Recycling and Sustainable Development 12 (2019) 43-51

www.rsd.tfbor.bg.ac.rs

Recycling and Sustainable Development

RSD

Online ISSN 2560-3132
Print ISSN 1820-7480

Model for evaluating municipal waste management system applying the LCA - Part I: Review of LCA Software

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ARTICLE INFO

Received 25 April 2019
Accepted 09 September 2019

Review article

Keywords:
Life cycle assessment (LCA)
Municipal solid waste
Life cycle inventory model (IWM-2)
Life cycle impact assessment method (Impact2002+)

ABSTRACT

Focusing on the concept according to which waste is considered as a resource, sustainable waste management objectives implying environmentally effective, economically affordable, and socially acceptable management, have been developed. To achieve a sustainable system, the concept of LCT (life cycle thinking) is an appropriate approach. LCT approach can help to reduce environmental impacts. There are several methodologies for assessing and measuring these impacts, and the LCA (Life Cicle Assessment) is one of the analyses based on this approach. LCA is regulated in accordance with ISO 14040 and implies a process that examines environmental aspects and potential environmental impacts on the life cycle of the product or service. The aim of this study is to develop a model for the evaluation of the municipal waste management system using LCA methods to ensure a sustainable system. With this model, it is possible to assess the efficacy and the cost of the treatment of municipal waste and to determine the influence of both the total system and the individual waste treatment on the environment. In the first part of this study, LCA as a useful tool for the planning or management of solid municipal waste is presented in details, including the phases of the LCA study. The second part of this study deals with several models for assessing environmental consequences of solid waste management systems with the life cycle thinking approach. In the last part of the study, the model for the evaluation of the municipal waste management system using the life cycle assessment method is developed. This model can estimate the environmental performance and economic costs of various options for waste management.

1. Introduction

In the EU member states, waste management has been regulated for decades on the basis of the waste management hierarchy principle. At the top of the hierarchy is the reduction of waste at source and waste minimization. Next in the hierarchy come a series of options: reuse, recycling, composting, waste to energy, incineration without energy recovery and disposal.

However, the hierarchy of waste management has several limitations. Using this hierarchy to determine which options are preferable does not necessarily result in the lowest environmental burdens, nor in an economically sustainable system (McDougall et al., 2008). Efficient or sustainable waste management is conditioned by numerous factors such as the amount and

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doi: 10.5937/ror1901043Č

the composition of waste, socio-economic, technological, spatial and other aspects. Therefore, there are generally no best or worst options, but only the appropriate options for the different waste fractions.

The LCA proved to be a useful tool for supporting the planning or management of solid municipal waste. It can be used for the identification of environmental hotspots and opportunities for optimising environmental performance in a product's life-cycle, for informing the decisionmakers, for the selection of relevant environmental performance indicators, as well as for environmental marketing (Merrild, 2009).

Applying the LCA method may change the ranking of the waste treatment options in the hierarchy because the treatment of waste and waste treatment optimal rate are determined by the composition of the waste.

Also, the need for the LCA analysis of the waste management system stems from the fact that its application can address the various effects of pollutant emissions that certain waste treatment technologies produce, and reduce the consumption of natural resources.

The application of the LCA method to the waste management system contributes to finding an optimal and sustainable municipal waste management strategy, providing a comparative analysis of different strategies and different waste treatment technologies.

Within the 14040 series ISO is trying to establish a flexible framework under which LCAs can be carried out in a technically credible and practical manner. The application of the LCA method is flexible, it can be implemented based on the specific application and requirements of the user. This method has become a useful tool in the decision making process regarding the design of the product at the end of the nineties, and the interest for its use in the waste management is on the rise the past 15 years.

