Environment Protection Engineering

Vol. 44 2018 No. 3

DOI: 10.5277/epe180303

JASNA STEPANOV[1], DEJAN UBAVIN[2], DUNJA PROKIC[1], IGOR BUDAK[3],
HRISTINA STEVANOVIC-CARAPINA[1], NEMANJA STANISAVLJEVIC[2]

COMPARISON OF MUNICIPAL WASTE MANAGEMENT SYSTEMS USING LCA. SOUTH BACKA WASTE MANAGEMENT REGION. A CASE STUDY

The Republic of Serbia as a candidate country for the EU is obliged to comply with EU directives. This refers to the waste management sector as well. Different goals need to be fulfilled and the current waste management practice has to be improved in order to meet all regulatory EU requirements. Therefore, any piece of information that would support future waste management decisions is of great significance for developing and streamlining future strategies. The life cycle assessment (LCA) is a popular tool widely used for assessment of environmental impacts of waste management systems. This paper focuses on a LCA of four waste management scenarios used in selected region in Serbia (South Backa) and five indicators for the comparison and evaluation of municipal solid waste management strategies. The analysis includes the current situation of waste management in this region, as the base scenario, and three alternative scenarios. The combined life cycle inventory (LCI) model and life cycle impact assessment (LCIA) method has been used to evaluate the municipal solid waste system with the purpose of identifying environmental benefits and disadvantages, as well as economic cost of defined scenarios of waste management systems that could be implemented. The results clearly indicate the difference between the scenarios and show the influence of implementation of composting, RDF treatment, incineration and increased recycling rates on the environmental performance and economic cost of municipal solid waste management in the South Backa region.

---

[1] Faculty of Environmental Protection, Educons University, Vojvode Putnika 87, 21208 Sremska Kamenica, Serbia, corresponding author J. Stepanov, e-mail address: jasnastepanov@gmail.com

[2] Faculty of Technical Sciences, Department of Environmental Engineering and Occupational Safety and Health, University of Novi Sad, Trg Dositeja Obradovica 6, 21 000 Novi Sad, Serbia.

[3] Faculty of Technical Sciences, Department of Production Engineering, University of Novi Sad, Trg Dositeja Obradovica 6, 21 000 Novi Sad, Serbia.

1. INTRODUCTION

Waste is a by-product of our daily activities, which poses a serious threat to societies all over the world [1]. A specific waste management system can greatly influence quality of the environmental factors. The decisions regarding selection of different options for municipal waste management are crucial for development and improvement of a sustainable waste management system.

The landfill directive, the waste incineration directive, the waste framework directive (WFD), the packaging and waste packaging directive [2–5] are the basis for the current European policy on waste. The Republic of Serbia as a candidate for the EU is obliged to harmonize national legislation with EU directives in the near future.

Waste management practice in Serbia can generally be characterized as unsatisfactory as it consists mainly of waste collection and land disposal. Until 2000 almost all collected waste in Serbia was disposed of in uncontrolled landfills or open dump sites [6]. Non-compliant landfills need to be closed more quickly and waste legislation should be enforced. Full alignment with the waste framework directive is still to be achieved.

Waste management in Serbia is regulated by the waste management strategy (WMS) for the period of 2010–2019, the law on waste management (LWM), the law on managing packaging and packaging waste (LMPW) and the regulation on waste disposal in landfills (RWDL) [7–10]. The waste framework directive (WFD) [4] was transposed in 2010 by adopting amendments to the LWM [8] and its implementing legislation. However, the WFD has not been fully transposed yet. The directive on packaging and packaging waste [5] has been fully transposed by the law on packaging and packaging waste (LMPW) [9] and it has been in the process of implementing legislation. The national goals and objectives related to recycling and recovery of packaging waste are defined in the regulation on developing the Plan for Reducing Packaging Waste for the period 2010 to 2014 (PRPW) [10]. The Directive on the Landfill of Waste [2] and the Council Decision on establishing criteria and procedures for the acceptance of waste at landfills have mostly been regulated according to LWM and the RDWL.

Life cycle assessment (LCA) is a widely used method that quantitatively supports life cycle thinking. LCA is generally based on an inventory of all flows of resources, energy, and emissions that compose each element of individual operations in the system [11].

In the last 15 years several models (UMBARTO, ORWARE, EASETECH, IWM-2) have been developed for the special purpose of assessing environmental consequences of solid waste management systems [12]. The majority of them is based on LCA, whereas there are methods that are based on the material flows analysis (MFA) and the substance flow analysis (SFA) [13]. Today, LCA is considered as well-established method for supporting decision making related to waste management. Until now, a number of review studies have investigated the application of LCA to the field of solid waste management. Their focus has been limited to specific methodological aspects or specific types of waste or waste management systems [14]. At the European level, it is being applied as a decision-supporting tool to policy-makers [19], but the level of knowledge of LCA remains worryingly low in the public domain, especially in Serbia. The goal of implementing LCA models in solid waste management is not necessarily to obtain a final single number, but rather to generate an indication of the best choices when considering uncertainties [16]. Laurent et al. [14] analyzed 222 published LCA studies of solid waste management system. Results showed that LCA applications have largely been limited to developed countries, hence indicating that a number of environmental problems specific to waste management in developing countries have not been investigated. LCA can identify not only the best scenario, but also the analytical contribution of single operations to the overall environmental performance of the system [15]. LCA has been extensively applied for the evaluation of the environmental aspects and support environmentally sound decision-making in the waste management context [17].

To assess the environmental impact, it is necessary to apply LCIA method. Until today, a range of LCIA methods have been developed. Among them, the most frequently used are: CML 2002, EDIP, Eco-Indicator 99, Impact2002+ and ReCiPe. Damage oriented methods such as Eco-indicator 99 are focused on the cause-effect chain up to the damage and quantify endpoint CFs. The Impact2002+ proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results via 14 midpoint categories to four damage categories [21].

The aim of this study was to compare alternative waste management solutions (which are in accordance with the EU membership requirements), to assess their impact on the environment and evaluate the level of operating costs of the system.

