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Challenges and Prospects of Small and Medium Ecopreneurs (SMEcos) in Contemporary Nigerian Circular Economy

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A B S T R A C T

Small and Medium Ecopreneurs (SMEcos) are essential actors of the circular economy system and sustainable development agenda. This is fundamentally true since SMEcos are businesses and individuals who engage in socio-economic activity that is built on the principle of a circular system (reduce, reuse and recycle) which significantly promote sustainable utilization of environmental resources and mitigation of developmental challenges. For this reason, this paper examines the challenges and prospects of small and medium ecopreneurs in Nigeria's Circular Economy. The paper explains the concept of sustainable development, the circular economy as well as ecopreneurship. It also examines the roles of small and medium ecopreneurship (SMEco) in fostering a circular economy. The paper adopts the sustainability theory as the theoretical framework for the study. Extensive research was conducted using current and relevant academic publications and reports. The research design was descriptive with the use of qualitative data gathered through in-depth interviews (IDIs). A total of 15 purposively selected in-depth interviewees were engaged in the study. Responses from the interviewees were analysed using qualitative content analysis or direct quotes. The study found that small and medium ecopreneurship (SMEco) have huge prospects for the development of the circular economy in Nigeria. However, lack of adequate funding, government support, technical skills, modern facilities, as well as the market for eco-products serve as barriers to SMEcos in fostering Nigeria's circular economy. Based on these findings, the study recommends that government and non-governmental organizations should collaborate for the purpose of advancing Nigeria's circular economy.

1. Introduction

The sustainable development paradigm is fast gaining acceptance by governments, non-governmental organizations, academics, and entrepreneurs in today's global world. Its acceptance, as argued by scholars, had opened a window of business opportunities, ideas, and innovations for socio-economic advancement across the world (Morelli, 2011; Stoddart, 2011; Solaja, 2017). This fascinating report is connected to the fact that sustainable development envelopes series of actions, ideas, and policies that are aimed at creating new ways in which environmental resources and human potentials can be utilized in achieving desirable socio-economic growth. Desirable socio-economic growth, to a large extent, can be achieved through the adoption and implementation of the sustainable development paradigm - that aims to lower the rate at which

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socio-economic activities contribute to environmental degradation and resource depletion in contemporary societies (Akanle, 2014; Solaja et al., 2015) and the insurance that the future generations will have the needed resources and opportunities for attaining desirable development (Brundtland, 1987; Robert et al., 2005). One part of this process is the involvement of individuals or groups of people (ecopreneurs) who engage in business activities that revolve around the 3Rs (reduce, reuse and recycle) or a Circular Economy.

A circular economy is one of the growing economic systems in today's sustainable development era. Circular economy involves the application of sustainable techniques in production, distribution, and consumption of goods and services (Ellen MacArthur Foundation, 2013; Ellen MacArthur Foundation, 2013a). Circular economy practically depicts a momentous change from the linear economic system to a cyclical economic system that covers a wide range of eco-friendly business initiatives that guarantee sustainable utilization of resources in improving socio-economic and environmental conditions (Zhu, 1995; Preston, 2012; Allwood, 2014). Thus, the circular economy is a novel economic ideal whereby materials and energy from unwanted products are re-introduced into the economic system (Ellen MacArthur Foundation, 2013; Lehmann et al., 2014). It includes the adoption of eco-design, renewable energy, refurbishment, remanufacture, product sharing, waste prevention and waste recycling initiatives (Banaitė, 2016). However, an extensive review of the literature revealed that very little or no empirical research has been done to document the challenges and prospects of small and medium ecopreneurs (SMEcos) in advancing circular economy in Nigeria. This is the gap that this study aims to fill. The study is imperative because small and medium scale ecopreneurs play critical roles in the function and nurturing of a circular economy. It is based on this research gap that this paper set out to examine the challenges and prospects of small and medium ecopreneurs in Nigeria's circular economy.

The paper explains the concept of sustainable development, the circular economy as well as ecopreneurship. It also examines the role of small and medium ecopreneurship (SMEco) in fostering a circular economy in Nigeria.

2. Clarification of concepts

A brief description or meaning of some terms that are used in the study is necessary at this point for a proper understanding of the subject matter.

2.1. Concept of Sustainable Development

The term "sustainable development" has been explained by diverse viewpoints.

Historically, the concept materialized from the theoretical postulations of modern economists like Malthus and Ricardo who had predicted resource limitation as for the major impediment to future economic growth. This inspired the report given at the World Conference on Environment and Development (WCED) known as Brundtland Commission, on the concept "Sustainable Development" which has gained international recognition (Alao, 1995; Solaja et al., 2015). Sustainable development is a concept, goal, and movement towards building the capacity of the current generation to meet its needs and develop without jeopardizing the opportunity of the future generations to meet theirs and develop further (Brundtland 1987, Stoddart, 2011; Akanle, 2014; Solaja et al., 2015). In other words, sustainable development is a kind of developmental approach that promotes intergenerational equity, accessibility, compatibility and quality control of the environment (Solaja et al., 2015).

