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Planning of Waste Management Systems in Urban Area Using Multi-criteria Analysis

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ABSTRACT

Planning of waste management system in urban area should take into consideration many legal, technological, financial, economic, technical, ecological, social and spatial aspects. The aim of the paper is to propose the method, which can be helpful in planning procedure of waste management system in European cities or regions, which comprise with following steps: identification of produced volume and municipal solid waste characteristics in the region for providing grounds to design a technological system, identification of other financial, economic, legal, social aspects for creation of waste management scenarios, definition of the criteria allowing evaluate designed waste management scenarios based on plan requirements, make an the multi-criteria analysis for choosing the best scenario in the region. Such analyses were conducted to evaluate the proposed different waste management systems in city of Cracow in 2000, 2004 *and* 2007. *This comparison of theses systems shows that evaluating criteria were tightened as a result of toughening regulations of both Polish and the EU laws.*

Keywords: *Municipal Waste, Urban Area, Planning, Multi-criteria Analysis, Waste Management System*

1. Introduction: Waste Management System as a Base for Planning

In Poland, waste management plans worked out on the national, provincial, county and district levels are one of the most important instruments supporting the realization of correct actions regarding waste management. The Act on Waste [1] sets out the form and scope of these plans, however the scope is very general. These plans can be a tool for setting targets at national and local level, and present challenges to local authorities and to plan necessary facilities. However, to achieve sustainable waste management the complex system should be implemented for every urban area. The complex waste management system should allow achieve many inconsistent goals: technical, legal, economic, ecological, spatial, and social. Planning and selection of waste management system structure is a multi-stage process involving identification of differences and common elements of variant solutions, selection the most favourable solution, and evaluation of operation results [2-6].

Planning scenarios of waste management system in the urban area should be developed on the basis of existing legal articles and local determinants, which determine quality of generated waste stream and its size [3,5]. Waste characteristics provide grounds to design a technological system with more or less complex structure, which has to ensure safe for environment proceeding with all waste generated in the region [4,7]. The next stage is to find criteria allowing evaluate designed technological system. These criteria should comprehensively assess the functioning of a complex waste management system. Taking into account the principles of sustainable development, the following groups of criteria have been proposed [2,8]:

- Technical determining e.g. the degree of waste stream reduction resulting from the system functioning, operation time of landfill site for final wastes, reduction in mass of biodegradable wastes, the volume of secondary materials recovered as a result of the system functioning, energy recovery level, etc.
- Ecological e.g. emissions from individual waste management system installations, emissions from means of transport, the impact of complex waste management system on natural environment, environmental benefits resulting from waste stream reduction, emis-

sion reduction, etc.

- Economic taking into account investment outlays and the system operating costs, and possible economic profits arising from the system functioning, e.g. profits from the sale of secondary materials.
- Social most difficult to use in measurable assessment, which may take into account the following: approval of system solution or individual technologies, possibility to create new jobs, approval of the impact of waste processing technologies on environment, but also political criteria, compliance with directions indicated by legal articles and waste management plans, etc.
- Spatial/regional in urban area the shortage of land for waste facilities (landfills, incinerations) is a significant problem, strengthening the NIMBY effect.
- Legal/political according to strategy for the Malopolska region the aim is to reduce the volume of waste produced and to introduce of a system of waste recycling and disposal, compatible with European standards [9].

Acceptance and calculation of individual criteria are dependent on numerous factors and specificity of the city, in which the system is expected to function. Description of system functions should cover all criteria. Due to the fact that not all of them are measurable and easy to compute, some may be omitted in computational process. In order to make computations easier, it is also possible to combine individual groups of criteria, e.g. technical and ecological [10-12].

