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Model for evaluating municipal waste management system applying the LCA - Part II: Model verification

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ABSTRACT

The aim of this study was to use the life cycle assessment (LCA) instrument to assess the different municipal solid waste (MSW) management scenarios for the South Bačka region. LCA has proven to be a very effective instrument for identifying strategies that minimize negative environmental impacts. A comparative analysis is very important for decision makers and planners in the waste sector. This paper presents the application of the LCA model described in the Part I of this study. This model combined life cycle inventory model (IWM-2) and life cycle impact assessment method (Impact2002+) to compare and evaluate the municipal solid waste system with the purpose of identifying environmental benefits and disadvantages, as well as the economic cost of defined scenarios of waste management systems that could be implemented. The model was applied to a regional municipal waste management system in South Bačka (The Republic of Serbia). Four scenarios of waste management are defined. The scenarios include the combination of different treatments of waste (biological and thermal), and a sanitary landfill. The results show clear differences between the scenarios in the selected indicators and quantify the relative advantages and disadvantages of different waste management scenarios. The model is a useful tool to support decision-makers to choose the technology of solid municipal waste treatment. Also, the participants in the planning of solid waste management will enable a better understanding of the importance of LCA method. Finally, it will help the improvement of the strategic planning process in the field of environmental protection, without which it is impossible to achieve the concept of sustainable development in the AP Vojvodina.

1. Introduction

The implementation of EU requirements concerning municipal solid waste (MSW) management is a complex problem in Serbia. Until 2,000 almost all collected waste in Serbia was disposed of in uncontrolled landfills or open dump sites (Stanisavljević et al., 2012).

Noncompliant landfills need to be closed more quickly and waste legislation should be enforced. Noncompliant landfills need to be closed more quickly and waste legislation should be enforced.

The Republic of Serbia as a candidate country for the EU is obliged to comply with EU directives in the near future (Stepanov, 2018). The law states that each municipality is responsible for the proper collection and treatment of municipal waste, in accordance with the

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BAT (best available techniques), with the aim of achieving EU objectives that relate to reducing the mass of biodegradable waste going to the landfill and increasing the recycling rate of packaging waste.

LCA is a process recommended in many EU documents. A Thematic Strategy on the prevention and recycling of waste (EU Thematic Strategy, 2005) is the first document that mentions that the LCA is a suitable tool. This is supported by the numerous LCA computer models related to solid waste management.

2. Methodology

The LCA (IWM-2/Impact2002+) model has been applied to the regional waste management system in South Bačka for the purpose of evaluating recycling, composting, RDF treatment, incineration, and sanitary landfill. The test region includes seven municipalities and the City of Novi Sad. The basic information about the region, as well as the data that determine the functional unit are given in Table 1.

Table 1
The population number and quantity of generated waste in the Region

Scenario 1, 2, 3, 4		
Population	532,200	
Average number of persons per household	2.7	
Amount generated	368 kg/ person·year	
Fraction	**Amount (tons)**	**% by weight**
Paper	28,398	14.5
Glass	10,772	5.5
Metal	4,700	2.4
Plastic	28,398	14.5
Textiles	7,638	3.9
Organics	90,091	46
Other	25,852	13.2
Total	195,850	100

The model was verified by the four scenarios - the current state of waste management in the region and three alternative scenarios. The Scenarios are developed in accordance with the objectives defined in The Landfill Directive (Council Directive 99/31/EC) and The Packaging and Packaging Waste Directive (Directive 2004/12/EC).

The Scenario 1 describes the current situation of waste management in the region and includes collection and transport of unselected waste and disposal to landfill without landfill gas collection or leachate collection (unsanitary landfills).

Only the city of Novi Sad has a plant for the separation of certain fractions. The waste collected in residential buildings in the urban area is delivered to this plant. The field research has provided data on the average amount of waste in a separation plant and it amounted to approximately 19,000 tons/year (9 %) in 2014. Waste collection covers 96 % of the population.

The Scenario 2 includes the following processes: sorting and recycling of certain fractions (paper and cardboard 60 %, glass 60 %, metals 50 %, and plastics 22.5 %), composting about 65 % of total generated biodegradable waste and disposal of waste to landfill with landfill gas collection and energy recovery and leachate collection and treatment. Organized waste collection covers 100 % of the population.

The Scenario 3 includes sorting and recycling of certain fractions (paper and cardboard 60 %, glass 60 %, metals 50 % and plastics 22.5 %), composting about 65 % of total generated biodegradable waste, RDF treatment (sorting and incineration) where residues from the treatment are disposed of in the landfill with landfill gas collection and energy recovery and leachate collection and treatment. Waste collection covers 100 % of the population.

