EVALUATION THE ECONOMIC INDICATORS OF WASTE TREATMENT TECHNOLOGIES

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Abstract: Developing evaluation criteria and methods that reliably measure economic sustainability is a prerequisite for selecting the best waste treatment technology and identifying non-sustainable scenarios. In most cases, used economic indicators are: investment costs, operating and maintenance costs, fuel costs, energy costs and revenues. Unfortunately, cost estimation is relatively crude in solid waste management. Published cost data are often fragmented or reflecting specific unique cases with limited information.

In this paper developed mathematical model for calculation of the economic indicators of waste treatment technology depending on the composition and quantity of waste, is presented. The model is based on the analysis of the structure of investment costs (project and permits costs, land acquisition costs, costs of site development, construction costs, facility costs) and operating costs (fixed operational costs (the number of employees, maintenance costs of buildings and equipment) and variable operating costs (fuel and electricity costs, chemical costs etc.) and revenues (gate fee, revenue from selling the produced electricity and heat, revenue from selling the compost) for each waste treatment technology and supported by the data available on the field and in the literature. The model is applied to calculate the indicators for the biochemical waste treatment technology – anaerobic digestion. The model is verified in the case study the city of Niš.

Keywords: Economic indicators, mathematical model, investment costs, operating costs, revenue, anaerobic digestion.

INTRODUCTION

Developing evaluation criteria and methods that reliably measure sustainability is a prerequisite for selecting the best alternative, identifying non-sustainable waste treatment technique, informing design-makers of the integrated performances of the alternatives and monitoring impacts on the environment (Wang et al. 2009).

The criteria used to evaluate the waste treatment technique in the literature are mainly divided into four aspects: technical, economic, environmental and social criteria. When adopting the economic criteria, they are usually associated with certain costs of waste treatment. Unfortunately, cost estimation is relatively crude in solid waste management. In order to provide a more accurate determination of waste treatment costs, several methods have been used: unit cost method, benchmarking and cost functions (Parthan et al. 2012a). In the unit cost method each activity is disaggregated into separate items such as salaries, consumables, fuel costs or maintenance costs, and the required quantity of each item is noted. Multiplying this with the cost per item or unit cost, the total cost of each item is calculated and the overall cost of the service is then calculated by summing the total costs incurred by each item (Massarutto et al. 2011). Benchmarking is a quick way to make a reasonable cost assessment by using actual cost data from a similar organization due to the lack of data in the considered country (Aye & Widjaya 2002) or from the literature (Lavee & Nardiya 2013). The cost function is used to describe more broadly the relationship of cost to variables. The cost functions method relates the cost of solid waste management to production factors or to variables such as amount of processed waste (Tsilemou & Panagiotakopoulos 2006) or population density (Parthan et al. 2012b).

In this paper a developed mathematical model with the aim of calculating the economic sustainable indicators (investment costs, operating and maintenance costs and revenues) of biochemical waste treatment technique – anaerobic digestion is presented. All of the above indicators are calculated depending on the composition and quantity of waste. The model is based on the analysis of the structure of investment and operating costs and revenues and supported by the data available in the field and in the literature. The model is verified in the case study of the city of Niš and applied to calculate the indicators for the anaerobic digestion.

ANAEROBIC DIGESTION

Anaerobic digestion (AD) is a biochemical process producing biogas through the biodegradation of organic material in the absence of oxygen with anaerobic microorganisms. More widespread uses of anaerobic digestion include: co-digestion of organic fraction of municipal solid waste (OFMSW) from different sources; digestion of sludge from wastewater treatment plants; manure; industrial wastewater with high content of organic matter (Nixon et al. 2013). The systems for anaerobic digestion can be divided technologically according to four characteristics of the digestion process: dry/wet digestion; thermophilic/mesophilic digestion; one-stage/two-stage digestion and one-phase/two-phase digestion. The division into dry or wet processes is a question of the moisture content in the biological reactor. The choice of moisture content in the process takes its starting point from the moisture content in the waste. The digestion temperature is 20-40 ºC for mesophilic digestion or 50-65 ºC for thermophilic digestion (Bolzonella et al. 2003). The thermophilic process is more difficult to operate and the need for heating and insulation adds an extra cost to the treatment. Mesophilic digestion is the most common.

The anaerobic digestion plant consists of several major technological elements: reception of waste; pre-treatment; digestion; gas handling; management of digest from digestion and odour control.