2. MATERIALS AND METHODS

A combination of LCI and LCIA models has been applied to the regional waste management system in South Backa in order to evaluate the introduction of biological treatment of waste (composting), RDF treatment and incineration, to increase the level of recycling and fulfill the conditions regarding disposal of municipal solid waste in a sanitary landfill. The reason for LCI/LCIA model application is that they can determine the economic costs, environmental burdens, midpoint impacts and damage impacts.

The test region comprises seven municipalities (Backa Palanka, Backi Petrovac, Beocin, Zabalj, Srbobran, Temerin and Vrbas) and the City of Novi Sad in which the waste is mostly deposited in landfills, that are not sanitary nor technically organized. It certainly does not represent a sustainable waste management system. In regard to the waste composition in the test region, garden and biodegradable waste is dominant with 46%, then paper and cardboard 14%, plastic 14%, glass 5,5%, metal 2,4%, textile 3,9% and others 13,2%. Data on general population and waste quantities are given in Table 1.

Table 1

The population number
and quantity of generated waste in the test region [18]

Indicator	Value
Number of households	194 452
Population	532 200
Amount of municipal solid waste, kg·person^{-1}·d^{-1}	1.01
Average number of persons per household	2.7
Total waste input, t·yr^{-1}	195 850
Amount generated, kg·person^{-1}ton·yr^{-1}	368

The scenarios are developed in accordance with the objectives defined in the landfill directive [3] and the packaging and packaging waste directive [5]. The landfill directive obliges all member states to reduce the amount of biodegradable waste disposed to landfills to 35% in the period of 15 years compared to the quantities disposed in 1995. More specific objectives regarding recycling of certain materials are regulated by the packaging and packaging waste directive: 60% for paper, cardboard and glass, 50% for metals, 22.5% for plastics and so on. Due to lack of some regional-specific data needed for development of the scenarios, we have used those adopted from the literature.

General assumptions for all scenarios are: the compost produced is considered to be marketable 50%, the gross efficiency of energy recovery from thermal treatment (RDF, incineration) and landfilling is 30% (energy recovered as electricity only). For this particular purpose the following scenarios have been analyzed:

Scenario 1 (S1, recycling 9% and landfill 91%) refers to the current state of municipal waste management and includes: collection of unselected waste, transportation and disposal of solid waste to unsanitary landfills. In the whole region, only the town of Novi Sad has a plant for the separation of certain fractions. Only 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 t·yr^{-1} in 2014.

Scenario 2 (S2, recycling 16%, composting 31% and landfill 53%) includes the following processes: selected fractions collection and waste transport, scaling up of the recycling process (60% paper, cardboard and glass, 50% metals and 22.5% plastic), biological treatment of waste (composting) in the proportion of about 65% of the total amount of biodegradable waste and disposal of the remaining quantities of waste to the regional sanitary landfill. This landfill is equipped with a system for collection and treatment of landfill gas and landfill leachate in accordance with all sanitary and technological requirements.

Scenario 3 (S3, recycling 16%, composting 31% and RDF 53%) includes: the collection of selected fractions and waste transport, recycling (60% paper, cardboard and glass, 50% metal and 22.5% plastic), biological treatment of waste (composting) in the proportion of about 65% of the total amount of biodegradable waste, RDF treatment (sorting and incineration) whereas residues from the treatment are disposed of in the landfill.

Scenario 4 (S4, incineration 100%); this option includes: collection of unselected waste fractions and 100% of the municipal solid waste in the case study area has been sent to incineration. This option does not conform to the waste recovery targets but meets the landfill directive targets. It should be noted that the landfill directive targets do not include recovery rates for specific processes such as recycling and composting [19].

LCA was conducted in accordance with ISO 14040 standards. The functional unit is the comparison unit in a life cycle inventory. The functional unit is the management of the household and similar waste from a given geographical area in a time period of 1 year. The system boundaries consider the whole life cycle of waste, from the moment it becomes waste by losing value, to the moment it regains value or leaves the waste management system as an emission.

The scope of IWM-2 model is to enable LCI of a specific waste management system to be carried out [20]. This model was used in this paper, with some modifications relating to the adjustment of the specifics of the test region. The tool can then estimate the environmental performance and economic costs of various options for waste management. This is based on life cycle emissions and resource consumption data (inventory) for a variety of waste management and related operations, including waste collection, sorting, recycling different materials, biological treatment, thermal treatment and landfilling. The results from this particular tool are in the form of emissions into the air, water and inert landfill material but in the form of useful products as well, for instance, energy.

For LCI results to be further discussed in the context of the impact assessment, it is necessary to multiply them with the CFs given in LCIA method. As far as possible, the Impact2002+ method aims to connect each LCI result (elementary flow or other intervention) to the corresponding environmental impacts by using CFs. LCI results are classified into impact categories, each with a category indicator. The category indicator can be located at any point between the LCI results and the damage category in the cause-effect chain [21]. In the Impact2002+ method at the damage level, the impact from global warming is presented in a separate damage category (climate change) unlike other methods in which the influence of climate change is associated with ecosystem quality or human health. The modeling up to the damage of the impact of the climate change on the ecosystem quality and human health is not accurate enough to derive reliable damage characterization factors [22].

In the paper, the results of the research are presented on two levels: 1) at the level of the inventory results – LCI indicators and 2) at the level of results regarding the assessment of impact on life cycle – LCIA indicators. Selected indicators for the comparison of the scenarios are total energy consumption (GJ) and cost per capita (€) as LCI indicators and global warming, land occupation and terrestrial acidification as the LCIA indicators. These indicators have been selected based on the most important national issues in order to meet the obligations arising from EU legislation and which the Republic of Serbia as a candidate should meet. There is a significant degree of consensus in the scientific community that greenhouse gases (GHG) emissions and land degradation are the key issues when it comes to waste management. Waste sector is a significant contributor to GHG emissions for approximately 5% of the global GHG. Municipal and industrial wastes contribute most to soil contamination (38%) in EU [22].

LCIA indicators in the midpoints are associated with indicators in the end positions, i.e., indicators of damage, as shown in Table 2.