2.2. Concept of Circular Economy

Circular Economy was first introduced in 1976 in a report submitted to the European Commission (Banaitė, 2016) and it has gain popularity and relevance among researchers in today's sustainable development epoch. Its relevance lays in the global desire to attain sustainable development by 2030 (Ellen MacArthur Foundation, 2013; Banaitė, 2016). According to current literature, circular economy can be portrayed as an industrial economy that depends largely on the "invigorating capacity of natural resources" (Bastein et al., 2013) and intends to reduce - if not remove - waste, develop renewable sources of energy and end the use of harmful substances in production activities (Ellen MacArthur Foundation, 2013a).

The circular economy encapsulates different forms of eco-friendly ideas as well as the careful deployment of two different types of materials within a closed-loop economy. The first type of materials can be referred to as the biological materials which can return to the biosphere as feedstock (biological nutrients, e.g. forest products) and the other type is called the technical materials which cannot biodegrade and enter the biosphere (technological nutrients, e.g. plastics and metals) (Ellen MacArthur Foundation, 2013a; Vanner et al., 2014;). Hence, circular economy extend beyond the 'end of pipe' approaches of the linear economy (Ellen MacArthur Foundation, 2013a) and pursues transformational changes across the coverage of the value chain in order to preserve both biological and technological types of materials in the 'circular economy loop' and preserve their value for as long as possible (Vanner et al., 2014; World Economic Forum, 2014). In essence, the circular economy can be defined as an economic system that involves a cyclical process of "resources-design-production-distribution, consumption, collection and recycling" which make the whole economic system to reduce or eliminate waste and guarantees improvement of socio-economic and environmental conditions. This information is diagrammatically represented below.

Furthermore, it is essential to note that the main goal of a circular economy is to protect the environment against any form of degradation and to improve the socio-economic conditions of a particular society. This goal can be deduced from its 3R principles (Reduce, Reuse and Recycle) that serves as a modus operandi for the running of socio-economic activities in a circular economy. Reduce principle necessitates that fewer raw materials and energy inputs should be used in production or consumption purposes. Re-use principle maintains that products and packaging should be repeatedly used to avoid the proliferation of one-time items. Recycling principles (Recycle) demands that productions should become available resources rather than useless waste after the completion of its function. Another important fact about the circular economy is the benefits or advantages it offers. These benefits can be categorized into three parts. First is the economic benefit which includes monetary (profitability) and non-monetary (competitiveness) gains (Ellen MacArthur Foundation, 2013; Banaitė, 2016). Second is the social benefit which entails resource regeneration, responsible consumption, and availability of scarce resources for social prosperity (Banaitė, 2016). The third benefit of the circular economy is the environmental impact which comprises the reduction of environmental pollution and degradation through activities such as reuse, remanufacturing and/or recycling (Lieder and Rashid, 2016; Banaitė, 2016).

2.3. Circular Economy in Nigeria: A cursory examination

To trace the origin of circular economy in Nigeria is highly complex because some of the activities that revolve around 3R (reduce, reuse and recycle) have been in existence in Nigeria long before the popularity of circular economy as a pro-environmental strategy. Though, activities like reduction of resource consumption, reusing of products and recycling of waste was not too common in Nigeria prior to the implementation of structural adjustment programmes (SAPs) in 1986. It was the advent of SAPs that encouraged people's engagement in informal economic activities as an alternative source of employment and income generation in Nigeria. Also, structural adjustment programmes brought a significant change in the national economy which motivated individuals and business organizations to move toward a new economic paradigm which encouraged the re-introduction of waste materials and energy into the economic system (Ellen MacArthur Foundation, 2013; Lehmann et al., 2014). Nonetheless, it is important to note that the rate at which individuals and organizations are venturing into activities that include waste collection, mining and recycling is increasing due to the growing level of awareness and knowledge about waste to wealth creation-ecopreneurship. Similarly, the emergence of a sustainable development agenda has significantly encouraged people with business initiatives to take up meaning businesses on climate change and environmental sustainability in contemporary society (Oluwatobi and Ogunrinola, 2011). Sustainable development era can be regarded as the boom of circular economy in Nigeria because a large number of unemployed youths, men and women move into informal businesses and activities such as waste collection, urban mining, environmental conservation, recycling and sales of handiworks made with eco-friendly materials in order to improve the socio-economic conditions in Nigeria.