Biogas released during anaerobic digestion (comprising largely of methane, 55-60%, and carbon dioxide, 30-45%) can be used directly as a fuel for power generation, and has an energy content of 20-25 MJ/m3. Typically around 100-350 m3/t of biogas can be produced (Braber 1995). Compost can also be obtained from aerobically cured bio-solid. As by-product 1 t of OFMSW produces 0.415 t of compost (Murphy & Power 2006). Parasitic loads (the energy required in the AD process that is not contributing to the net electric yield) are relatively high at around 20-40% (Braber 1995). In AD the OFMSW volume is reduced by around 70%, therefore, assuming a 50% organic fraction, the total waste volume is reduced by around 35% (Hartmann & Ahring 2006), but all products (biogas) and by-products (fibre and liquor) from anaerobic digestion can be used and none of these are landfilled.

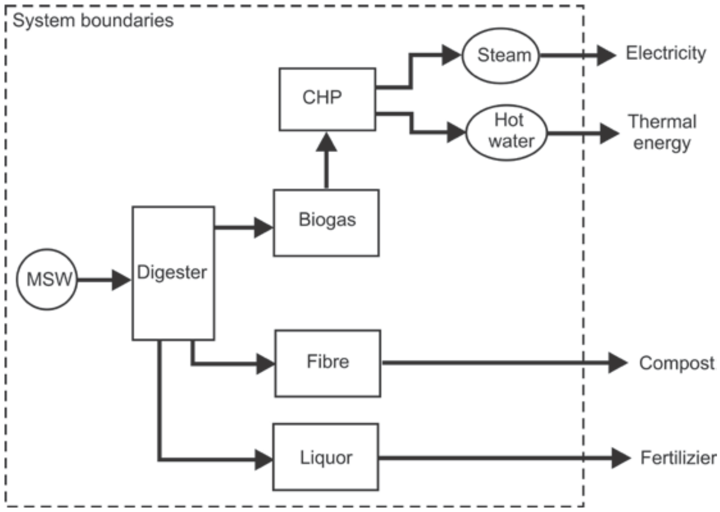

Figure 1 The anaerobic digestion process and system boundaries

The capital costs for dry anaerobic composting plant (DRANCO process) capacity of 5,000-100,000 t/y, range considerably from 200-1000 €/t, while the operating costs range from 40-15 €/t. If biogas is utilised in CHP, typically the electricity is produced at 30-35% efficiency and the thermal energy is produced at 40-50% efficiency (Murphy & McKeogh 2004).

ECONOMIC INDICATORS

In the conducted literature review, the most commonly used are: investment cost, operation and maintenance cost, revenues, net cost per ton, fuel cost, electricity cost, net present value payback period, service life, etc. In order to choose a solid waste management system in Finland, using a multi-criteria decision analysis Hokkanen &

Salminen (1997) used net cost per ton as economic criteria. For the selection among renewable energy alternatives in Turkey, Kahraman et al. (2009) suggested a fuzzy multi criteria decision-making methodology, while implementation cost, economic value and availability of funds are used as economic criteria. Wang et al. (2008) used the following economic criteria are used: investment cost, investment recovery period, total annual cost and net present value, for trigeneration systems selection and evaluation. Energy costs, investment costs and efficiency are used by Begic & Afgan (2007) for multi-criteria sustainability assessment with various options of the energy power system of Bosnia and Herzegovina. In order to perform technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process, Chatzimouratidis & Pilavachi (2009) used capital cost, operational and maintenance cost, fuel cost and external cost. Nixon et al. (2013) used capital cost, generation cost and operating and maintenance cost to evaluate options for energy recovery from municipal solid waste in India using the hierarchical analytical network process. To assess a sustainable waste management model, Milutinovic et al. (2014) used investment cost, operational cost and revenue as economic indicators.

Investment costs comprise all costs relating to: land acquisition, the purchase of mechanical equipment, technological installations, construction of roads and connections to the national grid, engineering services, construction work, drilling and other incidental construction work. Investment costs are the most used economic criteria. Operating and maintenance costs consist of two parts: fixed and variable costs. Operating and maintenance costs are other most used economic criteria. Revenues comprise all revenues obtained from selling the products of waste treatment (gate fee, produced electricity and heat, compost and other fertilizer). Fuel costs refer to the funds spent for the provision of raw material necessary for energy supply system operation. Fuel costs are excluded from operation costs when fuel costs and operation and maintenance costs are both selected for evaluation. Electricity costs, which are the product costs of a power plant, are observed as a criterion to evaluate its economic performance from the viewpoint of consumers. Net present value (NPV) is defined as the total present value of a time series of cash flows. NPV is often used to assess its feasibility of an energy project by investor. Payback period of an energy project refers to the period of time required for the return on an investment to “repay” the sum of the original investment. Shorter payback periods are obviously preferable to longer payback periods to investors. A longer service life is preferable to investors and it is employed to select the best scheme from alternatives.

MATHEMATICAL MODEL

Model parameterization and assumptions

For the needs of the present study the following considerations were taken in account:

The input variables for the developed model are the amount of waste and waste composition. The chemical composition of waste fractions is taken from the literature (Tchobanoglous et al. 1993).