2. Waste Management Systems in Cracow City Scenarios Analysis

The total amount of municipal solid waste generated in Cracow city was about 327,000 Mg in 2007. Waste is generally collected through "one-container system", with variable capacity of containers and mainly (86%) disposed on landfills (Barycz landfill in Cracow), about 4% is composted and 10% separate collected, *i.e.* in 2007 there were 550 recycling banks, which allowed to collect 4537 Mg of metal, paper, PET bottles, and glass. Cracow also plans to construct with the help of EU-fund a 240,000 Mg per year an incinerator plant, but as the protest of local citizen was very strong, therefore many variants for localisation have been taken into account. The introduction of new solutions in waste management system in Cracow was necessary to be in accordance with Polish and EU legal requirements and tasks indicated in waste management plans. In 2007 in Cracow waste management procedures were carried out according to the entries in Municipal Waste Management Plan [13].

- Continuation of current state model based on existing infrastructure. When implementing scenario S0, it will be required to extend the waste management system by adding another landfill site not later than in years 2017-2018. However, this scenario will not meet requirements specified in the Law on Waste [1,14] regarding reduction in mass of biodegradable municipal waste sent for dumping after 2013.
- Extension of sorting lines and adding new composting plant modules. When implementing scenario S1, it will be required to build another waste sorting and composting installations, mechanical and biological unit for processing not segregated (mixed) municipal waste, and landfill site in years 2017-2018. Additionally, implementation of scenario S1 will require considerable financial outlays for ecological education and developing segregation "at the source". The scenario will also require construction of another landfill site for final waste.
- Extension of sorting lines and adding new composting plant modules. When implementing scenario S2, it will be required to extend waste management system by adding another waste sorting and composting installations, mechanical and biological unit for processing not segregated (mixed) municipal waste(and since 2016 also collected selectively), and to build landfill site in years 2018-2019. Additionally, implementation of scenario S2 will require considerable financial outlays for ecological education and developing segregation "at the source". Functioning of this scenario will also require adding landfill site for final waste.
- Taking into account thermal processing of waste, as the system element. Implementation of scenario S3 will require first of all financial outlays for building thermal processing plant for waste.

The scenarios are presented in **Table 1**. For evaluation of these scenarios, three groups of criteria, which describe the system, are shown in **Tables 2** and **3**.

3. Multi-criteria Analysis as the Method Used to Compare Scenarios of Waste Management Systems

Multi-criteria analysis was proposed to compare these scenarios using proposed 11 criteria [11,12,15-19]. Compromise programming method using the concept of arranging/ordering individual strategies according to their distance from predetermined ideal point X' (x1', x2', ..., xM') was employed to solve the decision-making task. Coordinates of ideal point xM' are the most favourable values of criteria. Mathematical notation of the method is an equation defining criterion value, which aggregates the measure of distance between examined strategy and ideal point:

Table 1. Technical description of waste scenarios for the city of Cracow in 2007.

Elements system	S0—continuation of current state—model based on existing infrastructure	S1—extension of sorting lines and adding new composting plant modules	S2—extension of sorting lines and adding new composting plant modules	S3—taking into account thermal processing of waste, as the system element
Landfiling	approximately 2 million m^3			
Composting plant for green waste	Two installations, each processing green waste amounting to 6000 Mg/year			
Composting plant for wet fraction	–	Two-container system with output of 45,000 Mg/year	Two-container system with output of 65,000 Mg/year	Two-container system with output of 12,000 Mg/year
Sorting plant	8000 Mg/year	16,000 Mg/year, 20,000 Mg/year	16,000 Mg/year, 25,000 Mg/year	16,000 Mg/year,
Mechanical and biological processing	–	For mixed waste (not segregated) municipal waste with output of 120,000 Mg/year		–
Incineration plant	–	–		240,000 Mg/year
Large-size waste		12,000 Mg/year,		
Recovery of building waste	12,000 Mg/year	30,000 Mg/year		
Selective waste collection	Sets of containers for selective waste collection—ultimately 750 sets ensuring collection of 9,000 Mg/year, 9 within the city			
Export of municipal waste to other region	Export of municipal waste reaching 70,000 Mg/year out of the system, and import of municipal waste into the system at the level of ca. 7000 Mg/year until the end of 2012			
	Comments			
Two-container municipal waste collection system	–	cover approximately 45% residents in the City of Cracow	cover all residents in the City of Cracow	cover approximately 12% residents in the City of Cracow