The continuously increasing amount of solid waste in the world requires the development of a solid waste management strategy that ensures environmental sustainability. By quantifying environmental impacts of systems, life cycle assessment (LCA) is a tool, which can contribute to answering that call (Laurent et al., 2014). The basic difference between LCA products and LCA waste is the difference in usage or potential users and the functional unit. The different life-cycle stages of a product system and a waste management system are shown in Figure 1. In the life cycle of waste we take into account "from the cradle to the grave" approach; the cycle starts from the moment you put items in bins until the moment they give useful substances, energy or are converted into emissions to water and air, or when disposed of in a landfill as an inert material. Product life cycle data can be combined with other environmental assessment information and instruments to improve the eco-characteristics of products or services. Also, it is possible to keep the product constant, and to change the treatment of waste and thus to assess the environmental impact. Assuming that the details on the composition of waste are known, for municipal solid waste it can be determined how different waste management options affect the characteristics of the environment.

There are four phases in an LCA study (ISO 14044, 2006):

a) the goal and scope definition,
b) the inventory analysis (LCI phase),
c) the impact assessment (LCIA phase) and
d) the interpretation phase.

In the goal and scope phase, the most important (often subjective) choices are described, such as the reason for executing the LCA, which processes will be included, which environmental concerns will be included, as well as the description of the system boundaries and the level of details.

The life cycle inventory provides information about all environmental inputs and outputs from all parts of the product system. It involves the collection of the data necessary to meet the goals of the defined study.

In the life cycle impact assessment phase, impacts on the environment are classified and evaluated. The assessment takes inventory data and converts it to indicators for each impact category.

Life cycle interpretation is the last step of the LCA procedure which leads to the conclusions, recommendations, and decision-making in accordance with the goal and scope definition.

a) Product life-cycle

Raw material acquisition	Production	Use	End-of-life treatment	Recycling	Final disposl

b) Waste management life-cycle

Collection	Treatment	Final disposal

Figure 1. Product life-cycle stages (Figure a.) and waste life-cycle stages (Figure b.) (Merrild, 2009)

2. Previous LCA models for the evaluation of the waste management system

In the last 15 years several models have been developed for the special purpose of assessing environmental consequences of solid waste management systems taking life cycle thinking approach (Kirkeby, 2005) (Table 1).

The models allow decision-makers and managers of waste to use LCA analysis for their specific waste management system and enable them to learn how changes in the system affect the environment through scenario analysis.

UMBERTO is software (developed and distributed by the IFU-Institute in Hamburg) for modelling costs, process optimization, environmental management, and life cycle assessment (Hansen et al., 2006). This module has shown to have very little sensitivity to the type of waste input that is being chosen in the model (Kirkeby, 2005).

ORWARE is a model originally developed for the environmental assessment of biodegradable liquid and solid waste. However, the model can also handle the treatment of mixed waste, and therefore enable comparisons between different waste systems including treatment of mixed and source-sorted waste. The model is developed by a co-operation of the Swedish Institute of Environmental and Agricultural Engineering, the Swedish University of Agricultural Sciences, the Royal Institute of Technology, and the Swedish Environmental Research Institute and was financed by the Waste Research Council and the Swedish Environmental Protection Agency (Hansen et al., 2006).

The Decision Support Tool (DST) is a computer-based tool developed by the Research Triangle Institute (RTI), North Carolina State University and the United States Environmental Protection Agency (Office of Research and Development) to evaluate integrated municipal solid waste strategies in the United States with respect to environmental and economic impacts (Hansen et al., 2006). The ORWARE model and the DST model offer the opportunity of changing all implemented waste management processes on every level, but it is very difficult for a user to implement new processes, although it is feasible (Winkler and Bilitewski, 2007).

EPIC/CSR is a Canadian model for assessing the environmental and economic impacts of the waste management system. This model provides the ability to model the most important waste management processes, which can be altered to some extent, but do not allow major changes.

EASETECH is a model for environmental assessment of waste systems developed by the Technical University of Denmark. The model considers environmental impacts from waste generation, collection, treatment, and disposal (Hansen et al., 2006). This model allows calculation of the consequences of the changed composition of waste.

The model is able to support several different life cycle impact assessment methodologies as emissions can be given environmental impact factors for any potential environmental impacts and for any methodology (Kirkeby, 2005).

IWM-2- the goal of this model is to be able to, as accurately as possible, predict the environmental burdens and economic costs of a specific waste management system (McDougall et al., 2008).