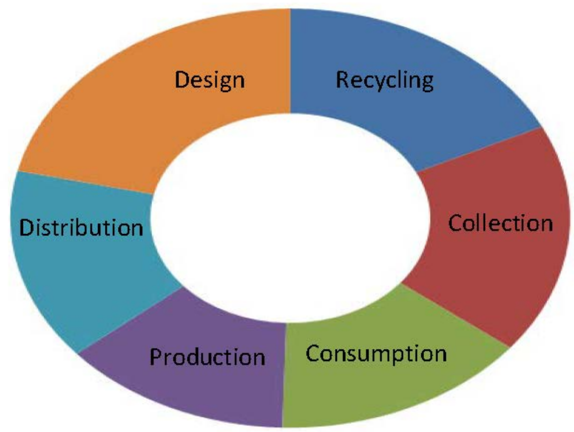

Figure 1. Circular economy (European Commission, 2014)

2.4. Concept of Ecopreneurship: The Small and Medium Scale Approach

The term 'ecopreneurship' is formed by stringing together two words namely, ecological (eco) and entrepreneurship (McEwen, 2013) to denote an innovation or entrepreneurial action that hinged on the motive to produce environmentally suitable products and services (Schaltegger, 2002), recycling and turning waste to wealth (Shane and Venkataraman, 2000), and fulfilment of environmental obligation in business activity (Volery, 2002). Ecopreneurship can also be conceived as pro-environmental behaviour committed to achieving sustainable development (Conding et al., 2012). This is because the primary goal of ecopreneurs is to carry out business activities as well as to minimize environmental footprint, that is, to improve the well-being of the people and the planet (Kainrath, 2009; Kearins and Collins, 2012). Similarly, ecopreneurship is an essential component of the sustainable development agenda because it enables entrepreneurs to focus on converting environmental threats into opportunities and solutions towards a sustainable world (UNEP, 2012; Solaja, 2017). It is, therefore, necessary at this point to define the word 'ecopreneur' in relation to scholar's perspectives. An ecopreneur, according to Isaak (2002), is *a person who seeks to transform a sector of the economy towards sustainability by starting a business in that sector with a green design with green processes and with the life-long commitment to sustainability in everything that is said and done*. In this regard, an ecopreneur is a person who based his/her business philosophy on the sustainability (Kirkwood and Walton, 2010) due to strong interest for social and environmental values (Gibbs, 2009). Thus, an ecopreneur could be a person who owns or operates a company that fulfils both social and environmental requirements (Chopra, 2014), or is engaged in green businesses by producing green products and services, also a person who introduces clean production techniques to boost demand for green products and services, as well as a person who creates green jobs (Schaper, 2002; Rivera-Camino, 2007; OECD, 2011). Furthermore, studies have noted that ecopreneurship as a business concept can be carried out under three stages which are micro-small, meso-medium, and macro-large ecopreneurship (Kearins et al., 2010; Solaja, 2017). These stages ultimately vary in size and capacity in which they operate and contribute to socio-economy development.

2.4.1. Micro-Small Scale

The micro-small scale ecopreneurship is facilitated by individuals that have the mind-set of creating small-scale eco-friendly goods and services in order to add value to the process of restoring the human environment and its resources. Micro or small-scale ecopreneurship involves collecting, sorting and trading of waste materials for industries or individuals who will transform them into usable products. It also includes setting up an eco-friendly business such as tree planting, horticulture, wall beatification, and production of green handcrafts on a small scale or at the grass-root. Small-scale entrepreneurship usually requires very little or no capital to commence. A typical example of micro or small-scale ecopreneurship are the urban waste miners, scavengers or private waste collectors that go to neighbourhoods or doorsteps asking for unwanted or waste materials. Studies have established that those who engage in micro-small scale ecopreneurship do so because they want to create employment opportunities and increase family income (Ebiringa, 2011).

2.4.2. Meso-Medium Scale

The meso-medium scale ecopreneurship comprises of a group of individuals, networks or community of eco-minded business persons who consciously pull resources together to embark on eco-friendly businesses on an average standard in order to promote pro-environmental behaviour and conservation of resources. For instance, a community supported agriculture program designed to grow healthy food, and then sell memberships (or shares) to consumers who in turn receive a designated allocation of seasonal produce throughout the farming season. In relation to entrepreneurship, meso-level ecopreneurship materialize in form of networking or clustering of entrepreneurs who are operating green business enterprises or interested in investing in eco-friendly business ideas. For example, meso-ecopreneurship has networks and clusters of investors who are willing to give loan, prize awards and technical assistance to small and medium enterprises that are innovating in green entrepreneurship to help them grow their businesses (Hamdouch and Depret, 2012). According to empirical studies, meso-medium scale entrepreneurship generates more employment opportunities (about 67 per cent) for interested individuals and unemployed youths across regions of the world (Schmeimann, 2008; Ebiringa, 2011).