$$L_\alpha\left(S_n\right)=\sum_{m=1}^{M} w_m^\alpha\cdot\left(x_m'-r_{NM}'\right)^\alpha \quad (1)$$

while the best strategy is selected according to the following rule:

$$S_j=\dot{S}\Leftrightarrow L_\alpha\left(S_j\right)=\min L_\alpha\left(S_n\right)_{;n=1,2,\cdots} \quad (2)$$

where: $L_\alpha(S_n)$—measure of the distance between examined strategy sn and ideal point; S_n—selected strategy; w_m—weight coefficient for criterion m; x_m'—mth coordinate of utopian point; r_{NM}'—normalised criterion value; M—number of criteria; α—power exponent measuring deviation of strategy from utopian point X'—In—practice 1, 2 and ∞ is taken.

The method allows weigh criteria, and assign weights to them, besides attributed values measuring achievement of goals [11,16,19,20]. The outcome of completed computations includes ordering of strategies for waste management system solutions in the region, depending on assumed weights of criteria or weights of individual groups of criteria. Final decision concerning selection of shape and function for waste management system in the region shall be made by decision-maker, who may assume specific weights of criteria and accept resultant solution, depending on preferences and needs of the region. Accepted waste management system solution shall be verified after few years of its functioning and evaluated once more [11,12,17,19].

4. Results of Multi-criteria Analysis for the Selection of Waste Scenarios

For computational purposes it is necessary to adopt validity hierarchy of individual criteria, determining priorities for decision-making process participants [8,10,11,16]. In case 1 weight 1 was assigned to each criterion. In the second case, minimisation and recovery criteria were given weight 5, while all other criteria—weight 1. Whereas, in the last line minimisation and recovery criteria and social and political criteria were given weight 5, and economic criteria—weight 1. Analysis results are shown in **Table 4**.

This method allows further weighing of criteria by using power exponent α in the formula. This exponent allows to additionally weighing all deviations from ideal point, proportionally to their size. The higher value α the more important are high strategy deviations from ideal point. Individual computational cases taking into account various values of coefficient α are shown in three different columns in **Table 4**. Ordering of strategies for waste management system in Cracow is the outcome of the analysis, presented in the last column in **Table 4**.

Table 2. Technical social and political criteria for identified scenarios of waste management in Cracow, after 2007.

	Criterion	Limit specified in legal articles, or best value	*Scenario* [*thousand Mg*]			
			S0	S1	S2	**S3**
K1	Reduction in the volume of dumped municipal waste	44,000 Mg until the end of 2014 according to Voivodship Waste Management Plan	52 (>100%)	95.3 (>100%)[b]	101.3 (>100%)[b]	243.5 (>100%)[b]
K2	Reduction in the volume of dumped biodegradable municipal wastes (requirement of the Act on Wastes and 99/31/EC of 2011)[c]	until the end of 2010 65,600 Mg	28.2 (43.1%)	33.3 (50.8%)	52.0 (79.3%)	34.6 (52.7%)
		until the end of 2013 97,500 Mg	29.3 (30.0%)	102.6 (>100%)	120.1 (>100%)	154.2 (>100%)
		until the end of 2020 123,700 Mg	29.3 (23.7%)	126.6 (>100%)	131.9 (>100%)	162.9 (>100%)
K3	Materials recovery	89,100 Mg	38.4 (43.1%)	72.9 (81.8%)	89.1 (100%)	51.6 (57.9%)
K4	Energy recovery	97.5 GWh	8 GWh (8.2%)	4 GWh (4.1%)	4 GWh (4.1%)	97.5 GWh (100%)
K5	Landfill site operation time	counted since 2005	12 years (31.6%)	13 years (34.2%)	15 years (39.5%)	38 years (100%)
K6	Compliance with directions indicated by the KPGO and WPGO	0/1	0	1	1	1
K7	Compliance with the EU directives	0/1	0	1	1	1
K8	Regional and prospective character of the solution	0/1	0	0	0	1
K9	Social acceptance	0.86	0.4	0.83	0.83	0.86