This model is an LCI model, no impact assessment is performed. This model was used in the development of the LCI module in this paper.

Table 1
Characteristics of the LCA models

Model	Developed by	Elements of LCA covered	Number of substances modelled
UMBERTO	IFU - Institute in Hamburg	LCI/LCIA	Not limited
ORWARE (ORganic WAste REsearch)	University Sweden	LCI/LCIA	Air: 69 water: 68
DST (Decision Support Toll)	University/Research Institute USA	LCI/LCIA	Air: 23 water: 17
EPIC/CSR (Environment and Plastic Industry Council/Corporation Supporting Recycling)	Industry Association Canada	LCI	Air: 12 water: 5
EASETECH (Environmental Assessment for Environmental TECHnologies)	Univezitet (Danska)	LCI/LCIA	Air: 45 water: 45
IWM-2 (Integrated Waste Management)	Industry UK	LCI	Air: 24 water: 27

3. LCA model - IWM-2/Impact2002+

A model for the evaluation of the municipal waste management system using the life cycle assessment method is conceived through the modules that follow the basic phases of the LCA method. A schematic representation of the model conception is shown in Figure 2.

For the purpose of developing models for assessing the life cycle of municipal waste were used:

- guidelines for LCA in a series of ISO 14040 (ISO 14040, 2008),
- LCI model, IWM-2, CPM LCA data base (McDougall et al., 2008),
- LCIA methodology Impact2002+ (Humbert et al., 2012),
- specfic data about the waste management system under study and
- data from publications in the field of LCA and municipal waste management.

3.1. Module 1

The goal of implementing LCA analysis within the model, the impact assessment of the life cycle of municipal solid waste on the environment. The scope of the study includes the system of municipal waste management in a certain geographical area and the impact of this system on energy consumption, global warming, land degradation (acidification and land occupation) and costs.

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 (Mahmoudakhani et al., 2014). Municipal and industrial wastes contribute most to soil contamination (38 %) in EU (Panagos et al., 2013).

The reasons for the analysis are the prediction and comparative analysis of the environmental burden of the solid waste management system, in order to provide a response to decision makers when choosing the optimal solution for the waste management system.

Product system is subdivided into a set of unit processes (waste collection, sorting, biological treatment, thermal treatment, and landfilling). The functional unit is defined as the amount of municipal waste specified geographical area in a given time period. System boundaries are set from the point where the product loses usable value and becomes waste to the point where waste re-receives usable value or emits from the system as emissions and residual waste.

The results of LCA analysis have been increasingly used as indicators in recent times. Indicators can be useful when communicating scientific results to the non-scientific community as these can describe complex results in a more comprehensible and condensed format, decreasing the number of parameters used in the presentation of the results.

The main purpose of using indicators is to enhance communication and indicators should thus be relevant and understandable for decision-makers (Merrild, 2009).

Indicators are the most effective form for monitoring changes and achieving sectoral policies and strategies.

They contribute to the decision - making process through: better understanding of complex issues, identification of priorities, simulation of required activities, periodic review, and correction (Stevanović Čarapina, 2011).

They can be used for different purposes: for comparing environmental characteristics, identifying potential improvements, and hence it is important that the indicators are aligned with the purpose, quantitatively expressed, and that the values have the same denominator (eg, tons of municipal waste).

When presenting the LCA results with the help of indicators and the selection of a set of relevant indicators, the level of influence in which the indicator is located must be clearly stated.

In the life cycle assessment context, the impact assessment methodologies can be grouped into two groups based on the type of indicator they use; those presenting the results with midpoint indicators and those presenting the results with endpoint indicators.

A midpoint indicator can be defined as a parameter located on the impact pathway at an intermediate position between the life-cycle inventory results and the ultimate environmental damage (Jolliet et al., 2004).

Endpoint indicators express the damage at the end of the cause - effect chain, e.g. damage to the natural environment (Merrild, 2009).

Also, there are results that describe the efficiency of the system (LCI results) and results that describe the impact of the system (LCIA results).