2.4.3. Macro/Large Scale

Macro or large-scale ecopreneurship entails corporate organizations or manufacturing companies based on large-scale environmental conservation and waste management activities. This form of ecopreneurship is literally called the “Green Goliaths” or “Green Capitalists”- large companies or incumbents that are determined to invest huge amount of resources on eco-entrepreneurship innovations and initiatives on a large scale with the aim of fostering autonomous trends, paradigms, and technical changes to the accomplish economic and environmental sustainability (Elkington and Burke, 1989). These sets of eco-entrepreneurs engage in mass production of eco-friendly products and services such as the production of hybrid cars, clean technologies, renewable power project, solar energy etc. In another dimension, the goal of macro-large scale ecopreneurs in the context of sustainable development also includes a desire to foster technological advancement, cultural change, resource efficiency and massive reduction of social vices stemming from the increasing abuse of environmental degradation across regions of the world.

2.5. The Challenges of Ecopreneurship

This section examines some of the militating factors to the progress of ecopreneurship in the context of sustainable development. These factors are:

- Double externality: Ecopreneurship contends with several external forces emanating from technological and environmental landscapes (Rennings, 2000). Ecopreneurs are faced with financial uncertainties that usually characterized investment in green business (McEwen, 2013).
- Financial uncertainties: Access to funding is extremely difficult for ecopreneurs due to the immaturity of the market, the trouble associated

with accurately pricing the relative risk of the investment, and the lack of history or track record of success (McEwen, 2013).

- Risk-bearing: Given the challenges characterizing the current and future environmental issues, ecopreneurs are faced with enormous and unpredictable business risks. In particular, McEwen (2013) noted that the market in which ecopreneurs operate does not encourage efficient inter-temporal allocation of risk bearing and risk-aversion.
- Clean technologies and facilities: Ecopreneurship is often faced with the challenge posed by production, commercialization research and development costs of acquiring recycling technologies and infrastructural facilities (Grübler et al., 1999).
- Information, education, and knowledge: Lack of quality information is a major obstacle to ecopreneurship. This is inherently true because eco-innovations involve high technical operations which can only be accomplished when there is reliable information on nature and extent of the problems, the range of solutions available, costs and how to reduce them (Banks and Heaton, 1995).
- Government policies on the circular economy: The biggest challenge ecopreneurs encounter is policy insufficiency. Government at all levels, therefore, is expected to help to implement policies and programmes that will aid acceptance of eco-products in recent times (Banaitė, 2016).

2.6. Theoretical Framework

This study utilized sustainability theory as the theoretical guide. Sustainability theory emanated from the proliferation of intellectual approaches to connect and explain the issues of socio-economic development and environmental quality together in a sustainable manner.

Sustainability theory (ST) therefore attempts to arrange and integrate social responses to environmental and socio-economic problems (Wallis and Valentinov, 2017). In this regards, ST synthesizes polemic ideas about balancing the interaction between socio-economic factors and environmental resources in the context of attaining desirable development for the present generation and to also guarantee future generations their opportunities to develop (Robert et al., 2005; Morelli, 2011; Stoddart, 2011). It also emphasizes the idea of the long-term stability of the economy and environment (Cornel and Mirela, 2008) which is only achievable through the integration of economic, environmental, and social concerns relating to development agenda throughout the decision-making process (Emas, 2015). Following the proposition of sustainability theory, socio-economic activity should be organized or designed based on the principles of mutual benefits (Popescu and Zamfir, 2011). That is, it should be done in a way that promotes positive improvement in the three distinct sustainability dimensions: environmental, social, and economic sustainability (Kozic and Mikulic, 2011). As such, developmental activities must not be carried out in contrast to sustainability principles otherwise there will be social disorderliness or dysfunctional effects on the people's well-being, livelihood and social development (Kiper et al., 2011). It is thus imperative to assess the social, economic and environmental impacts of developmental activities and to ensure that they conform to sustainability standards and principles.

3. Methodology

This study was conducted in Ago-Iwoye, Ijebu zone of Ogun State, Nigeria where a large number of small and medium ecopreneurs (SMEcos) operate. A descriptive survey design was adopted. The study employed both primary and secondary data sources. The primary data was gathered through in-depth interviews with SMEcos which have been doing the business for more than five years while the secondary data was collected from archival sources. The participants in the study consisted of SMEcos (which comprised of waste merchants and ecopreneurs) in Ago-Iwoye, Ogun State, Nigeria. There is no actual figure representing the total number of SMEcos in the studied area, however, efforts were made to investigate 15 SMEcos which were knowledgeable about the subject matter and were willing to share their knowledge with the researchers for in-depth interviews.

The purposive sampling method was used to select the participants. The criteria for being selected in the study was that each participant had to be engaged in solid-waste trading, recycling or mining for at least five years prior to the study. These participants were selected across political wards in Ago-Iwoye, Ogun State, Nigeria in order to accommodate the heterogeneous nature of the study area. Respondents who were below the age of 18 years were excluded from the study. This was done in order to have an in-depth view from adult's point of view on the problem of the study. Digital tape recorder was employed in recording information.

Data collected from the participants were critically examined, transcribed, and responses relevant to the objectives of the study were purposively applied on the basis of merit.