Table 2

LCIA indicators, reference substances and units used to express values

Midpoint indicator	Midpoint reference substance	Damage indicator	Damage unit
Global warming	kg CO_2 into air_{eq}	climate change	kg CO_2 into air_{eq}
Terrestrial acidification	kg SO_2 into air_{eq}	ecosystem quality	PDF$\cdot$m$^2\cdot$y
Land occupation	m^2 organic arable $land_{eq}\cdot$y	ecosystem quality	PDF$\cdot$m$^2\cdot$y

The damage category climate change is the same category as the midpoint category global warming. Even if it is considered as a damage category, climate change impact is still expressed in kg CO^2_{eq}.

kg substance s_{eq} (kg equivalent of a reference substance s) expresses the amount of a reference substance that equals the impact of the considered pollutant within the midpoint category studies.

PDF$\cdot$m$^2\cdot$y (potentially disappeared fraction of species over a certain amount of m^2 during a certain amount of year) is the unit to “measure the impacts on ecosystems. The PDF$\cdot$m$^2\cdot$y represents the fraction of species disappeared on 1 m^2 of earth surface during one year [21].

Total energy consumption. Power consumption is an essential factor when it comes to sustainability assessment of waste management systems in the context of resource conservation. Energy balance is used for the purpose of describing the relation between energy production and the necessary amount of energy needed for the functioning of a particular system [6]. This indicator includes energy production and consumption in the process of collecting, sorting, biological treatment, thermal treatment, recycling and disposal of waste.

Cost per capita. The financial parameter is the decisive factor in the processes of decision making and evaluation of the waste management system. The relationship between socioeconomic and technological aspects is often a major obstacle for improving the quality of the environment. The introduction of modern waste treatment options is often related to the additional costs. The costs represent an indicator which is directly correlated with purchasing power of the population.

Global warming (*climate change*). Climate change prevention and the reduction of greenhouse gas emission are among the biggest challenges of the European Union. The share of the waste management sector in the total emissions of greenhouse gases in the

EU 28 amounted to 3%. European 2020 strategy has set a goal to reduce emissions of greenhouse gases by 20% by 2020 compared to the starting year of 1990. The Republic of Serbia as a candidate for the EU membership is obliged to reduce its greenhouse gases emissions in all sectors, including waste management sector.

Terrestrial acidification and *land occupation* (*ecosystem quality*). These indicators have been discussed because the correlation between soil pollution and waste management is obvious. Waste disposal is a method that requires large tracts of land, and at the same time, it is the most common method of waste treatment in Serbia. Inadequate waste management has led to a large number of sites that are potentially contaminated due to inadequate waste disposal [6]. According to the data of The European Environment Agency from 2007, approximately 250 000 contaminated sites require urgent rehabilitation. In the Republic of Serbia, according to official data, 43.5% of the total number of the identified contaminated sites are illegal waste dumping landfills [23].

LCI results in the form of air emissions expressed in kg and the amount of waste disposed at the landfill (m^3) obtained in the LCI model, were further evaluated using characterization factors in the Impact2002+ method in which the results of the analysis of inventory are processed in the context of environmental impact. However, the impact category for land occupation cannot be calculated directly from the inventory. The Impact2002+ requires the value expressed in $m^2 \cdot y$ as an input. Therefore, the following assumption has been used for the determination of this indicator: total volume of landfilled waste (m^3), divided by an average landfill depth (15 m assumed) and multiplied by an average occupation time (70 years assumed: 20 for waste disposal and 50 for monitoring) [24].

3. RESULTS AND DISCUSSION

The results of the inventory of waste life cycle (LCI indicators) and comparison of the scenarios 1–4 are shown in Tables 3 and 4. All results are reported in relation to the annual quantity of waste (195 850 t). In comparison with the scenario 1, the scenarios 2–4 haves shown a significant advancement in terms of environmental performances.

Energy consumption in the treatment of waste is negative: in the process of dumping waste in sanitary landfill in the scenarios 2 and 3, in the process of recycling waste in the scenarios 1, 2 and 3 and in the process of thermal treatment of waste in the scenarios 3 and 4. It means that the energy recovered at the landfill site in the form of landfill gas or in the RDF process or incinerator, plus the energy saved thanks to the recycling program, is larger than the energy needed for waste processing. The scenario 3 is the most favorable scenario with regard to the energy aspect.

In the waste management scenarios, economic costs include collection, transport, sorting and treatment of waste and refer to 195 850 t of municipal solid waste. The costs of collecting and treating waste are also a substantial part of the total costs used on overall environmental issues in the society [12]. The costs shown in Table 4 represent costs per capita in the form of waste disposal. The economic costs of various systems are determined by the cost of processing, transport, revenue from subsequent sales of sorted materials, compost and electricity market price. The economic costs per capita increase proportionally with the increase in complexity of the applied technologies of waste treatment. Although more advanced scenarios 2–4 generate greater savings through material and energy recovery, they also require a larger number of vehicles or specialized vehicles for selected fractions collection and additional sorting of waste fractions which increase overall costs.

Table 3

Results at the level of inventory, LCI indicator total energy consumption

Stage of the process	Total energy consumption [GJ]			
	S1	S2	S3	S4
Collection	132 256	137 767	137 767	137 767
Sorting	8128	12 867	126 802	0
Composting	0	19 043	31 180	0
Thermal	0	0	–389 361	–1 227 006
Landfill	6078	–204 650	–88 206	1946
Recycling	–365 426	–764 667	–920 318	0
Total	–218 965	–799 640	–1 102 136	–1 087 293

Negative values reflect the net benefits.