Some authors divided indicators into indicators of impact and performance indicators. Impact indicators are indicators commonly used in the presentation of life cycle assessment results and are related to parameters in the inventory. The performance indicators are related to the more traditional criteria for successful waste management (Villeneuve et al., 2009).

LCA waste management indicators suggest that more detailed and quality - assured waste statistics are needed, especially covering the many different treatment operations and options (Manfredi and Goralczyk, 2013).

Indicators supporting modern policies have to take the life cycle view of the supply chain (production, use, and end-of-life), accounting for all relevant environmental impacts and resources consumed along it (EC JRC, 2012). Table 2 presents the indicators included in a range of studies.

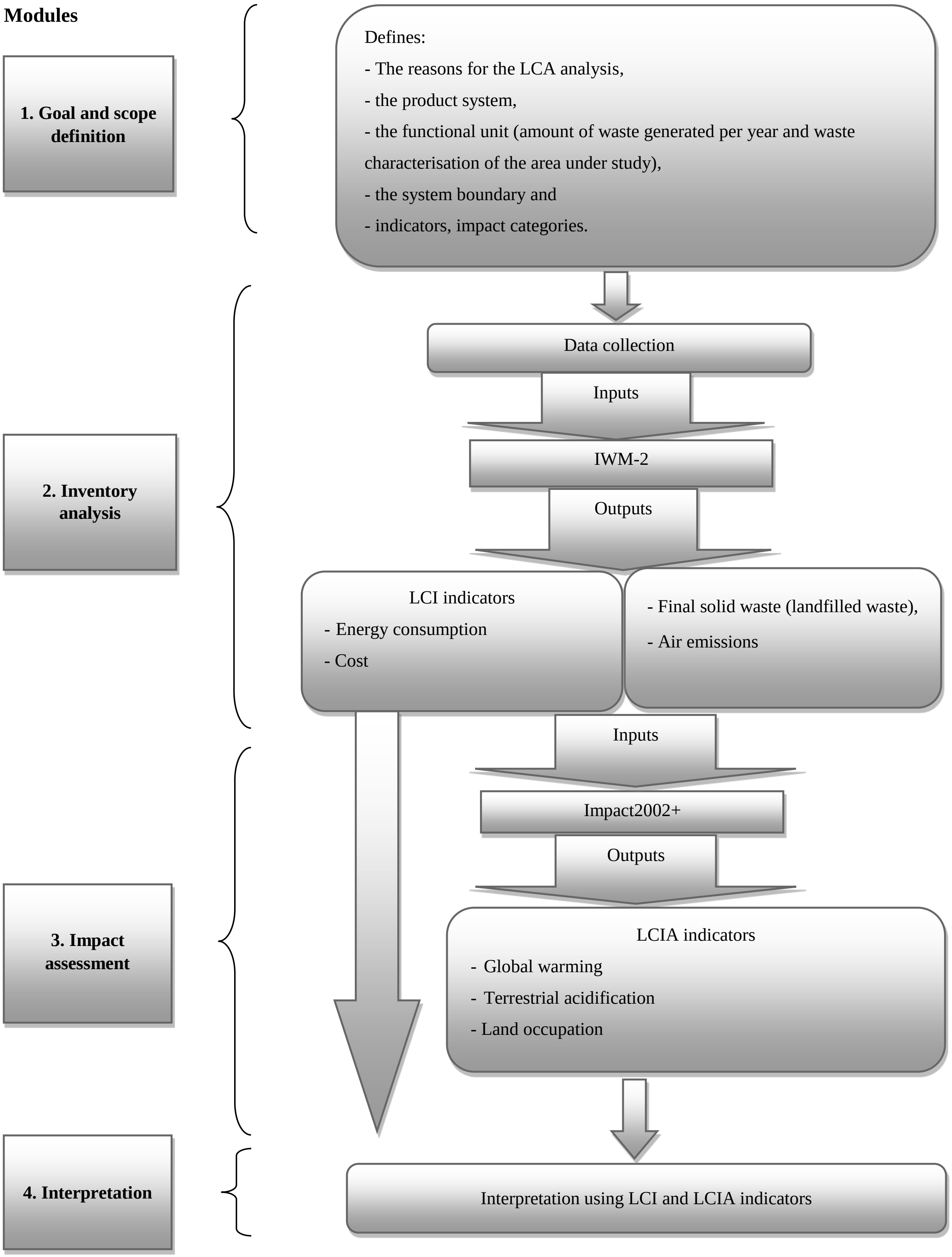

Figure 2. Modular structures of the model for evaluation of municipal waste management system using the method of life cycle assessment