The amount of waste was forecasted over the lifetime of the waste treatment facilities. A waste generation forecast requires a combination of data normally used for town planning purposes along with specific waste generation data. The forecast for the amount of solid waste (x) for the year (n) was calculated according to Equation 1 (The World Bank 1999).

$$x = PP * (1 + GR_{pp})^n * w_c * (1 + GR_{KF})^n \quad (1)$$

where: x – the forecasted amount of waste (facility capacity), PP – the present population, GRpp – the growth rate of population, wc – the actual key figure (the amount of waste per capita), GR_{KF} – the growth rate of key figure, n – the facility lifetime.

It is assumed that the waste composition does not change during facility lifetime.

Composition of biogas generated in anaerobic digestion is calculated from the elemental composition (C, H, O, N, S) using a Buswell Equation (Equation 2):

$$C_cH_hO_oN_nS_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2O \rightarrow \frac{1}{8}(4c - h + 2o + 3n + 2s)CO_2 + \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S \quad (2)$$

Energy yield from biogas is calculated taking into account that the low heating value of methane is 36 MJ/m^3 i.e. 10 kWh/m^3 and assuming that 80% of organic fraction of waste is broken down.

Investment costs

The investment costs include project and permits costs, land acquisition costs, costs of site development, construction cost and facility costs (Equation 3).

$$IC(x) = P(x) + LA(x) + SD(x) + CC(x) + FC(x) \quad (3)$$

where: P(x) – the project and permits costs, LA(x) – the land acquisition costs, SD(x) – the costs of site development, CC(x) – the construction costs, FC(x) – the facility costs.

Project and permits costs (Equation 4) depend of facility capacity, but also on legislation, technology, etc.

$$P(x) = BA(x) * P_p \quad (4)$$

Land acquisition costs depend of land-take area (LT(x) – the land area required for the building footprint and the entire site (including supporting site infrastructure). A land-take area depends on the necessary infrastructure, technology and plant capacity, and land price (Pi) (Equation 5).

$$LA(x) = LT(x) * P_l \quad (5)$$

Table 1 provides an overview of land-take and building area for the anaerobic digestion facility.

Table 1 Land-take and building area for sitting anaerobic digestion facility

Facility capacity x(t/y)	Land-take LT (ha)	Buildings Area BA (m^2)
40,000	0.6	2,420

164,000		5,420
38,000	1.5	
5,000		2,500
300,000		35,000
60,000	1.8	

Source: The Office of the Deputy Prime Minister (2004), Ramsey (2009), SAOS (2009), Kraemer & Gamble (2014), FOE (2010)

From the presented data it can be concluded that LT(x) for an anaerobic digestion facility is typically 1.50 – 3.00 ha per 100,000 t of waste (Equation 6)

$$LT(x) = 1.50 \div 3.00 * \frac{x}{100{,}000} \quad (6)$$

Also, from the data presented in Table 1 for building area (BA(x)), it can be concluded that the building area of 2,400 – 11,000 m^2 per 100.000 t of waste is required for the anaerobic digestion facility (Equation 7).

$$BA(x) = 2{,}400 \div 11{,}000 * \frac{x}{100{,}000} \quad (7)$$

Site development costs (SD(x)) include costs of excavation, levelling, access roads, link to technological networks. Generally, site development costs also depend on the land-take area and price of civil works per square meter (Equation 8).

$$SD(x) = LT(x) * P_{sd} \quad (8)$$

Construction costs (civil works on building construction) (CC(x)) depend on the building area (BA) which houses facilities and price of construction work per square meter (P_c) (Equation 9).