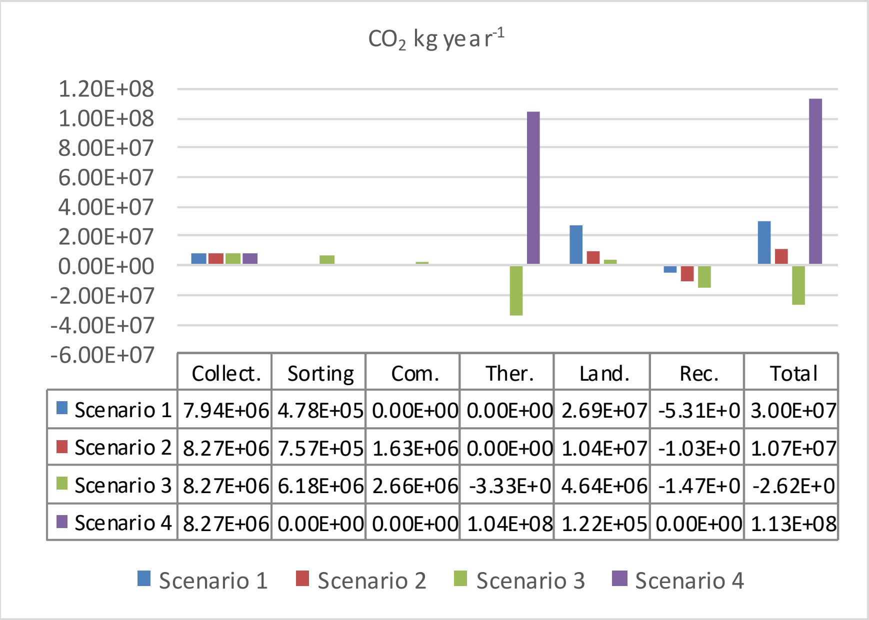
Table 4

Results at the level of inventory, LCI indicator cost per capita

Stage of the process	Cost capita·yr^{-1} [€]			
	S1	S2	S3	S4
Collection	19	30	30	20
Sorting	–1	–3	4	0
Composting	0	3	5	0
Thermal	0	0	–4	23
Landfill	4	8	6	4
Recycling	0	0	0	0
Total	22	38	41	47

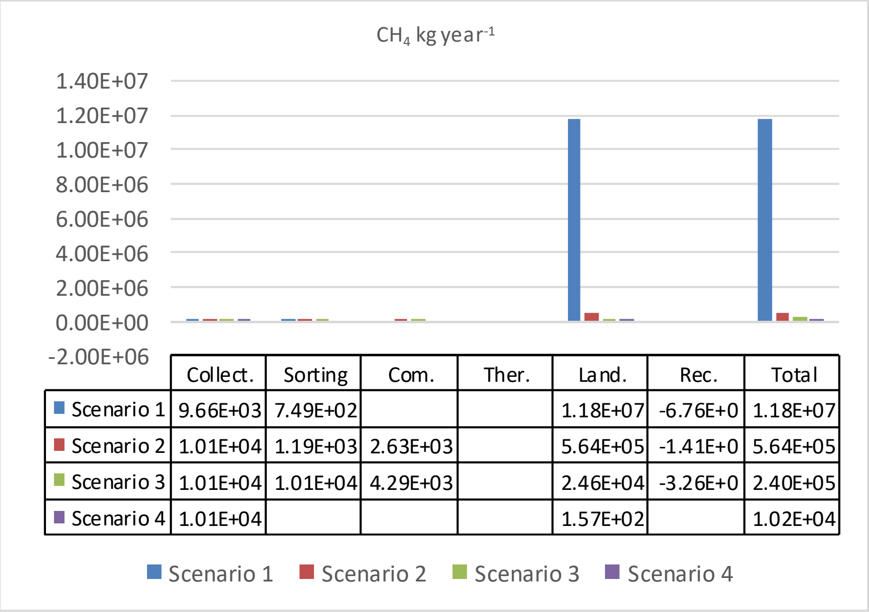
Negative values reflect the net benefits.

LCI results that contribute to the following indicators: global warming (CO_2, CH_4 and N_2O), terrestrial acidification (SO_x, NO_x and ammonia) and land occupation (waste volume) are given in Figs. 1–7.



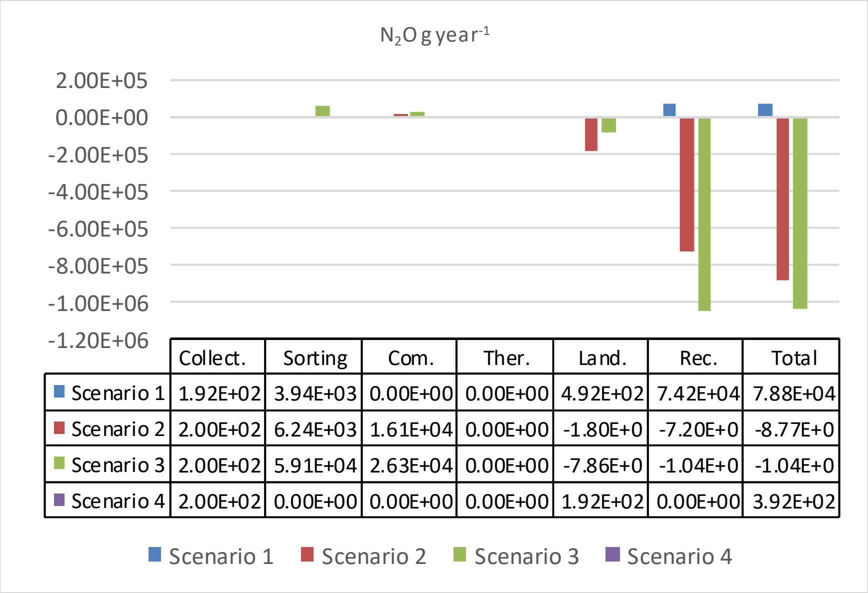
	Collect.	Sorting	Com.	Ther.	Land.	Rec.	Total
Scenario 1	7.94E+06	4.78E+05	0.00E+00	0.00E+00	2.69E+07	-5.31E+0	3.00E+07
Scenario 2	8.27E+06	7.57E+05	1.63E+06	0.00E+00	1.04E+07	-1.03E+0	1.07E+07
Scenario 3	8.27E+06	6.18E+06	2.66E+06	-3.33E+0	4.64E+06	-1.47E+0	-2.62E+0
Scenario 4	8.27E+06	0.00E+00	0.00E+00	1.04E+08	1.22E+05	0.00E+00	1.13E+08