Table 2
LCA indicators included in a range of studies performed on integrated waste management systems

The author	Indicator
Klang et al., 2008	Greenhouse effect, acidification, eutrophication
Mohareb et al., 2008	Greenhouse gas emissions, energy consumption
Chester et al., 2008	Energy consumption, greenhouse gas emissions
Villeneuve et al., 2009	Energy balance, greenhouse gas emissions, air acidification, non-hazardous waste landfilled
Blengini and Garbarino, 2010	Land use (land occupation and land transformation)
Mahmoudkhani et al., 2014	Greenhouse gas emissions
Zhang and Huang, 2014	Greenhouse gas emissions
Kulczycka et al., 2015	Climate change, acidification / eutrophication, ecotoxicity, fossil fuel consumption

From Table 2 it can be noted that the "land occupation" indicator is represented in a very small number of publications, in contrast to the "global warming", "acidification" and "energy consumption" indicators used in almost all studies. "Land occupation" is directly related to waste disposal conditions and this indicator can be extremely relevant for the waste management system.

3.2. Module 2

The LCI phase involves collecting data about the type and amount of material, energy, and economic inputs for all the defined processes of the life cycle of waste. This module has been developed based on models of the IWM-2 with certain modifications and adjustment phase of the life cycle of waste inventory of specific composition, and the analyzed geographic territories.

3.3. Module 3

The LCIA methodology involves the implementation of a combined midpoint/damage approach, which is an approach linking all types of life cycle inventory results via several midpoint categories to several damage categorie. Thus LCIA methodologies aim to connect, as far as possible and desired, each LCI result (elementary flow or other intervention) to the corresponding environmental impacts by using CFs (characterization factors) (Humbert et al., 2012). The most frequently used LCIA methods are shown in Table 3.

Table 3
Overview LCIA methods

Name	The author	Short description
CML	Guinée et al., 2002	CML is an impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms or commonly accepted groupings.
EDIP 1997-2003	Wenzel et al.,1997; Hauschild and Potting, 2005	EDIP 2003 is the update of the EDIP 1997 LCIA method methodology and covers a larger part of the environmental mechanism and lies closer to a damage - oriented approach.
Eco-Indicator 99	Goedkoop and Spriensma, 2001	Eco-Indicator 99 includes characterisation factors for the damage oriented approach.
ReCiPe	CML 2000 and Eco-indicator 99	ReCiPe can be seen as a fusion of the two methodologies, taking the midpoint indicators from CML and the endpoint indicators from Eco-Indicator.
Impact 2002+	Jolliet et al., 2004	The Life Cycle Impact Assessment methodology IMPACT 2002+ suggests a feasible implementation of a combined midpoint/damage approach. These combinations will link all types of Life Cycle Inventory (LCI) results, the elementary flows and other interventions, throughout the 14 midpoint categories summed up to four damage categories.

Methods that combine impact categories on midpoint and endpoints, such as Impact 2002+ and ReCiPe, are gaining increasing importance and application in evaluation analyses. In this study, the Impact 2002+ method was used, but there is a possibility to apply other LCIA methods.

The Impact2002+ method was developed by a team of Dr. Olivier Jolliet, a professor at the University of Michigan in the United States, and earlier at the Polytechnic University of Lausanne, Switzerland.

The IMPACT 2002+ methodology gives midpoint characterization factors, damage factors, normalized midpoint characterization factors, and normalized damage factors for about 1,500 different life cycle inventory results (Humbert et al., 2012).

At the damage level the impact from global warming is presented in a separate damage category (Climate Change) that is expressed in kg $CO_{2\text{-eq}}$ into air/kg, identical to the midpoint category.