The Scenario 4 includes collection and transport of the unselected waste fractions, and 100 % of the municipal solid waste in the case study area has been sent to incineration with energy recovery. Organized waste collection covers 100 % of the population.

Table 2 gives the main characteristics and waste streams in the scenarios considered for the Region.

Table 2
Main characteristics of municipal solid waste management scenarios

Scenario	**Sorting**	**Composting**	**RDF**	**Incineration**	**Landfill**
1.	9 %	0 %	0 %	0 %	91 % + residual waste
2.	16 %	31 %	0 %	0 %	53 % + residual waste
3.	16 %	31 %	53 %	0 %	Residual waste
4.	0 %	0 %	0 %	100 %	Residual waste

3. Discussion

After the modeling, the results were obtained with respect to the functional unit; however, in the discussion, the results were considered per ton of waste treated in a particular process in order to be comparable with the results of similar studies.

3.1. Energy consumption

Table 3 presents a comparative overview of the results of energy consumption in the defined scenarios. Negative values reflect the net benefits.

Scenarios 2, 3, and 4 have achieved a positive energy balance. The incineration of waste that is generated in the South Bačka region shows the best results, 82 % more energy is generated in Scenario 4 than in Scenario 3.

As one might expect, the energy balance in Scenario 1 is negative because the percentage of recycling that is present in this scenario is extremely small, and landfill is without collecting and treating landfill gas.

LCA analysis of waste of similar composition showed similar results, which leads to the conclusion that the incineration as a waste treatment is a suitable option from the aspect of energy production.

In Scenario 3, in thermal treatment, (RDF process) 643 kWh of energy per ton of waste was produced. In LCA studies, this value ranges from 284 to 685, which depends on the degree of sorting and system efficiency (Lombardi et al., 2005; Cherubini et al., 2009).

Electricity derived from landfill gas in Scenario 3 is 110 kWh per ton waste, and in Scenario 2 it is 163 kWh per ton waste. The amount of the generated gas depends on the landfill content of waste going to landfill.

Considering that in Scenario 3 only waste remaining from recycling, composting, and RDF treatment is deposited at the landfill, it is clear that the potential for generating waste gas from this type of waste is lower than in the case of Scenario 2. These values range from 80 to 171 kWh of energy per ton of waste in the published papers (Cherubini et al., 2009; Wittmaier et al., 2009; Hong et al., 2010). The energy converted to electricity in the process of incineration is 606 kWh per ton waste.

LCA study by Cherubini et al. (2009) conducted for the city of Rome and the composition of waste is very close to the composition of waste in the Novi Sad region; it gives a result of 594 kWh energy per ton of waste.

In the LCA studies, the values of the amount of electricity that can be generated in waste incineration plants ranges from 262 to 696 kwh of energy per ton of waste (Villeneuve et al., 2009; Hong et al., 2010).

From the aspect of energy consumption, Scenario 4 represents the most favorable option for the environment.

3.2. Cost

In the waste management Scenarios, economic costs include collection, transport, sorting, and treatment of waste and refer to 195,850 tons of municipal solid waste (Table 4).

Based on the results shown, it can be clearly concluded that the most favorable scenario for waste management is Scenario 1 (58 € per ton of waste).

The economic costs of different systems are determined by the cost of processing, transport, revenue from subsequent sales of sorted materials, compost, and electricity market price. Many of these parameters can vary over time and within different geographical regions (Thorneloe et al., 2007).

Table 3
Energy consumption in waste management scenarios (GJ)

	Collection	Sorting	Compost.	Thermal	Landfill	Recycling	Total
Scenario 1	132,256	7,978			6,218	-82,113	64,339
Scenario 2	137,767	12,867	19,043		-204,650	-298,961	-333,934
Scenario 3	137,767	126,802	31,180	-389,361	-88,206	-356,850	-538,668
Scenario 4	103,325			-1,089,751	1,946		-984,480

Table 4
Waste management costs (€ per year)

		Collection	Sorting	Compost	Thermal	Landfill	Total
Scenario 1	€ /year	10,152,864	-1,161,232			2,429,701	11,421,332
Scenario 2		16,059,700	-4,278,275	858,993		4,312,696	16,953,115
Scenario 3		16,059,700	-684,620	1,732,972	-123,923	3,103,215	20,087,344
Scenario 4		10,575,900			13,265,586	2,316,746	26,158,232

In Scenarios 2 and 3, the costs are increased by 48 % and 75 % in relation to Scenario 1. The highest cost management option is the Scenario 4 (133 € per ton of waste). Without the revenue from the sale of electricity generated during incineration, these costs would be even higher. Authors Stypka and Flaga (2005) analyzed waste management scenarios for the city of Krakow, and the costs in this analysis range from 60 (landfill) to 125 € per tonne of waste (incineration).