[a][16] assumes achieving the goal of reducing by the end of 2014 mass index for dumped municipal wastes to maximum 85%, compared to total mass generated in a year; [b][16] assumes achieving the goal of reducing mass of dumped municipal wastes to maximum 85% of generated municipal wastes by the end of 2014; [c]reduction in the volume of dumped municipal wastes, in target version (since 2013) it concerns all municipal wastes (excluding building and hazardous wastes) generated in the city without importing and exporting wastes outside the system.

Table 3. Economic criterion for identified scenarios of waste management in Cracow, after 2007 [PLN].

Scenario	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Comparison of monthly charges per 1 *resident in individual scenarios*														
S0 without subsidy	6.72	8.06	9.32	9.73	10.18	10.64	12.07	12.56	13.08	14.00	17.41	18.17	18.85	19.61
S1 without subsidy	6.77	9.16	10.85	11.74	12.37	13.08	18.34	19.40	20.23	21.41	22.50	26.26	27.18	28.38
S2 without subsidy	6.77	9.51	11.28	12.33	13.17	13.95	17.97	19.27	20.53	21.89	23.07	27.20	28.70	30.15
S3 without subsidy	6.69	8.38	9.99	10.87	11.43	12.02	16.61	17.22	17.87	18.87	19.65	20.43	21.17	22.05
S3 with subsidy	6.46	8.15	9.66	10.37	10.91	11.48	13.88	14.47	15.08	16.01	16.77	17.53	18.23	19.07
Comparison of management (*disposal*) *costs for* 1 *Mg of wastes in individual scenarios* [*PLN/Mg*]														
S0 without subsidy	306	366	422	440	459	478	540	560	580	618	764	793	817	844
S1 without subsidy	308	416	492	531	558	588	821	865	898	945	987	1 146	1 178	1 221
S2 without subsidy	308	432	511	557	594	627	804	859	911	966	1 013	1 187	1 244	1 297
S3 without subsidy	305	381	453	492	515	540	743	767	793	833	863	891	917	948
S3 with subsidy	294	370	438	469	492	516	621	645	669	707	736	764	790	820

Explanations: option without subsidy—in which the Municipality does not use opportunities to obtain subsidies from the European funds to purchase permanent assets; option with subsidy—when the Municipality uses subsidies of this sort.

Table 4. Multi-criteria analysis results for identified scenarios of waste management system for the City of Cracow after 2007.

Validity hierarchy for the following criteria: minimisation and recovery of wastes:social and political:economic	Ordering of strategies		
	$\alpha = 1$	$\alpha = 2$	$\alpha = \infty$
1:1:1	s3a)→s2→s1→s0	s3a)→s1→s2→s0	s3a)→s2→s1→s0
5:1:1	s3a)→s1→s1→s0	s3a)→s2→s1→s0	s3a)
10:1:1	s3a)→s2→s1→s0	s3a)→s2→s1→s0	s3a)
1:5:1	s3a)→s2→s1→s0	s3a)→s1→s2→s0	s3a)
1:10:1	s3a)→s2→s1→s0	s3a)→s1→s2→s0	s3a)
1:15:1	s3a)→s2→s1→s0	s3a)→s1→s2→s0	s3a)
1:1:2	s3a)→s1→s2→s0	s3a)→s0→s1→s2	s3a)
1:1:5	s3a)→s0→s1→s2	s3a)→s0→s1→s2	s3a)→s1→s0→s2
1:1:6	s3a)→s0→s1→s2	s3a)→s0→s1→s2	s3a)→s1→s0→s2
1:1:10	s3a)→s0→s1→s2	s0a)→s3→s1→s2	s3a)→s1→s0→s2
5:1:5	s3a)→s0→s2→s1	s3a)→s0→s1→s2	s3a)
1:5:5	s3a)→s1→s2→s0	s3a)→s1→s2→s0	s3a)
5:5:1	s3a)→s2→s1→s0	s3a)→s2→s3→s0	s3a)

$S_n^{a)}$—acceptable strategy.