The Intergovernmental Panel on Climate Change - IPCC defined a model based on the calculation of the global warming potential through equivalent carbon dioxide. The midpoint CFs for global warming are expressed in kg $CO_{2\text{-eq}}$ into air / kg and taken from the IPCC list (CO_2, CH_4 and N_2O).

The impact of the waste management system on the terrestrial acidification is reflected through the emission of sulfur oxides, nitrogen oxides, and ammonia.

Terrestrial acidification is an indicator of the impact on the midpoint level and is expressed in kg of $SO_{2\text{-eq}}$, and it is related to the endpoint indicator ecosystem quality expressed in $PDF \cdot m^2 \cdot y$ ("Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of year").

The impact category for land occupation cannot be calculated directly from the inventory. Methodology Impact2002+ requires the value expressed in square meter·year ($m^2 \cdot y$) 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 meters assumed) and multiplied by an average occupation time (70 years assumed; 20 for waste disposal and 50 for monitoring) (Stypka et al., 2005).

Land occupation is an indicator of the impact of the midpoint level and is expressed in m^2·year, and belongs in the damage category *ecosystem quality* that is expressed in the $PDF \cdot m^2 \cdot y$.

3.4. Module 4

The interpretation of the results is the linking of the LCI and LCIA results with the goal and scope of the analysis in order to provide conclusions and recommendations, i.e. interpereting the results through energy consumption, costs, global warming, terrestrial acidification, and land occupation.

4. Conclusion

This model gives results on two levels: 1) at the level of the inventory results - LCI indicators and 2) at the level of results regarding the assessment of the impact on life cycle - LCIA indicators. The model can 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, and also in the form of useful products, such as energy. The model gives the possibility of linking the results with any LCIA methodologies. Model verification was carried out in the part II of this study.

Acknowledgements

The data presented in this document are the results obtained in the PhD thesis by author Jasna Stepanov.

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Model za evaluaciju sistema upravljanja komunalnim otpadom, primena LCA – Deo I: Pregled LCA modela

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INFORMACIJE O RADU

Primljen 25 april 2019
Prihvaćen 09 septembar 2019

Pregledni rad

Ključne reči:
Ocenjivanje životnog ciklusa (LCA)
Čvrst komunalni otpad
Model inventara životnog ciklusa (IWM-2)
Metoda ocenjivanja uticaja životnog ciklusa (Impact2002+)

IZVOD

Održivi ciljevi upravljanja otpadom, zasnovani na konceptu da je otpad resurs, podrazumevaju ekonomski, društveno i po životnu sredinu prihvatljivo upravljanje istim. Da bi se postigao održiv sistem upravljanja otpadom, primenjuje se pristup zasnovan na životnom ciklusu. Primena ovog pristupa može pomoći da se smanji uticaj na životnu sredinu. Postoji nekoliko metodologija za procenu i merenje ovih uticaja i ocenjivanje životnog ciklusa (LCA) je jedan od njih. Regulisana je standardom ISO 14040 i podrazumeva proces koji ocenjuje ekološke aspekte i potencijalne uticaje na životnu sredinu tokom celokupnog životnog ciklusa proizvoda ili usluge. Cilj ove studije je da razvije model za evaluaciju sistema upravljanja otpadom, zasnovan na LCA. Primenom ovog modela moguće je proceniti efikasnost i troškove tretmana komunalnog otpada, kao i uticaj ukupnog sistema upravljanja otpadom i individualnih tretmana na životnu sredinu. U prvom delu studije, detaljno je predstavljena LCA, kao alat za planiranje i upravljanje čvrstim komunalnim otpadom, uključujući i faze LCA studije. Drugi deo rada je fokusiran na prikaz različitih modela za procenu posledica sistema upravljanja otpadom na životnu sredinu, zasnovanih na životnom ciklusu. U poslednjem delu studije, razvijen je model za evaluaciju sistema upravljanja komunalnim otpadom, zasnovan na oceni životnog ciklusa. Ovaj model procenjuje uticaj na životnu sredinu, kao i troškove različitih opcija upravljanja otpadom.