3.3. Global warming

Table 5 shows the results of the impact of the life cycle of waste on the midpoint and endpoint level of the environmental impact for the indicator global warming. As can be seen in Table 5, Scenario 1 represents the most disadvantageous option from the point of view of the impact on global warming.

Scenario 1 emits 326,914 tons of $CO2_{-eq}$ or 1.67 tons of CO_{2-eq} per ton of waste. In the paper by Hong et al. (2010), which analyzes the municipal waste disposal in China and conducts a comparison of the obtained results to the results from a number of scientific papers, this value ranges from 0.49 to 6.99 tons of CO_{2-eq} per ton of waste. High values of global warming potential occur in landfills that are not equipped with a system for collecting and treating landfill gas.

With more advanced waste management systems, presented in Scenarios 2, 3 and 4, this impact can be reduced by ≈ 93 %, ≈ 106 % or ≈ 63 %. More intensive recycling and composting, as well as sanitary waste disposal, achieve significant reductions in CO_{2-eq} emissions. The best effects in terms of reducing greenhouse gas emissions are achieved in Scenario 3. The impact on global warming in Scenario 3 is the most suitable since CO_2 emissions in the RDF process primarily depend on the ratio of the produced and consumed energy, RDF saving of CO_2 emissions, and the improvement of air emission quality as well.

In the process of incineration, fractions of waste from petroleum products are responsible for relatively high greenhouse gas emissions.

The incineration presented in Scenario 4 is a much less sustainable option than the treatment of wastes presented in Scenarios 2 and 3. According to the presented results, large amounts of CO_2 are emitted from the process of waste incineration, i.e. 0.62 tons of CO_{2-eq} per ton of waste.

LCA analysis of the incineration process in the paper of Eriksson et al. (2005) gives results of 0,33 tons of CO_{2-eq} per ton of waste, and in the paper of the author Banar et al. (2009) a value of 1.51 tons of CO_{2-eq} per ton of waste can be found, while the authors.

Liamsanguan and Gheewal (2008) give a value of 0.63 tons of CO_{2-eq} per ton of waste. In this paper, the emissions from the process of incineration are 0.75 tons of CO_{2-eq} per ton of waste.

However, considering this process from the perspective of the life cycle, and taking into account the savings of greenhouse gases emissions due to the renewal of energy of 0.13 tons of CO_{2-eq} per ton of waste, the total emissions from the process of incineration are 0.62 tons of CO_{2-eq} per ton of waste. From the aspect of contribution to climate change Scenario 4 is certainly not an acceptable option.

3.4. Terrestrial acidification

Table 6 shows the results of the impact of the life cycle of waste on the midpoint and endpoint level of the environmental impact for the indicator terrestrial acidification.

This indicator includes the impacts in the quality of ecosystems caused by the emissions of ammonia, sulfur oxide and nitrogen into the atmosphere (Thorneloe et al., 2007).

Table 5
Global warming

Global warming	**Midpoint level**	**Endpoint level**
Scenario 1	326,914 tons CO_{2-eq}	326,914 tons CO_{2-eq}
Scenario 2	24,827 tons CO_{2-eq}	24,827 tons CO_{2-eq}
Scenario 3	-20,547 tons CO_{2-eq}	-20,547 tons CO_{2-eq}
Scenario 4	122,502 tons CO_{2-eq}	122,502 tons CO_{2-eq}

Table 6
Terrestrial acidification

Terrestrial acidification	**Midpoint level**	**Endpoint level**
Scenario 1	794 tons SO_{2-eq}	827,162 PDF·m²·year
Scenario 2	379 tons SO_{2-eq}	395,410 PDF·m²·year
Scenario 3	41 tons SO_{2-eq}	43,616 PDF·m²·year
Scenario 4	-900 tons SO_{2-eq}	-947,374 PDF·m²·year

From the aspect of the life cycle of waste, the emissions of compounds that contribute to terrestrial acidification mostly occur on unsanitary landfills, 0.004 tons of $SO_{2\text{-eq}}$ per tons of waste (Scenario 1). These compounds are also emitted due to biological treatment or composting of waste (Scenarios 1 and 2). The increase in the temperature and pH of the compost pile encourages ammonia emissions. The incineration process (Scenario 4) presented in the paper is most favorably reflected on the terrestrial acidification and it has a value of -0.004 tons of $SO_{2\text{-eq}}$ per ton of waste.