$$CC(x) = BA(x) * P_c \quad (9)$$

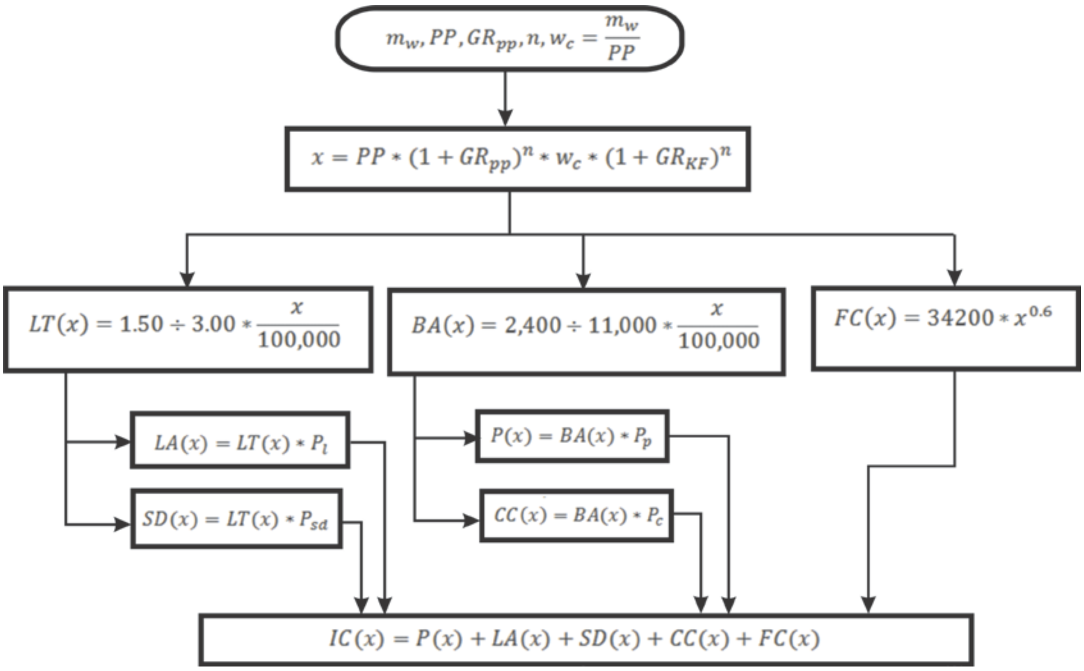

Figure 2 Block diagram of a mathematical model for evaluating the investment costs

Facility costs (technical installations and machinery) (FC(x)) also depend on the facility capacity and the authors suggest that for the calculation of facility costs one should use the empirical equations from Tsilemou & Panagiotakopoulos (2006), obtained by statistical processing of data relevant to European states which provides a reasonably accurate approximation of investment facility costs. Facility costs (€) for an anaerobic digestion facility with the capacity range 2,500 – 100,000 t/y is given in Equation 10.

$$FC(x) = 34200 * x^{0.6} \tag{10}$$

Operating costs

Operating costs include fixed operating costs (independent of waste quantity) and variable operating costs (dependent of waste quantity) as shown in Equation 11.

$$OC(x) = OC_{fix} + OC_{var}(x) \tag{11}$$

where: OC_{fix} – the fixed operational costs, $OC_{var}(x)$ – the variable operating costs.

The fixed operating costs (OC_{fix}) depend on the number of employees, the percentage of skilled and unskilled workers and engineers, and the local salary level and maintenance costs of buildings and equipment. In the literature we can find various information of the number of employees (FOE 2010, CEWEP 2011). The general conclusion is that for 10,000 t of waste 4-6 for anaerobic digestion. Maintenance costs of buildings and equipment in the literature are usually expressed in terms of percentage of investment costs (The World Bank 1999, Hogg 2001). Maintenance costs of buildings amounted to 1 % of investment costs and maintenance costs of equipment amounted to 4 % of investment costs. Variable operating costs ($OC_{var}(x)$) consist of costs of chemicals for the flue gas cleaning system, electricity, water and handling of waste water and residue disposal.

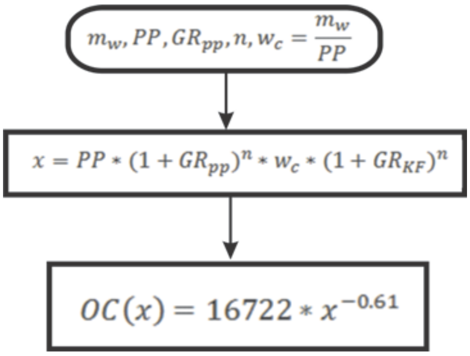

Figure 3 Block diagram of a mathematical model for evaluating the operating costs

Due to the influence of different elements in the structure of operating costs, the authors suggest that for the calculation of operating costs one should use the empirical equations from Tsilemou & Panagiotakopoulos (2006), obtained by statistical processing of data relevant to European states which provides a reasonably accurate approximation of operating costs. Operating costs (€/t) for an anaerobic digestion facility with the capacity range 2,500 – 100,000 t/y is given in Equation 12.

$$OC(x) = 16722 * x^{-0.61} \quad (12)$$

Revenues

Revenues consist of revenue from the gate fee (R_{gf}), produced electricity (R_{ee}) and heat (R_{he}) and compost as by-product (R_c) and depend on the capacity and efficiency of the plant and waste composition, represented in Equation 13.

$$R(x) = R_{gf} + R_{ee} + R_{he} + R_c \quad (13)$$

The gate fee (R_{gf}) vary greatly between regions and countries and is in the range of 40 €/t of waste in France to 120 €/t in United Kingdom (Hogg 2001).

$$R_{gf} = GF * m_w \tag{15}$$

Fig. 4 presents a block diagram of a mathematical model for evaluating the revenues.