4. Results and discussion

The response of respondents in accordance with the stated research questions was presented below using content analysis to ascertain the opinion of respondents on each research question asked.

4.1. The Role of Small and Medium Scale Ecopreneurship in Nigeria Circular Economy

From the findings, small and medium ecopreneurship (SMEco) contribute significantly to the growth of the circular economy in Nigeria. This fact cannot be overestimated as evidenced in the responses of the interviewees who state that:

> "Small and medium ecopreneurship is a key source of socio-economic development in Nigeria. Because it creates a means of survival and jobs for people (educated and non-educated) who would have been a burden to their family members and the government" (IDI/Respondents/2017).

To support the above assertion, an interviewee affirmed that:

> "I have been doing this business for close to 10 years now. I have about 3 centres where waste is being collected, sorted and sold in Ago-Iwoye alone. I have engaged more than 50 youths since I have started doing the business, though the majority of them are not well read, they have a basic level of formal education before joining the waste trading business. At least some of them are now self-employed running their own businesses still on waste collection, sorting and sales" (IDI/Respondent/ Maryam Junction/ Ago-Iwoye, 2017).

Another interviewee corroborates the above by stating that,

> "…For instance, this waste business had been the means of my survival and the source of my family sustenance since I was not opportune to secure formal employment after I graduated from the Polytechnic (a tertiary institution)…I also sent my children to school and established my wife with the money I make from the waste business. Sometimes, I fulfil extended family responsibilities through my earnings from the business" (IDI/Respondent/ Ijesha Road/ Ago-Iwoye, 2017).

More positive impacts of SMEco on the growth of the circular economy in Nigeria were further revealed by the interviewees who asserted that:

> "Engaging in waste mining as a business helps generate resource or materials that can be useful for the production of consumable goods and services. For example, some of the waste materials (aluminium, plastic, paper, bottle, iron, cloths, leather and engine) that we collected and sorted in this place are useful for production activities in many industries (small and large) as well as local artisans (i.e. welder, mechanic, shoe cobbler)…..We do supply some essential materials that we do generate from waste mining and sorting to manufacturing companies who do recycle them and sell them to consumers at an affordable price compared to if they have to import those materials from abroad" (IDI/Respondent/ Aiyegbami/ Ago-Iwoye, 2017)

Investigating the issue further, an interviewee who is an artisan, disclosed that:

> "Virtually all the products (toys, wall decorations, local lantern, folder, fetcher, and baskets) that you see here are made from waste materials such as textile, discs, wood, plastic, aluminium and iron. I made these products myself and with the assistance of my children who assisted me in collecting the materials I used in producing them…They go out to collect waste from house to house using wheelbarrow without collecting a fee from the disposers and bring them here for sorting and recycling. This initiative encourages many people to frequently dispose of their waste in an acceptable free of charge, and in a very convenient way. It also helps us too, because some material that we used to buy from the scavengers, we get it free of charge through the process" (IDI/Respondent/ Market Street/ Ago-Iwoye, 2017).

Furthermore, another interviewee admitted that:

> "Small and medium ecopreneurship generates income for the government at all levels (Local, State, and Federal)… This is because we use to pay tax and other levies to appropriate officials who remit the money to government covers. Also, SMEco brings income to landowners whose land we use as a space for the waste collection, sorting and storing annually. Thus, SMEco encourages a circular flow of income among stakeholders" (IDI/Respondent/ Ijesha Road/ Ago-Iwoye, 2017).

Arising from the responses above, it is clear that small and medium ecopreneurship (SMEco) provides a way out of unemployment, poverty and family sustenance in Nigeria.

It has encouraged creativity, innovation, and the availability of raw materials for industrial development. Similarly, the development of SMEco ensures effective waste management and increases public health impact in Nigeria.

Scenery pictures that were taken at some of the waste collection centres are shown below:

Figure 2. Showing rubber and metal waste that have been sorted out for recycling or trade

4.2. The Challenges of Small and Medium Scale Ecopreneurship in Nigeria

Studies have shown that small and medium scale ecopreneurship are faced with several challenges which hindered SMEco growth. With this in mind, the objective here is to examine the challenges associated with small and medium scale ecopreneurship in Nigeria. Interrogating the interviewees on the barriers affecting their businesses, brought the following responses.

An interviewee responded by stating that:

> "The major challenge facing my business is capital or fund to expand the business and to get more workers to do the job for me. It is true that this job did not really require a huge fund to start but to expand it, one needs money. For example, I use to pay my workers a thousand and five hundred nairas (an equivalent of USD $4) per day and I am responsible for their feeding (breakfast and launch) during work days. Aside from that when they are sick or sustain an injury during working hours I use to be responsible for their hospital bills… All of these factors require that one should have some level of financial support in the business" (IDI/Respondent/ Maryam Junction/ Ago-Iwoye, 2017).