Fig. 1. LCI results for CO_2 emission



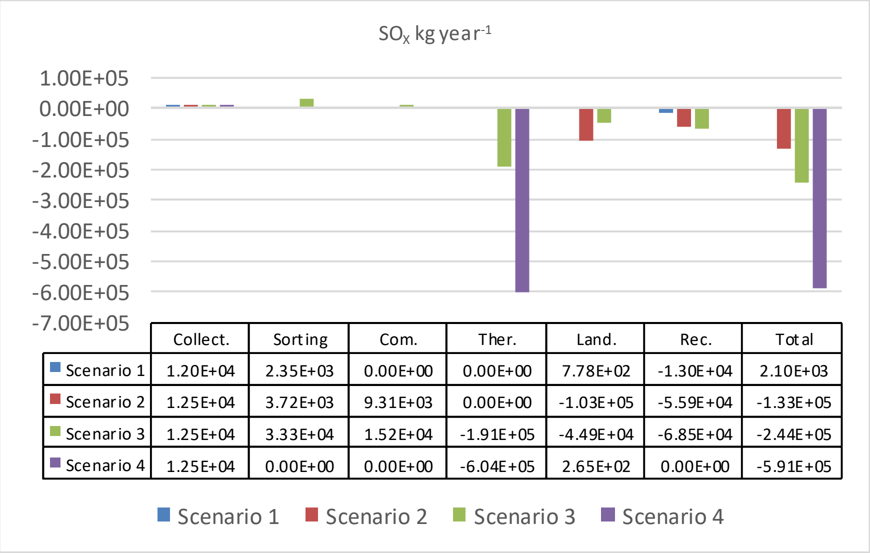
	Collect.	Sorting	Com.	Ther.	Land.	Rec.	Total
Scenario 1	9.66E+03	7.49E+02			1.18E+07	-6.76E+0	1.18E+07
Scenario 2	1.01E+04	1.19E+03	2.63E+03		5.64E+05	-1.41E+0	5.64E+05
Scenario 3	1.01E+04	1.01E+04	4.29E+03		2.46E+04	-3.26E+0	2.40E+05
Scenario 4	1.01E+04				1.57E+02		1.02E+04

Fig. 2. LCI results for CH_4 emission



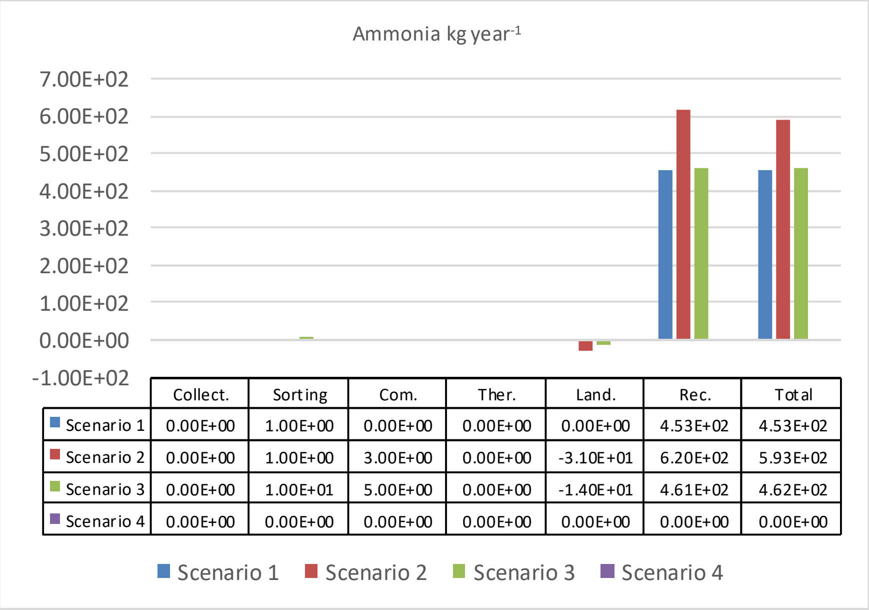
	Collect.	Sorting	Com.	Ther.	Land.	Rec.	Total
🟦 Scenario 1	1.92E+02	3.94E+03	0.00E+00	0.00E+00	4.92E+02	7.42E+04	7.88E+04
🟥 Scenario 2	2.00E+02	6.24E+03	1.61E+04	0.00E+00	-1.80E+0	-7.20E+0	-8.77E+0
🟩 Scenario 3	2.00E+02	5.91E+04	2.63E+04	0.00E+00	-7.86E+0	-1.04E+0	-1.04E+0
🟪 Scenario 4	2.00E+02	0.00E+00	0.00E+00	0.00E+00	1.92E+02	0.00E+00	3.92E+02

Fig. 3. LCI results for N_2O emission



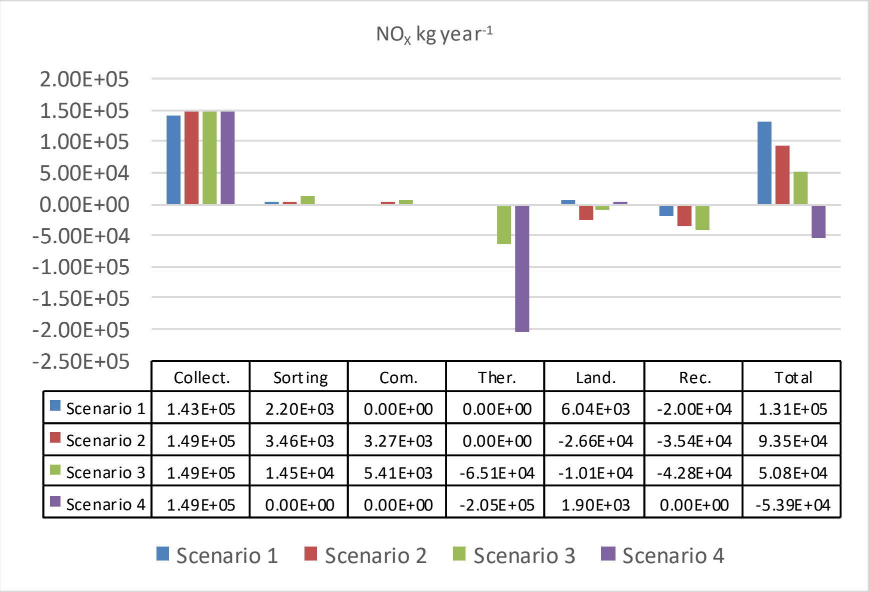
	Collect.	Sorting	Com.	Ther.	Land.	Rec.	Total
🟦 Scenario 1	1.20E+04	2.35E+03	0.00E+00	0.00E+00	7.78E+02	-1.30E+04	2.10E+03
🟥 Scenario 2	1.25E+04	3.72E+03	9.31E+03	0.00E+00	-1.03E+05	-5.59E+04	-1.33E+05
🟩 Scenario 3	1.25E+04	3.33E+04	1.52E+04	-1.91E+05	-4.49E+04	-6.85E+04	-2.44E+05
🟪 Scenario 4	1.25E+04	0.00E+00	0.00E+00	-6.04E+05	2.65E+02	0.00E+00	-5.91E+05