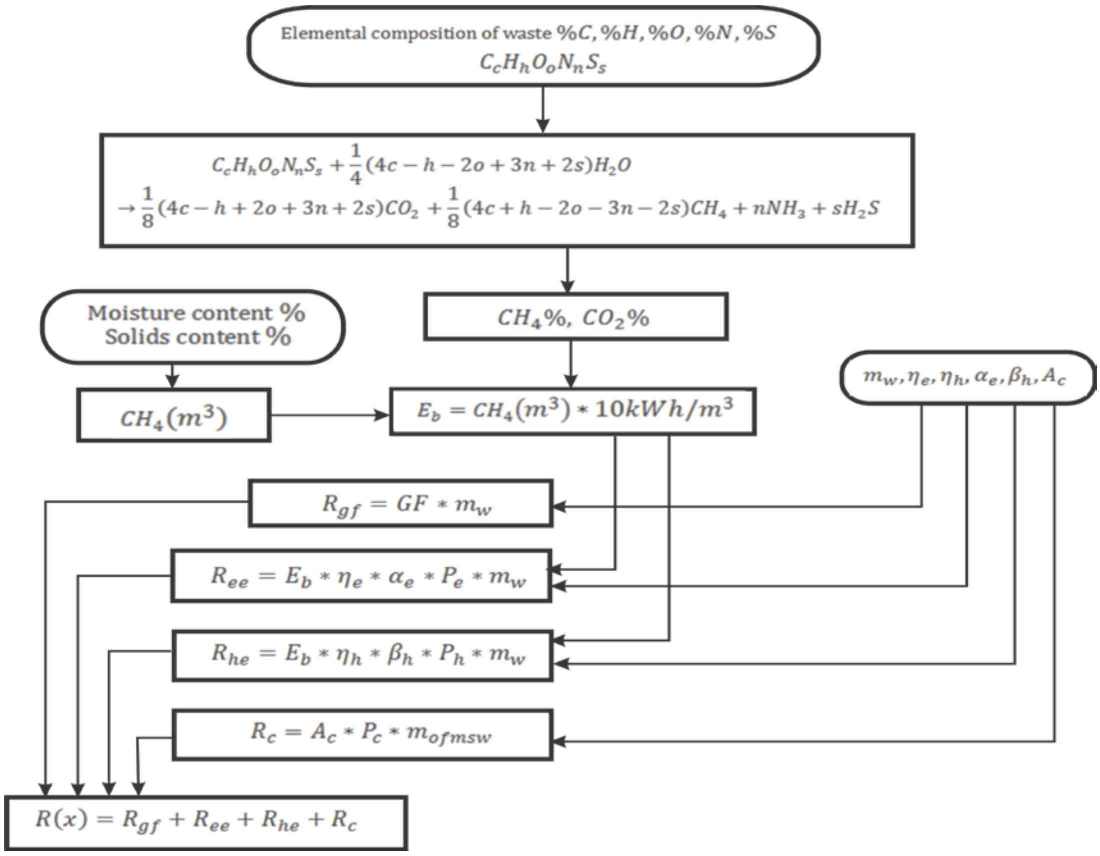

Figure 4 Block diagram of a mathematical model for evaluating the revenues

Revenues obtained by selling produced electricity (R_{ee}) depend on waste composition (amount and composition of generated biogas and energy yield) i.e. energy value of biogas (E_b), efficiency of energy recovery systems (η_e), selling rate of produced energy (α_e) and price of produced electricity (P_e (€/kWh)) (Equation 16).

$$R_{ee} = E_b * \eta_e * \alpha_e * P_e * m_w \tag{16}$$

Revenues obtained by selling produced heat (R_{he}) depend on waste composition (amount and composition of generated biogas and energy yield) i.e. energy value if biogas (E_b), efficiency of heat recovery systems (η_h), selling rate of produced heat (β_h) and price of produced heat (P_h(€/kWh)) (Equation 17).

$$R_{he} = E_b * \eta_h * \beta_h * P_h * m_w \quad (17)$$

Revenues obtained from selling compost (R_c) depend on the amount of compost obtained from 1 t of waste (A_c), and price of compost (P_c(€/t)) (Equation 18).

$$R_c = A_c * P_c * m_{ofmsw} \quad (18)$$

RESULTS AND DISCUSION

To verify the developed mathematical model for evaluating economic indicators, the city of Niš was chosen as a case study. Table 2 shows the composition and quantity of generated waste (PUC "Medijana" 2014).

Table 2 The composition of municipal solid waste in the city of Niš ((PUC "Medijana" 2014) and chemical composition of waste fraction (dry basis) (Tchobanoglous 1993).