Terrestrial acidification as an indicator is considered in only a few research papers dealing with mixed municipal waste, mainly analyzed in the works dealing with specific waste streams. Hong et al. (2010) analyzes the incineration process in its work and as a result the value of -0.001 tons of $SO_{2\text{-eq}}$ per ton of waste is obtained. Regarding that, the process of incineration is benefitial to the environment. In the paper that analyzes the region in Italy, the emissions of $SO_{2\text{-eq}}$ are -0.004 tons per ton of waste (Arena et al., 2003).

Savings are also made in the case of sanitary waste disposal; however, due to the combination of several treatments in Scenarios 2 and 3 in this paper, these values did not result in savings on the overall impact of the system.

Scenario 1 describing the existing state of waste management in the Region, releases as much as 795 tonnes of $SO_{2\text{-eq}}$ per year, and the damage done to *"terrestrial acidification"* reflects over 827,162 PDF·m^2·year.

In the alternative waste management system options presented in Scenarios 2, 3 and 4, the amount of $SO_{2\text{-eq}}$ emitted is significantly reduced by 47 % in Scenario 2, by 94 % in Scenario 3 and by 22 % in Scenario 4.

3.5. Land occupation

Table 7 shows the results of the impact of the life cycle of waste on the midpoint and endpoint level of the environmental impact for the indicator land occupation.

Based on the presented results it can be concluded that the land area that is intended for the treatment of waste is significantly reduced in the developed scenarios compared to the existing scenario. It is evident that landfilling takes up the largest land surface and that the treatments that are included in the developed scenarios occupy significantly less areas.

Composting is a process that requires a certain area of land, but it is much smaller than landfilling, and the smallest area is taken up by combustion plants. Therefore, this indicator provides information on changes in land use and is an important factor in determining the degree of soil degradation and, in this sense, the impact on the ecosystem quality (loss of habitat or area). Land degradation implies the reduction or loss of biological or economic productivity and the complexity of the soil (Official Gazette, 2010).

Land occupation in Scenario 1 is 3.63 $m^2_{\text{-eq}}$ per ton of waste, and in Scenario 4 only 0.53 $m^2_{\text{-eq}}$ per ton of waste.

Incineration is the best option, as in the case of similar analyses. In the LCA study in which the Impact 2002+ method was used, author Hong et al. (2010) for the composition of waste very similar to that in the investigated region, land occupation due to landfilling is 4.21 $m^2_{\text{-eq}}$ per ton of waste, and at 0,76 $m^2_{\text{-eq}}$ per ton of waste.

By sanitary landfilling, increasing the recycling rate and composting, which is covered in Scenario 2, this load is reduced by ≈ 59 % compared to Scenario 1.

By implementing the RDF treatment, which is implied by Scenario 3, the land load is reduced by ≈ 76 %, and the implementation of the incineration decreases by ≈ 85 %. The loss of biodiversity over a period of one year can be reduced by 2 to 6 times by alternative scenarios.

Graph 1 summarizes all the indicators, i.e. the share of each scenario in a given indicator.

Observing the scenarios from the aspect of savings or benefits, there are two scenarios, i.e. Scenarios 3 and 4.

Scenarios 3 and 4 achieve savings in two out of five indicators. By introducing Scenario 3, energy savings and favorable influence on global warming are achieved.

The implementation of the incineration provides energy savings and a favorable impact on terrestrial acidification.

Table 7
Land occupation

Land occupation	Midpoint level	Endpoint level
Scenario 1	712,134 $m^2_{\text{-eq}}$	776,873 PDF·m^2·year
Scenario 2	360,810 $m^2_{\text{-eq}}$	393,611 PDF·m^2·year
Scenario 3	170,567 $m^2_{\text{-eq}}$	186,106 PDF·m^2·year
Scenario 4	104,770 $m^2_{\text{-eq}}$	114,295 PDF·m^2·year