Fig. 4. LCI results for SO_x emission



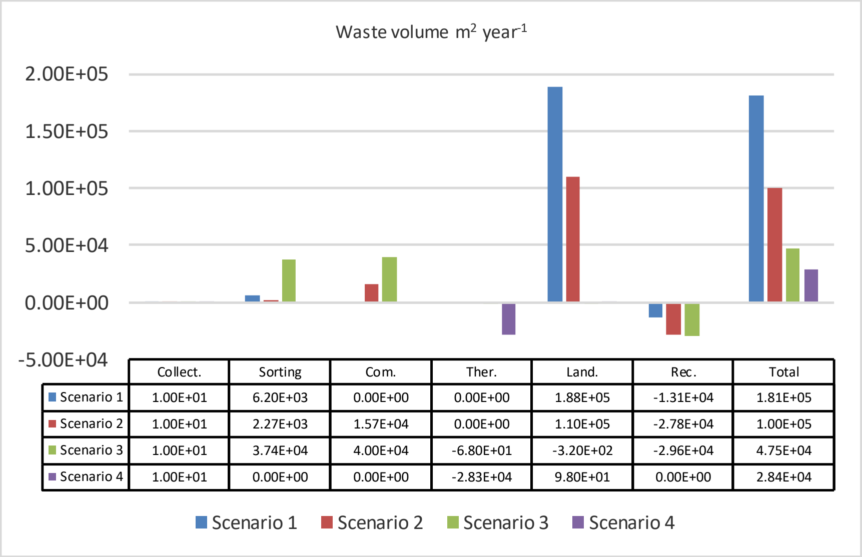
	Collect.	Sorting	Com.	Ther.	Land.	Rec.	Total
🟦 Scenario 1	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00	4.53E+02	4.53E+02
🟥 Scenario 2	0.00E+00	1.00E+00	3.00E+00	0.00E+00	-3.10E+01	6.20E+02	5.93E+02
🟩 Scenario 3	0.00E+00	1.00E+01	5.00E+00	0.00E+00	-1.40E+01	4.61E+02	4.62E+02
🟪 Scenario 4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Fig. 5. LCI results for ammonia emission



	Collect.	Sorting	Com.	Ther.	Land.	Rec.	Total
🟦 Scenario 1	1.43E+05	2.20E+03	0.00E+00	0.00E+00	6.04E+03	-2.00E+04	1.31E+05
🟥 Scenario 2	1.49E+05	3.46E+03	3.27E+03	0.00E+00	-2.66E+04	-3.54E+04	9.35E+04
🟩 Scenario 3	1.49E+05	1.45E+04	5.41E+03	-6.51E+04	-1.01E+04	-4.28E+04	5.08E+04
🟪 Scenario 4	1.49E+05	0.00E+00	0.00E+00	-2.05E+05	1.90E+03	0.00E+00	-5.39E+04

Fig. 6. LCI results for NO_x emission



	Collect.	Sorting	Com.	Ther.	Land.	Rec.	Total
🟦 Scenario 1	1.00E+01	6.20E+03	0.00E+00	0.00E+00	1.88E+05	-1.31E+04	1.81E+05
🟥 Scenario 2	1.00E+01	2.27E+03	1.57E+04	0.00E+00	1.10E+05	-2.78E+04	1.00E+05
🟩 Scenario 3	1.00E+01	3.74E+04	4.00E+04	-6.80E+01	-3.20E+02	-2.96E+04	4.75E+04
🟪 Scenario 4	1.00E+01	0.00E+00	0.00E+00	-2.83E+04	9.80E+01	0.00E+00	2.84E+04

Fig. 7. LCI results for waste volume

Using characterization factors given in the Impact 2002+, these results are converted into LCIA indicators or impact categories. The results of the indicators at the midpoint and end positions are shown in Tables 5 and 6.

Table 5

Results at the level of the impact assessment, LCIA indicators at midpoint

Midpoint category	Midpoint reference substance	S1	S2	S3	S4
Global warming	kg $CO_{2\ eq}$	3.25×10^8	2.48×10^7	-2.05×10^7	1.13×10^8
Terrestrial acidification	kg $SO_{2\ eq}$	7.22×10^5	3.80×10^5	4.19×10^4	-8.86×10^5
Land occupation	$m^2 \cdot y$	6.52×10^5	3.61×10^5	1.71×10^5	1.02×10^5

Negative values reflect the net benefits.

Table 6

Results at the level of the impact assessment, LCIA indicators at the end points

Damage category	S1	S2	S3	S4
Climate change, kg $CO_{2\ eq}$	3.25×10^8	2.48×10^7	-2.05×10^7	1.13×10^8
Ecosystem quality. Terrestrial acidification, $PDF \cdot m^2 \cdot y$	7.51×10^5	3.95×10^5	4.36×10^4	-9.23×10^5
Ecosystem quality. Land occupation, $PDF \cdot m^2 \cdot y$	7.11×10^5	3.94×10^5	1.86×10^5	1.11×10^5

Negative values reflect the net benefits.

As one might assume, the scenario 1 presents the least favorable option from an environmental standpoint. The scenarios 2–4 represent a significant improvement of the scenario 1.