Figure 3. Showing leather waste and a sample of hand brush made from recycled waste materials

Furthermore, another interviewee affirmed that:

> "There are many challenges which small and medium ecopreneurship activities in Nigeria face. However, the most pervasive among the challenges are lack of manpower, poor attitude towards locally-made products, lack of adequate land space and modern facilities needed in

running the business" (IDI/Respondent/ Ijesha Road/ Ago-Iwoye, 2017).

In addition, an interviewee submitted that:

"Low political will and government support for the development of small and medium scale ecopreneurship in Nigeria is also part of the main challenges. The issues of market availability for eco-proof products and materials for recycling are imminent. Most of the times, the cost of advertising the products on the media platform discourage public awareness and sales of eco-supported products. This problem also reduces the level of patronage we get from our customers. Finally, economic instability also affects the growth of ecopreneurship and the circular economy in Nigeria" (IDI/Respondent/ Market Street/ Ago-Iwoye, 2017).

The inference that can be made from the above responses is that a lot of structural and financial constraints (ranging from the fund, lack of adequate government support, technical skills, modern facilities, and market for eco-products to low level of awareness) serve as hindrances to the development of small and medium scale ecopreneurship in Nigeria.

5. Conclusion and recommendations

This study examines the roles and challenges of small and medium ecopreneurship (SMEco) in Nigeria's Circular Economy in the context of the sustainable development agenda. The findings of the study revealed that small and medium ecopreneurship (SMEco) has huge prospects for socio-economic development in Nigeria. This is evident in the rate at which SMEco contribute to the employment creation, income and revenue generation, the source of livelihood and family sustenance, public health, efficient resource utilization, as well as environmental transformation. The prospects associated with small and medium ecopreneurship cannot be underestimated because it also provides new ways and opportunities for the growth of Nigeria's circular economy. Thus, the need for government at all levels to promote SMEco in Nigeria is evident. The study identified some constraints or challenges militating against desirable growth in SMEco in Nigeria. These problems can, however, be addressed if the recommendations provided below are given optimal priority.

- There is a need to provide financial support to small and medium ecopreneurs in order to be able to obtain funds or capital for running the business. This financial support should be a soft and non-political version of the fund in order to enable the SMEco the access to the funds when needed.
- There is also a need for training and education on how SMEco can better develop their ideas, initiatives, and products to meet internationally acceptable standards. The role of quality in product designing can be achieved if there is a platform for training and development. Furthermore, a periodic trade fair should be organized for SMEcos (local and internationally) to display their products and collaborate with one another to better enhance the circular economy in Nigeria and beyond.
- There should be public awareness and sensitization in regards to the socio-economic prospects that can be secured from the acceptance and utilization of locally made products in Nigeria. By doing so, the urge for international products by many Nigerian consumers would be averted and discouraged in favour of Nigeria economic development.
- Government and non-governmental organizations should invest in the provision of modern waste conversion and management facilities in Nigeria. A lot of effort is required in this aspect because waste collection and management is a big challenge facing contemporary Nigeria societies as available waste facilities are insufficient to meet the demand.
- A public-private partnership should be encouraged in securing a favourable market for the sales of eco-supported products and the exchange of raw materials required in the recycling process. More can be achieved if there is a favourable market for the circular economy to thrive in Nigeria and beyond.

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Izazovi i mogućnosti malih i srednjih eko-preduzeća u savremenoj cirkularnoj ekonomiji Nigerije

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I Z V O D

Mala i srednja eko-preduzeća predstavljaju glavne učesnike u sistemu cirkularne ekonomije i programu održivog razvoja. Razlog zbog koga je to istina je činjenica da su mala i eko-preduzeća kompanije ili osobe koje učestvuju u društveno-ekonomskoj aktivnosti koja se zasniva na principu kružnog sistema (smanjenje, ponovna upotreba i recikliranje) koji promoviše održivo korišćenje ekoloških resursa i smanjenje razvojnih izazova. Iz ovog razloga, u ovom radu se ispituju izazovi i mogućnosti malih i srednjih eko-preduzeća u cirkularnoj ekonomiji Nigerije. U ovom radu je objašnjen koncept održivog razvoja, cirkularne ekonomije, kao i pojam eko-preduzetništva. Takođe je ispitana i uloga malih i srednjih eko-preduzeća u podsticanju cirkularne ekonomije. U radu je primenjena i teorija o održivosti kao osnova za istraživanje. Sprovedeno je opsežno istraživanje koje se zasniva na aktuelnim i relevantnim akademskim publikacijama i izveštajima. Istraživanje, koje je izvedeno deskriptivno, je urađeno uz pomoć prikupljenih podataka tokom opsežnih intervjua. Učestvaovalo je 15 namenski odabranih učesnika. Odgovori učesnika su analizirani putem kvalitativne analize sadržaja ili direktnih navoda. Došlo se do zaključka da mala i srednja eko-preduzeća pružaju mogućnost za razvoj cirkularne ekonomije u Nigeriji. Ipak, nedostatak odgovarajućeg finansiranja, podrške vlade, tehničkih veština, modernih objekata, kao i tržišta za eko-proizvode, predstavljaju prepreke za jačanje cirkularne ekonomije u Nigeriji. Na osnovu ovih zaključaka, u ovom radu se preporučuje da vlada i nevladine organizacije sarađuju u cilju unapređenja cirkularne ekonomije Nigerije.