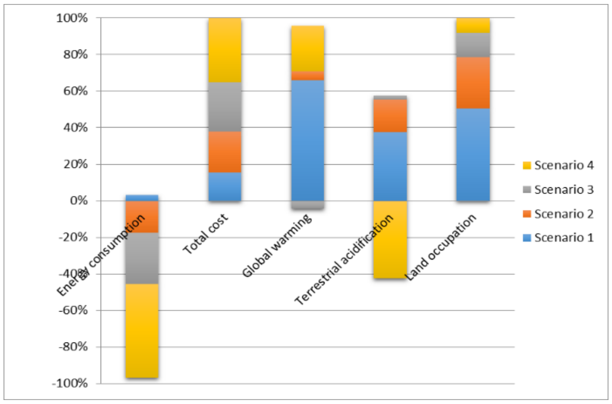

Figure 1. Comparison of scenarios

Scenario 3 meets the objectives of the Packaging Waste Directive as well as the Waste Disposal Directive, while Scenario 4 fulfills only the objectives of the Waste Disposal Directive.

4. Conclusion

The developed model provides the possibility of a comparison of scenarios, cost estimates, and environmental impact at the midpoint and endpoint level. This type of model is needed in identifying strategies that lead to a sustainable waste management system.

The results of the application of this model show that the current method of waste management in South Bačka is the most unfavorable and that significant environmental savings are achieved from recycling, biological, thermal waste treatment, and sanitary disposal. Thermal treatments, sanitary disposal, and recycling are treatments that save energy. Energy savings in Scenario 3 are higher than in Scenario 2 because in addition to the recycling and sanitary landfilling represented also RDF treatment. Scenario 4 achieves the highest savings due to the use of energy from the incineration of waste.

The economic costs increase proportionally with the increase in complexity of the applied technologies of waste treatment. From the life cycle perspective, the largest share in total costs is the costs of collecting and transporting waste, because in this phase there is no income that affects the reduction of the total costs of transport and waste collection.

Based on these results it can be concluded that the optimization of the existing waste management system can lead to significant reductions in the emissions that contribute to global warming and acidification. The greatest effect is achieved by the Scenario 3 (RDF treatment), but in other treatments significant reductions in $SO_{2\text{-eq}}$ and $CO_{2\text{-eq}}$ are evident.

Finally, based on the given analysis, Scenario 3 can be considered as the most suitable scenario for the Region. Even the incineration (Scenario 4) seems to be better than unsanitary landfilling (Scenario 1), from an environmental impact point of view.

The results presented in this research are of utmost importance to the decision makers for the development and improvement of solid municipal waste management systems both at the local and regional level.

When making the final decision on the choice of waste treatment technology for local conditions, it is necessary to include in the analysis the feasibility study and the analysis of the investment costs of the system.

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Model za evaluaciju sistema upravljanja komunalnim otpadom, primena LCA – deo II: Verifikacija modela

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I Z V O D

Cilj ove studije je da se korišćenjem instrumenta za ocenjivanje životnog ciklusa (LCA) vrednuju i porede različiti scenariji upravljanja komunalnim otpadom u Južnobačkom regionu. LCA je dokazano veoma efikasan instrument za identifikaciju strategija koje minimalizuju negativan uticaj na životnu sredinu. Dodatno, komparativna analiza je veoma značajna za donosioce odluka i planere u sektoru otpada. Ovaj rad predstavlja primenu LCA modela koji je detaljno predstavljen u Delu I ove Studije. Pomenuti model objedinjuje model inventara životnog ciklusa (IWM-2) i metoda procene uticaja (Impact2002+) sa ciljem komparacije i vrednovanja sistema upravljanja komunalnim otpadom, kako bi se identifikovali pozitivni i negativni uticaji na životnu sredinu, kao i troškovi potrebni za implementaciju scenarija upravljanja komunalnim otpadom.Model je primenjen na sistem upravljanja otpadom u Južnobačkom regionu u Republici Srbiji. Definisana su četiri scenarija upravljanja otpadom. Scenariji uključuju kombinacije različitih tretmana otpada (bioloških i termičkih) i sanitarnu deponiju. Rezultati pokazuju jasnu razliku između scenarija posredstvom odabranih indikatora i kvantifikuju prednosti i nedostatke različitih scenarija upravljanja otpadom. Model je koristan, pomoćni alat donosiocima odluka prilikom izbora tehnologije tretmana komunalnog otpada. Dodatno, pomaže učesnicima u postupku planiranja upravljanja otpadom da razumeju značaj primene LCA metode. Na posletku, model pomaže unapređenju procesa strateškog planiranja u oblasti zaštite životne sredine, bez koga nije moguće dostizanje održivog razvoja u AP Vojvodini.