By analyzing the scenarios of waste management through the use of selected indicators, it is possible to conclude that the scenario 1, which represents the current situation in the field of solid waste management, is the least acceptable option if we assume that in the existing practice the largest amount of waste is disposed of at landfill which does not possess the elements of sanitary protection. Therefore, a large amount of resources are lost and the polluting substances are uncontrollably emitted to the environment. Energy savings in this scenario are ca. 1 $GJ\cdot t^{-1}$ of waste due to recycling. The contribution to global warming is 1657 kg $CO_{2\,eq}\cdot t^{-1}$ of waste, terrestrial acidification is 3.6 kg $SO_{2\,eq}\cdot t^{-1}$ of waste and land occupation 3.3 $m^2\cdot t^{-1}$ of waste.

The scenario 2 achieves energy savings amounting ca. 4 $GJ\cdot t^{-1}$ of waste, thanks to recycling and exploitation of landfill gas. Global warming in this scenario amounts to 126 kg $CO_{2\,eq}\cdot t^{-1}$ of waste, terrestrial acidification 1.9 kg $SO_{2\,eq}\cdot t^{-1}$ of waste and land occupation 1.8 $m^2\cdot t^{-1}$ of waste.

Total energy consumption in the scenario 3 has shown the best results since it has generated savings of 5.6 $GJ\cdot t^{-1}$ of waste. The savings have also been generated when global warming is in question and amounts to 104 kg $CO_{2\,eq}\cdot t^{-1}$ of waste, whereas terrestrial acidification is 0.2 kg $SO_{2\,eq}\cdot t^{-1}$ of waste and the land occupation 0.9 $m^2\cdot t^{-1}$ of waste.

The scenario 4 generates large amounts of energy (ca. 5 $GJ\cdot t^{-1}$ of waste) but large amounts of emissions of greenhouse gases as well, so the global warming is 576 kg $CO_{2\,eq}\cdot t^{-1}$ of waste. The generation of CO_2 increases when incineration is added as the carbon content of the incinerator feedstock is converted to CO_2 during the incineration process [25]. These results show the sum of fossil and biogenic CO_2 emissions from the incineration process. Same LCA studies, tools and models divided CO_2 emission on fossil and biogenic, considering that this division has a crucial influence on the calculated amounts of climate-relevant CO_2 emissions. The climate-relevant CO_2 emissions from waste incineration are determined by the proportion of waste whose carbon compounds are assumed to be of fossil origin. The proportion of carbon of biogenic origin from waste is usually in the range of 33–50% [26]. In the case that in this study, the emission of CO_2 considered divided on emissions of fossil and biogenic origin, CO_2 emissions from the incineration process would be significantly reduced (ca. by 50%).

The indicators that affect the ecosystem quality (terrestrial acidification and land occupation) in this scenario have shown the best results. In the case of terrestrial acidification there are savings of 4.5 kg $SO_{2\,eq}\cdot t^{-1}$ of waste, while land occupation is 0.5 $m^2\cdot t^{-1}$ of waste.

In addition, the costs of waste management in the scenario 1 are, nevertheless, at the expense of environmental degradation and cannot be acceptable. Looking at the costs of waste management in the remaining waste management scenarios, costs per capita have been increasing together with the growing complexity of treatment technologies. Therefore, the costs the highest in the scenario 4, the scenario which includes incineration of unselected municipal waste. Costs per capita in the scenario 2 are 20% lower than in the scenario 4, i.e., by 13% lower than in the scenario 3, compared to the scenario 4.

Although the scenario 4 has shown as the most favorable for two indicators relating to the ecosystem quality, the scenario 3, nevertheless, has shown the lowest burdens in terms of climate change and total energy consumption which are among main objectives of the European Strategy 2020. The scenario 2 includes two processes of waste treatment, disposal and composting, that require large tracts of land. Therefore, this scenario proved to be inadequate when ecosystem quality is in question.

Impact on climate change in the 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 improvement of air emission quality as well. The quantities of CO_2 in the scenario 4 have negative effects on the results of this scenario, which speaks to the fact that waste with such morphological composition cannot be treated in the process of incineration.

If we consider the indicator per capita cost as well, the scenario 3 is a better option than the scenario 4 due to lower costs per capita.

4. CONCLUSION

This paper presents the application of combined LCI and LCIA approach for comparison and evaluation of different municipal solid waste strategies on a case study on waste management in the South Backa region. The results of the research will be very helpful to increase the life cycle inventory database of Serbia and provide useful information for policymakers in making decisions regarding to waste management strategies.

The approach does not give a definitive answer. It provides objective information on a broad scale of environmental costs and benefits. The combination of LCI and LCIA methods has shown some negative effects on environmental quality due to different ways of waste management in the test region. The conducted analysis shows how certain treatments of waste can affect differences in trends of selected indicators as well as the correlation with energy consumption and necessary costs. The results indicate that by composting of biodegradable municipal waste, by increasing the degree of separation of recyclable materials and by introducing thermal treatment of waste, certain parameters regarding waste management efficiency in the South Backa region can be improved.

There are different combinations of options presented in the scenarios of waste management, which show positive and negative implications of the analyzed indicators. In this regard, the scenario 1, which represents the current situation in the field of solid waste management in the studied region, has proved to be the least acceptable option.

Comparing the scenarios 2 and 3, and taking into account all considered indicators, including the costs of waste management as well, it can be concluded that the scenario 3 shows better performance. As it has already been mentioned, this particular scenario is specific since it assumes a plant for mechanical separation of combustible materials and their processing in order to obtain refuse-derived fuel. The produced RDF is used as an alternative fuel in a plant for energy production.

The technology of waste treatment presented in the scenario 4 (incineration of unselected municipal waste) has shown very good results for two, out of five, indicators. However, when making decisions about the choice of treatment technology that would be the most suitable for the South Backa region, it is necessary to take into account the cost of incineration plant construction, as well as operating costs, which are very high. Additionally, if the primary objective of decision-makers is to reduce emissions of gases that contribute to global warming and are consequence of bad waste management, it is certain that the combination of technologies presented in the scenario 3 is the right choice. The disadvantages of incineration technology are mainly related to the emission of harmful products in the process of burning. From the aspect of climate change, the scenario 4 is the least favorable. Also, if there is no possibility for the utilization of by-products of the combustion process, it is essential to dispose them in a proper way (ash landfill or hazardous wastes) because of the concentration of heavy metals and other harmful products.