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Stress Testing with System Dynamics for Enterprises: Proposing a New Risk Approach for the Transition to Circular Economy and Sustainable Development

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ABSTRACT

The goal of this paper is to examine the current state of research on optimal approaches to making effective models that simulate the behaviour of the enterprise as a whole, for the risk assessment purposes with an emphasis on stress testing. Stress testing can potentially aid in the development of highly uncertain policies like the shift to the circular economy, or other policies that have a high impact in the areas of sustainable development. The paper will examine this problem through the scope of system dynamics modelling, however, the goal of the paper is to examine the right heuristics where this kind of modelling can be done with different approaches. When proposing a novel concept like the shift to a more circular economy, a variety of economic and other benefits could be anticipated in the long run, but the potential for large losses in the short term should not be neglected. The paper explores novelty on two levels, in proposing the model for this use, as well as advocating for stress testing approach that has been neglected in use and research outside of the financial industry.

1. Introduction

Executives and managers of modern companies of all sizes face many difficulties of managing uncertainty in form of projects, strategies, and every day decisions. Globalization, which was hastened at the beginning of the 21st century, has brought hyper competitive markets, where mismanagement of resources by managers and executives can deliver high penalties to the enterprise. In 1965, the average tenure of companies on the Standard and Poor's listing was 33 years, by 1990, it was 20 years, and it has been estimated to shrink to 14 years by 2026 (Anthony et al., 2018). Another study (Mauboussin et al., 2017) points out that, between 1963 and 1982, life span of more than 250,000 analysed US manufacturing firms was 5 years for roughly 65 % of them, and for 20 % of them was 10 years. Companies failing at a high rate is not a new phenomenon, and certainly it is not exclusive for high tech companies and start-ups where the rate of failure is the highest (Dimov and De Clercq, 2006; Luo and Mann, 2011). It is important to observe the failure rate on a micro level inside of a company as well, where in certain industries the failure rate of projects can be close to 70 % (Daniels and La Marsh, 2007). A question emerges weather our tools for tackling complexity and uncertainty are efficient at all. There is a substantial proof of our inability to predict and forecast business events and crisis, but most of our risk management does

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precisely that (Makridakis, 1981, 1982). Also many popular books and publications have analysed the concept of predictions by expert opinion, and pointed out the low reliability of these predictions, where experts who analyse and judge potential future success and quality (that is not measured by technology) show extreme inconsistency in many areas (Camerer and Johnson, 1991; Tetlock and Gardner, 2016; Tetlock 2017; Barabási, 2018). With an increase of data gathering capabilities across many sectors, including the old bricks and motor industries, there is a demand for new modelling techniques that can facilitate the bottom line decision making process (Ellen MacArthur Foundation, 2013). This is especially true for highly uncertain initiatives like the switch to a circular economy operating model. The purpose of the circular economy is to develop ways to minimize waste within industries and the overall economy. As the name indicates the goal is to make the economy resemble a closed loop circular system, compared to the linear economy that has the final stage of waste disposal, where this final stage does not allow energy or used parts to go back to the producers in an efficient manner (Ellen MacArthur Foundation, 2013). The concept of a more circular economy started to gain serious recognition in both industry and academia after its adaption as one of the primary competiveness strategies by the European Union in 2014 (Avdiushchenko, 2018). If a search analytics tool like Google Trends is applied for the term circular economy for the period from the beginning of 2014 to the end of 2018, with the purpose of analysing the web searched trends on a platform like Google, a sharp increase in popularity can be observed. Other important ramifications can be observed as well, like the top searched queries are associated with the regulations (concerning circular economy) from the European Commission and the search for scholarly articles on this topic. The recognition of the circular economy concept by academics and policy makers is apparent; however, it is of the highest importance for the most waste generating industry within the economy to recognize and implement this concept.

In the period from 1998 to 2001 it was estimated that the Europe region was generating 2.2 billion tons of waste annually. Increase of waste produced by the economies is a rigorously studied phenomenon, and the initiation for research came from the increase of production capacities worldwide. For example in 1950s global production of plastic was around 2 million per year, however, the production capacity for the next sixty-five years was growing annually by around 8.5 % to reach global production of around 380 million tons per year in 2015 (Muthmann et al., 2003; Gourmelon, 2015; Geyer et al., 2017). There are other concerns that follow the issues of global waste build up, and they have to do with the slow technology transfer of waste management technologies from the developed world to the emerging economies (Ragossnig and Vujić, 2015; Vujic et al., 2017). The 21st century has started as the era of high technology devices that are made of complex materials which are not biodegradable; and these devices are intended to be changed by the user for the upgraded version when that product arrives to the market. This is one of the concerning facts that drives the push for a more circular economy. With the rapid economic growth in the developing countries the production capacity will have to meet the demand in new and more sustainable ways (World Economic Forum, 2017).