Fraction	Percentage (%)	Production (t/year)	C (% dw)	H (% dw)	O (% dw)	N (% dw)	S (% dw)
Food waste	13.79	9,011.49	48.0	6.4	37.6	2.6	0.4
Paper	7.26	4,744.26	43.5	6.0	44.0	0.3	0.2
Cardboard	4.24	2,770.76	44.0	5.9	44.6	0.3	0.2
Diapers	3.50	2,287.18	35.5	5.67	44.0	<0.1	-
Plastics	21.83	14,265.47	60.0	7.2	22.8	-	-

Textiles	2.63	1,718.65	55.0	6.6	31.2	4.6	0.15
Rubber	5.25	3,430.77	78.0	10.0	-	2.0	-
Leather	0.61	398.62	60.0	8.0	11.6	10.0	0.4
Yard waste	13.55	8,854.65	47.8	6.0	38.0	3.4	0.3
Glass	5.39	3,522.26	0.5	0.1	0.4	<0.1	-
Metals	1.62	1,058.64	4.5	0.6	4.3	<0.1	-
Dirt, ash, etc.	20.33	13,285.25	26.3	3.0	2.0	0.5	0.2
Total	100.00	65,348.00					

The input data was taken as follows: the quantity of waste generated is 65,348 t, waste composition as shown in table 2, the population of the city of Niš according to the last census from 2011 amounted to 260,237.00, population growth is -2.2, facility lifetime is adopted 20 years. Based on these data, the capacity of the plant is calculated as 171,320 t. The price of land in the City of Niš ranged 1,000–3,000 €/ha, site development costs are 20 €/m^2, the project and permits costs (utility costs) are 40 €/m^2 and construction costs are 50 €/m^2. Data for w_c–actual key figures (the amount of waste per capita) is calculated on the basis of the quantity of waste generated and the number of inhabitants per day, amounting to 0.76 kg. The gate fee is 20 €/t, and preferential prices for energy from waste are adopted as 12 c€/kWh for biogas power plants. Energy efficiency for anaerobic digestion is taken as 30%, and thermal efficiency as 45%. The selling rate of produced energy is adopted as 1 and the selling rate of produced heat is adopted as 0.55.

For the calculation of energy yield from biogas, the proceedings were conducted in several steps: biogas composition was calculated on the basis of a Buswell equation, where the formula for an organic part of municipal solid waste was used as $C_{32}H_{54}O_{16}N$. The calculated composition of biogas was 57.42% CH_4, 42.58% CO_2 and 3.13% NH_3. Then the amount of methane per ton of waste was calculated 290 m^3/t, and at the end of the energy yield from biogas was calculated as 2,905.35 kWh/t. The average amount of compost obtained from 1 t of OFMSW was 0.415 t (Murphy & Power 2006).

Based on the amount and composition of waste given in Table 2 and the input data, as well as using equations 1–18 and following the steps in the mathematical model for calculating the investment costs (Fig. 2), operating costs (Fig. 3) and revenues (Fig. 4), the calculated economic indicators are shown in Table 3, where: i(€/t) – the investment costs per ton of waste, r(€/t) – the revenues per ton of waste.

Table 3 Calculated economic indicators

Investment costs (€)		Operating costs (€)	
LT (ha)	4.70	OP (€/t)	10.73
LA (€)	14,133.94	Revenues (€)	
SD (€)	9,422.63	Rgf (€)	815,673.60
BA (m^2)	11,478.48	Ree (€)	4,265,663.97
P (€)	459,139.04	Rhe (€)	2,349,498.85
CC (€)	5,165,314.20	Rc (€)	507,756.82

FC (€)	47,240,203.83	R (€)	7,938,593.23
I (€)	52,888,213.65	r (€/t)	121.48
i (€/t)	308.71		

Table 3 presents investment and operating costs and revenues for anaerobic digestion, calculated by applying the mathematical model for the case study of the city of Niš. From the obtained results it can be concluded that investment costs of 308.71 €/t are at the lower limit of the costs in the EU, which range from 300-1000 €/t (Hogg 2001), due to the lower price of land, constructing costs, salary levels, etc. The operating costs are lower than EU average: they amounted to 10.73 €/t, while in the EU they range from 15-40 €/t. The calculated total revenues are 121.48 €/t and they are at the upper limit of EU average (ranging from 56–126 €/t (Hogg 2001)) due to the higher state subsidies, i.e. higher prices of electricity produced by waste treatment. In Serbia the electricity price obtained from anaerobic digestion is 12 c€/kWh for, while the EU electricity prices range from 2.0–4.0 c€/kWh.

CONCLUSION

The newly developed mathematical model for evaluating economic indicators of biochemical waste treatment technique (investment costs, operating costs, and revenues) is presented in the paper. The model is based on the analysis of the structure of investment and operating costs, as well as revenues. All of the above indicators are calculated depending on the composition and quantity of waste. For each indicator an algorithm that predicts several steps for its calculation is presented. The model, when calculating the revenues, requires the following input data related to the technical characteristics of the system: energy and thermal efficiency of the plant. The developed model is sufficiently general to be applicable to any case study, because it contains local elements (price of land, construction cost, design and permit prices, price of the produced electricity and heat, gate fee, the price of compost).