The results of such an analysis are of great importance to those involved in the process of decision making as a support tool when selecting waste management options at both local and regional level [27]. This approach enables: evaluation and comparison of the waste management system by using a number of environmental impact indicators, identification of strengths and weaknesses of the compared waste management systems, recognition of the optimal scenario for waste management and determination of an individual waste treatment and its influence on the improvement of environmental characteristics.

Further research is needed to enable the inclusion of a greater number of parameters important for the evaluation of system performances for waste management, as well as the analysis of a larger number of the scenarios (e.g., pyrolysis) which would give decision makers better insight into the consequences of development directions of waste management system in the South Backa region in the future.

ACKNOWLEDGEMENT

The results presented in the paper are an output from the research funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia Project, Project number 176019.

REFERENCES

[1] OGUNDIPE F.O., JIMOH O.D., *Life cycle assessment of municipal solid waste management in Minna, Niger State, Nigeria*, Int. J. Environ. Res., 2015, 9 (4), 1305.

[2] European Commission, *Directive 1999/31/EC of the European Parliament and of the Council of 26 April 1999 on the landfill of waste*, Brussels 1999, L182/1.

[3] European Commission, *Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste*, Brussels 2000, L 332/91.

[4] European Commission, *Directive 2008/98/EC of the European Parliament and of Council of 19 November 2008 on waste and repealing certain directives*, Brussels 2008, L 312/3.

[5] European Commission, *Directive 2004/12/EC of the European Parliament and of the Council of 11 February 2004 amending Directive 94/62/EC on packaging and packaging waste*, Brussels 2004, L 7/26.

[6] STANISAVLJEVIC N., UBAVIN D., BATINIC B., FELLNE J., VUJIC G., *Methane emissions from landfills in Serbia and potential mitigation strategies. A case study*, Waste Manage. Res., 2012, 30 (10), 1095.

[7] *Waste management strategy for period 2010–2019*, Official Gazette of the RS, No. 29/10, Belgrade, Serbia, 2010.

[8] *Law on waste management*, Official Gazette of the RS, No. 36/09 and 88/10, Belgrade, Serbia, 2010.

[9] *Law on managing packaging and packaging waste*, Official Gazette of the RS, No. 36/09, Belgrade, 2009.

[10] *Regulation on developing the plan for reducing packaging waste for the period 2010 to 2014*, Official Gazette of the RS, No. 88/09, Belgrade, Serbia, 2009.

[11] VILLENEUE J., MICHEL P., FOURNET D., LAFON C., MENARD Y., WAVRER P., GUYONNET D., *Process-based analysis of waste management systems. A case study*, Waste Manage., 2009, 29 (1), 2.

[12] KIRKEBY J., *Modelling of life cycle assessment of solid waste management systems and technologies*, Technical University of Denmark, Kgs. Lyngby 2005.

[13] STANISAVLJEVIC N., BRUNNER P.H., *Combination of material flow analysis and substance flow analysis. A powerful approach for decision support in waste management*, Waste Manage. Res., 2014, 32 (8), 733.

[14] LAURENT A., BAKAS I., CLAVREUL J., BERNSTAD A., NIERO M., GENTIL E., HAUSCHILD M.Z., CHRISTENSEN T.H., *Review of LCA studies of solid waste management systems. Part I. Lessons learned and perspectives*, Waste Manage., 2014, 34 (3), 573.

[15] BUTTOL P., MASONI P., BONOLI A., GOLDONI S., BELLADONNA V., CAVAZZUTI C., *LCA of integrated MSW management systems. Case study of the Bologna District*, Waste Manage., 2007, 27, 1059.

[16] DAMGAARD A., CHRISTENSEN T.H., *Implementation of life cycle assessment models in solid waste management*, Technical University of Denmark, Kgs. Lyngby 2010.

[17] MANFREDNI S., GORALCZYK M., *Life cycle indicators for monitoring the environmental performance of European waste management*, Res., Cons. Rec., 2013, 81, 8.

[18] *Regional Waste Management Plan for City of Novi Sad, and municipalities of, Bačka Palanka, Bački Petrovac, Beočin, Žabalj, Srbobran, Temerin and Vrbas*, Faculty of Technical Science, Novi Sad, Serbia, 2011.

[19] EMERY A., DAVIES A., GRIFFITHS A., WILLIAMS K., *Environmental and economic modelling. A case study of municipal solid waste management scenarios in Wales*, Res., Cons. Rec., 2007, 49 (3), 244.

[20] MCDOUGALL F.R., WHITE P.R., FRANKE M., HINDLE P., *Integrated solid waste management. A life cycle inventory*, Blackwell Publishing, Oxford, United Kingdom, 2008.

[21] HUMBERT S., SCHRYVER A.D., BENGOA X., MARGNI M., JOLLIET O., *Impact 2002+. User Guide, Draft for version Q2.21*, Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland, 2012, p. 45.

[22] PARKES O., LETTIERI P., DAVID I., BOGLE L., *Life cycle assessment of integrated waste management systems for alternative legacy scenarios of the London Olympic Park*, Waste Manage., 2015, 40, 157.

[23] PROKIC D., STEPANOV J., CURCIC LJ., CARAPINA H.S, MARJANOVIC P., *Examination of the possibility of soil remediation from waste disposal sites contaminated with arsenic (As)*, Rec. Sust. Dev., 2012, 5 (1), 10.

[24] STYPKA T., FLAGA A., *Application of the integrated waste management model (IWM-1) into the decision process* [Electronic version], Institute of Heat Engineering and Air Protection, Cracow University of Technology, Cracow 2005.

[25] BOESCH M.E., VADENBO C., SANER D., HUTER C., HELLWEG S., *An LCA model for waste incineration enhanced with new technologies for metal recovery and application to the case of Switzerland*, Waste Manage., 2014, 34, 378.

[26] JOHNKE B., *Emissions from waste icineration, IPPC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, IPCC National Greenhouse Gas Inventories Programme, Institute for Global Environmental Strategies, Kamiyamaguchi, Hayama, Kanagawa, Japan, 2001.

[27] CARAPINA H.S., JOVOVIC A., STEPANOV J., *Life Cycle Assessment as a tool in strategic planning of waste management*, Educons University, Sremska Kamenica, 2011.