When examining multi-criteria analysis results, we may state that:

- In 39 computational cases, strategy S3 has been chosen most frequently (thermal processing of waste as an element of a complex waste management system) 38 times,
- In remaining 1 case, strategy S0 has been selected, which assumes implementation of an existing waste management system. It is chosen in the case when we take the economic criterion as the most important one (10 times more important than the other ones),
- Strategies S1 and S2 ("deep" segregation of waste and composting) haven't been chosen as the most favourable in any computational case,
- Decision-maker may assume some limitations in the strategy selection. In current computations, limitations of this sort have been taken as the so-called acceptability threshold calculated as follows:

$$S_n^{a)} = 0{,}1 * L_\alpha\left(s_n\right)_{\min} \tag{3}$$

Acceptable strategies are indicated in **Table 4** by "*a*)", and they constitute a solution for decision-making task as the choice of strategy lying acceptably close to ideal point.

5. Comparison of Multi-criteria Analysis Results for the System of Waste Management in Cracow Carried out in Years 2004 and 2000

Programme [13] was developed in 2004. Based on its guidelines, individual waste management strategies were put to multi-criteria analysis. As in previous chapter, the same method of multi-criteria selection compromise programming was used in computations, whereas evaluating criteria were taken according to the above-mentioned plan. The five strategies were taken for the analysis (**Table 5**):

Scenario *S*1 continuation of current state,

Scenario *S*2 extension of selective collection system,

Scenario *S*3 extended composting range,

Scenario *S*4 thermal processing system for waste.

Scenario *S*5 extension of segregation and processing of fractions collected in a two-container system.

Multi-criteria analysis for individual strategies of waste management in Cracow was carried out on the basis of the 10 criteria presented with the results for

Table 5. Technical description of waste scenarios for the city of Cracow in 2004.

Elements system	*S*1	*S*2	*S*3	*S*4	*S*5
Landfill	approximately 2 million m^3				
Composting plant	6000 Mg/year	two installations, each processing green waste amounting to 6000 Mg/year	two installations, processing green waste and wet from segregation amounting to 12,000 Mg/year		two installations, each processing green waste amounting to 6000 Mg/year which may be extended up to 12,000 Mg/year; and additionally extendable up to 22,000 Mg/year for composting selectively collected wet fraction and organic fraction separated in sorting plant
Sorting plant	20,000 Mg/year				20,000 Mg/year for one shift (according to scenario guidelines designed for processing 60,000 Mg/year),
Incineration plant				200,000 Mg/year	
Large-size waste	12,000 Mg/year				
Selective waste collection	sets of containers for selective waste collection				
Export of municipal waste to other region	80,000 Mg/year				
Two-container municipal waste collection system	single-family houses, “dry” and “wet” fractions				

every scenario in the **Table 6**. As before, the compromise programming method has been used in computations. When examining analysis results, we may state that:

- In 24 computational cases, strategy 4 has been chosen most frequently (thermal utilisation of waste as the system element) 17 times,
- In all other 7 cases, strategy 3 assuming extended composting range has been chosen. This strategy is selected in cases when assigned economic criterion weight is 10,
- As in previous chapter, decision-maker may assume some limitations in strategy selection. In these computations, limitations of this sort have been taken as the so-called acceptability threshold calculated as follows:

$$S_n^{a)} = 0.1 \cdot L_\alpha \left(S_n \right)_{\min} \tag{4}$$

- Acceptable strategies are indicated in the table by “*a*)”, and they constitute a solution for decision-making task as the choice of strategy lying acceptably close to ideal point,
- Multi-criteria analysis is only a tool arranging waste management system strategies, whereas final decision concerning system selection is made by decision-maker; in 2004, Scenario 5 was chosen for implementation by the City of Cracow in spite of the fact that in none of computational cases Strategy 5 was selected as the most favourable,
- Strategy 5 usually ranks second and in one case third,
- Strategy 5 is most frequently selected second, after Strategy 4 or 3 (chosen most often). Taking into account all criteria and assigning weights to them, we may say that if the choice is between Strategy 4 and 5 strategy 4 is selected, and if we are choosing between 3 and 5 Strategy 3 is preferred. In spite of this, Strategy 5 has been chosen for implementation.

Multi-criteria analysis for waste management system in Cracow was carried out three times: in 2000 [11], 2004 and 2007. Each time, few waste management scenarios were taken for analysis, and among them, current state analysis was always taken into account for comparison purposes as the starting scenario. **Table 7** compares final results of all analyses.

6. Summary and Conclusions

- Selection of waste management strategy in the urban area is a difficult decision-making problem, which has to take into account different, often inconsistent goals and tasks, and social-economic and political interests.
- Defined measuring criteria allow establish quantitative and objectivised evaluation of waste management system functioning in technical, related to nature, economic and social aspects.
- On the basis of defined indicators and multi-criteria analysis it is possible to select most favourable scenario for waste management system in the urban area. The proposed methodology guarantees possibility to carry out quantitative, multidimensional, and at the same time objectivised evaluation of system solutions, which would replace intuitive or requiring experts opinions assessments used so far.
- In case of Cracow, the proposed method has been already employed three times, and this selection coincides with experts assessments; nevertheless decision-maker always makes final decision concerning

Table 6. Criteria and decision matrix for waste management scenarios in Cracow in 2004.

Criteria	Scenario				
	*S*1	*S*2	*S*3	*S*4	*S*5
crit. 1—reduction in the volume of waste achieved in 2011, in [%],	21.1	45.9	46	100	80.5
crit. 2—reduction of biodegradable waste – requirement of the EU directive, in [%]	30.7	46.9	65.3	100	83.1
crit. 3—recovery of secondary materials, in [%]	37.7	83.7	83.7	91.2	100
crit. 4—energy recovery (in scenarios without incinerating plant, energy recovery from landfill site) [GJ]	8.2	8.2	8.2	100	8,2
crit. 5—operation time of landfill site for processed waste, in [years]	11	12	13	27	14
crit. 6—compliance with directions indicated by the KPGO [21] and WPGO [13]	0	1	1	2	1
crit. 7—compliance with the EU directives	0	0	1	2	1
crit. 8—regional and prospective character of the solution	0	0	0	2	0
crit. 9—social acceptance	1	4	4	2	4
crit. 10—full monthly average financial charge per 1 resident [PLN/year]	4.0	4.52	4.68	6.35	5.27

Source: [22].

Table 7. Results of subsequent multi-criteria analyses for waste management system in Cracow.

Year	Number of waste management scenarios	Number of criteria evaluating the scenarios	Choice of scenario with incinerating plant in relation to the number of computed cases	Additional remarks
2000	4	8	17/27	-
2004	5	10	17/24	Additionally, the criteria take into account biomass reduction.
2007	4	11	62/63	Additionally, the criteria take into account penalties administered by the EU for failing to meet standards and the share of social factor in decision-making process.

the system form.

- Very good effect was obtained after including community side into the decision-making process for selection of waste management system in the city. Community not only discusses analysis results, but it also is able to join in it by creating a waste management scenario or specifying evaluating criteria, to discuss computation results with experts, and to assign weights to the evaluating criteria.
- According to environment management requirements, the proposed methodology allows carry out system evaluation systematically, even in case of change in the purpose or determinants in the city. This method may be employed in continuous planning of a technical system implementing waste handling strategy, which has been shown on the example of Cracow.

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