The obtained results for the city of Niš, for investment costs of 308.71 €/t and operating costs of 10,73 €/t, are at the lower limit of costs in the EU due to lower land prices, the construction costs, salary levels, etc. Due to government subsidies, the higher price of electricity generated by waste treatment affects the total revenues of 121.48 €/t, which are at the upper limit of the EU average.

The results obtained by this model can be used for assessing the sustainability of biochemical waste treatments.

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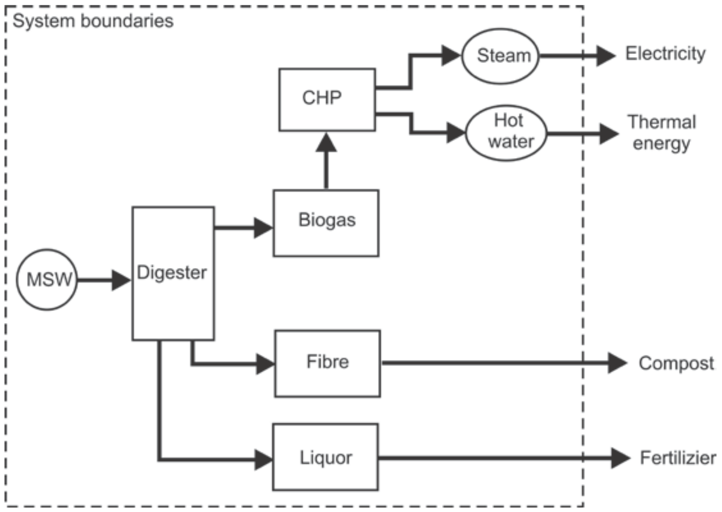

Figure 5 The anaerobic digestion process and system boundaries

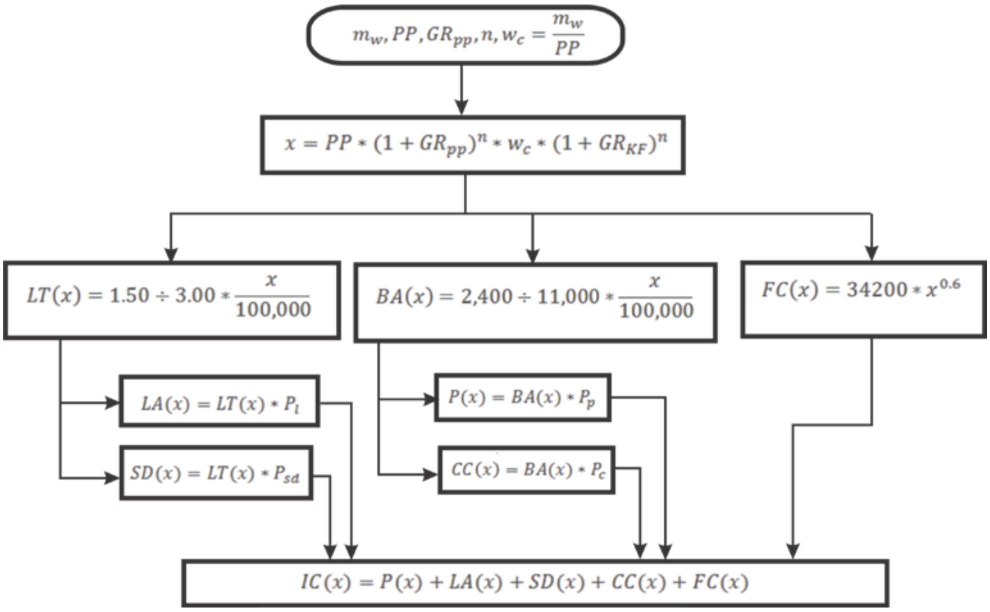

Figure 6 Block diagram of a mathematical model for evaluating the investment costs

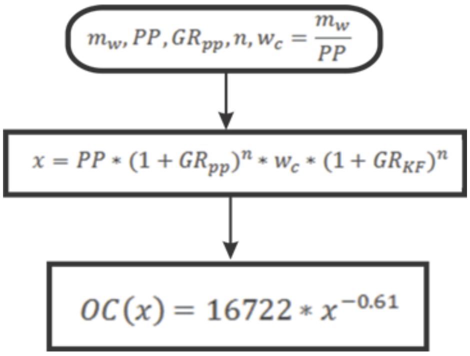

Figure 7 Block diagram of a mathematical model for evaluating the operating costs

