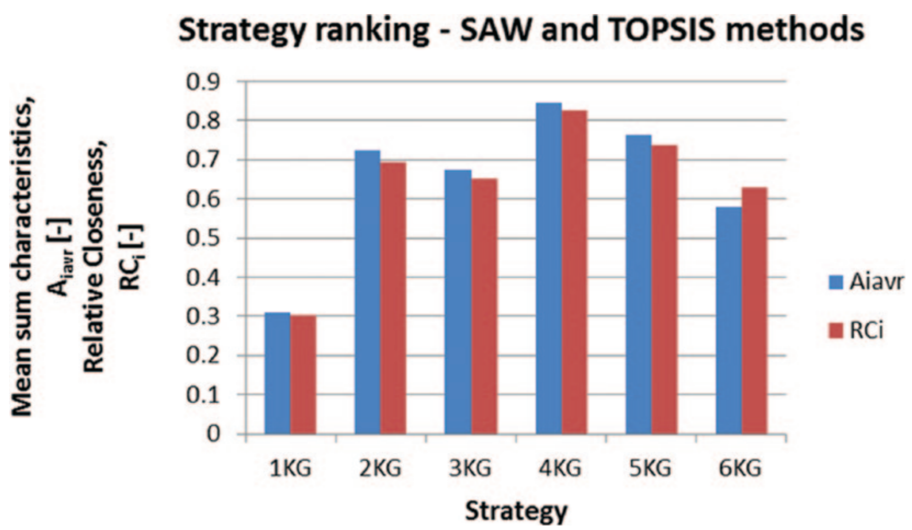

Figure 13. Comparative presentation of the strategies ranked using the SAW (simple additive weighting method) and TOPSIS (technique for order preference by similarity to ideal solution) methods.

greatest impact on the assessment of the quality of the proposed strategy. This impact is obviously much greater than the impact of the quantity of the waste directed to different treatment procedures. The optimal option clearly involves the adequate treatment of biological waste (difference between the strategies 3KG and 4KG) and a relatively limited amount of municipal waste to be incinerated (difference between the strategies 4KG, 5KG and 6KG). The assessment value of a certain strategy decreases with the increase of the amount of waste to be incinerated, which is mainly due to higher financial costs and increased CO_2 and PM emissions. Based on the values of the relative closeness factor (2KG and 3KG), it can be concluded that for the case of the investigated local waste management system (Community of Kragujevac) utilization of the landfill gas has more favourable effects on the strategy assessment than recycling of the same amount of the waste.

If the mean values of the sum characteristics (SAW method), given in Table 3 are compared with the values of the factor of relative closeness to the ideal solution (TOPSIS method, Table 8), a good agreement both in the ranking of the alternative strategies and values of the given factors can be noticed. Figure 13 gives the comparative diagrams of the values of these two factors for the proposed optional MSW management systems. Furthermore, it can be noticed that except for the 6KG strategy, all other proposed alternatives have slightly lower assessment values obtained using both the TOPSIS and the SAW method.

Conclusions

While choosing the optimal MSW management system, decision makers deal with numerous and often contradictory factors. This is why the MCDM method emerges as a useful tool.

In the first phase of the described selection process, six strategies of MSW management (1KG–6KG) were defined. They varied in the amount of waste treated and treatment methods as well.

The choice of the optimal variant is based on a relatively large number of analysed parameters – indicators – which makes reaching a decision a complex process. As part of the MCMD procedure, these parameters were assigned weighting coefficients and thus they became criteria.

In order to achieve better ranking of the proposed strategies, two procedures of multi-criteria analysis were performed – SAW and TOPSIS.

Both MCDM procedures pointed out the 4KG strategy as the best municipal waste management system for the city of Kragujevac. The choice has been additionally proven in the SAW method through analysis of the results sensitivity to the weighting coefficients variation.

The 4KG strategy is characterized with relatively large amounts of recycled waste (about 30%). One sixth of the waste undergoes biological treatment. A relatively small amount of waste (less than 10%) is incinerated, while the amount of the waste disposed to landfill is still significant – over 60%. In that sense, it is vital to install a landfill gas collection and utilization system.

Ranking of the strategies in both methods pointed out the importance of installation of the landfill gas collection and utilization system. Furthermore, it was shown that an increase in the amount of the waste to be incinerated increased system operating costs and had an adverse impact on CO_2 and PM emissions.

This procedure for selection of the optimal MSW management system in local communities is highly adjustable, which makes it very useful and valuable.

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