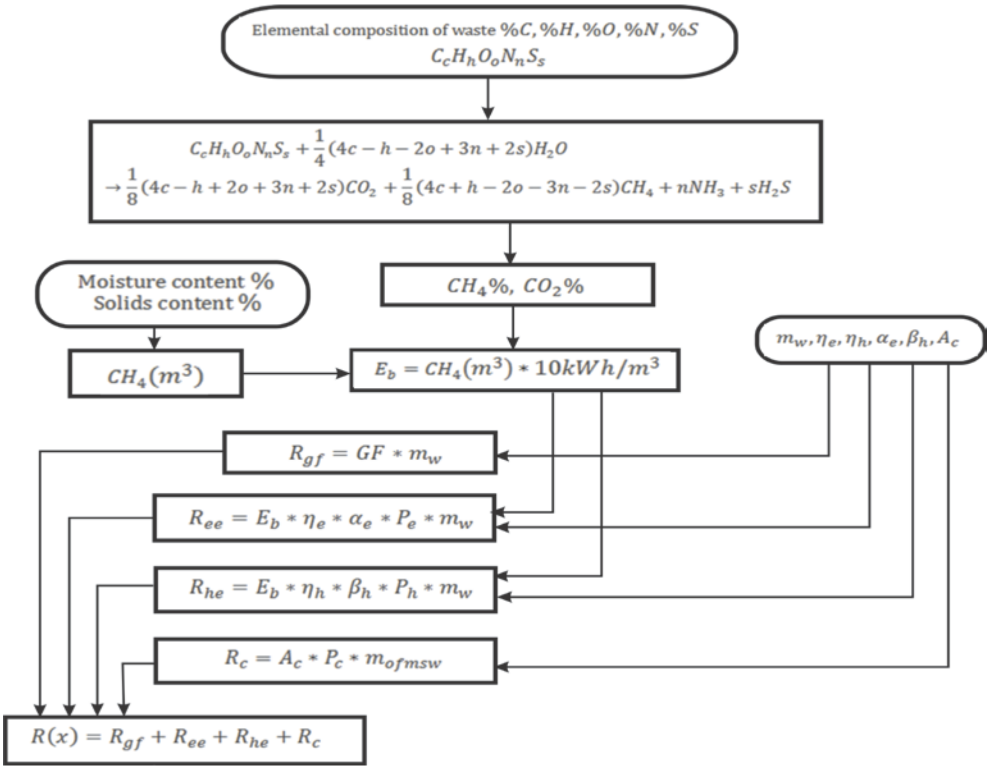

Figure 8 Block diagram of a mathematical model for evaluating the revenues

Table 4 Land-take and building area for sitting anaerobic digestion facility

Facility capacity x(t/y)	Land-take LT (ha)	Buildings Area BA (m^2)
40,000	0.6	2,420
164,000		5,420
38,000	1.5	
5,000		2,500
300,000		35,000
60,000	1.8	

Source: The Office of the Deputy Prime Minister (2004), Ramsey (2009), SAOS (2009), Kraemer & Gamble (2014), FOE (2010)

Table 5 The composition of municipal solid waste in the city of Niš ((PUC “Medijana” 2014) and chemical composition of waste fraction (dry basis) (Tchobanoglous 1993).

Fraction	Percentage (%)	Production (t/year)	C (% dw)	H (% dw)	O (% dw)	N (% dw)	S (% dw)
Food waste	13.79	9,011.49	48.0	6.4	37.6	2.6	0.4
Paper	7.26	4,744.26	43.5	6.0	44.0	0.3	0.2
Cardboard	4.24	2,770.76	44.0	5.9	44.6	0.3	0.2
Diapers	3.50	2,287.18	35.5	5.67	44.0	<0.1	-
Plastics	21.83	14,265.47	60.0	7.2	22.8	-	-
Textiles	2.63	1,718.65	55.0	6.6	31.2	4.6	0.15
Rubber	5.25	3,430.77	78.0	10.0	-	2.0	-
Leather	0.61	398.62	60.0	8.0	11.6	10.0	0.4
Yard waste	13.55	8,854.65	47.8	6.0	38.0	3.4	0.3
Glass	5.39	3,522.26	0.5	0.1	0.4	<0.1	-
Metals	1.62	1,058.64	4.5	0.6	4.3	<0.1	-
Dirt, ash, etc.	20.33	13,285.25	26.3	3.0	2.0	0.5	0.2
Total	100.00	65,348.00					

Table 6 Calculated economic indicators

Investment costs (€)		Operating costs (€)	
LT (ha)	4.70	OP (€/t)	10.73
LA (€)	14,133.94	Revenues (€)	
SD (€)	9,422.63	Rgf (€)	815,673.60
BA (m^2)	11,478.48	Ree (€)	4,265,663.97
P (€)	459,139.04	Rhe (€)	2,349,498.85
CC (€)	5,165,314.20	Rc (€)	507,756.82
FC (€)	47,240,203.83	R (€)	7,938,593.23
I (€)	52,888,213.65	r (€/t)	121.48
i (€/t)	308.71		