When proposing to an industry or a particular company to transition to a system where production and product disposal are integrated in a new circular way for the goal of minimising waste, both the needs and the risks associated with a system need to be recognized. There are a few early proposed concepts for this shift: product life extension, integrating resource recovery operations to the supply chain, creating sharing platforms, and incentivizing other participants in the supply and distribution networks to integrate to the circular model. Many of these concepts are not new, and have been proposed in different forms in the past for the purposes of sustainable development schemes and better integration of recycling and waste management within large scale value chains (Nikolić and Perović, 2008). This is particularly true for different forms of recourses recovery and product recovery management where these strategies have been integrated in the past with different companies and industries. However, the goal of making a circular economy operating model work, many of the above mentioned concepts like the product life extension along with all of the distribution and supply side changes need to be adapted through trial and error testing with the operating model of the company. The reason for this is the fact that many of the above mentioned changes have the potential to financially break the enterprise, while the economic benefits to transitioning to a more circular economy would show in the long run. In the short run there are eminent high costs, along with other risk associated with transitioning to new operating models. Many industries are structurally restricted to large shifts that present sizable upfront costs for future benefits due to large capital intensity along with shifting profitability across the industry. One of the largest and most important industries in the world having impact on the economy is the automotive industry; this industry has been targeted as one of the most important industries to make a shift to a more sustainable way of operating. However, it is important to point out that this is an industry that is highly fragile to regulatory, commodity, financial, or competitive volatility (Alvarado-Sieg and Huerbsch, 2019). With this being said, one of the key components to pursuing ambitious policies of a more circular economy is the use of right tools and methods that will allow companies to experiment and pursue goals that have high risks in the short term. The goal of this paper is to examine the novel tools for risk planning that can prove useful with highly uncertain changes and events that are not predictable.

This paper will observe the decision making and analysis instruments true System Dynamic simulations modelling. Despite the maturity of almost fifty years, the rise of popularity of this simulation modelling method accelerated in the beginning of the 21st century, partly due to the rapid development of software solutions and platforms that can support this type of modelling. System dynamics was invented in the mid-1950s by Jay Forrester (1989; 1995), but the development of commercial software solutions has made this modelling method accessible to wider use.

System dynamics studies complex systems and how they change over time, it has a strong recognition in many fields ranging from managerial sciences and economics, urbanism, ecology (Rogers et al., 2016), and biology for addressing complex issues in medicine and epidemiology (Forrester, 1990; Homer and Hirsch, 2006). The paper will not go any further in defining system dynamics modelling as there are many great textbooks and publications that cover this field of simulations modelling (Angerhofer and Angelides, 2000; Morecroft, 2015; Sterman, 2015). If a popular simulations modelling approach such as system dynamics is observed, the focus lies on isolating and modelling a wide range corporate activities ranging from: logistics, supply chain management (Richardson and Otto, 2017), marketing (Aburawi, 2005), human resources (Lyneis and Ford, 2007), project management to financial management (Qureshi, 2007; Poles, 2013), production and inventory system (Snabe and Größler, 2006), strategic management (Shafiei et al., 2015), energy systems (Kafeel, 2012; Hosseini and Shakouri, 2016), solid waste management (Arnold and Wade, 2015), system thinking (Golnam et al., 2010), and enterprise modelling (Trimble, 2014). There is a deficiency of research on the topic of modelling the whole enterprise, where the model simulates the behaviour of the enterprise with adequate precision and it has a high degree of universal applicability, and a wide spectrum of analytical approaches can be used and built around that model. The goal is finding a model that can be defined as a risk centric driven model of an enterprise, where the model is bottom up adopted for these purpose.

2. System Dynamics Approach

As shown in the Fig. 1, system dynamics has very differentiated approach compared to standard approaches in the corporate planning world. It usually has two steps in structuring the model (defining the relationships) a qualitative step where a set of non-quantitative mapping tools can be applied, in most cases a casual loop diagram is used, and a quantitative process is applied afterwards. Compared to most approaches to simulations, which are mostly focused on writing code in a specialised programming language, system dynamics (Fig. 1) allows easier interpretation of the model and many model building practices are done in groups (Jac and Vennix, 1999). This approach brings a differentiated and in many ways more comprehensive approach to modelling and analysis of complex systems.

A large emphasis in system dynamics is placed upon understanding the problem or the system first and not just crunching the numbers, like in the case of many purely statistical approaches to planning that are overly focused on forecasting and optimizations (Richardson and Otto, 2017). The brilliance of this modelling language is that

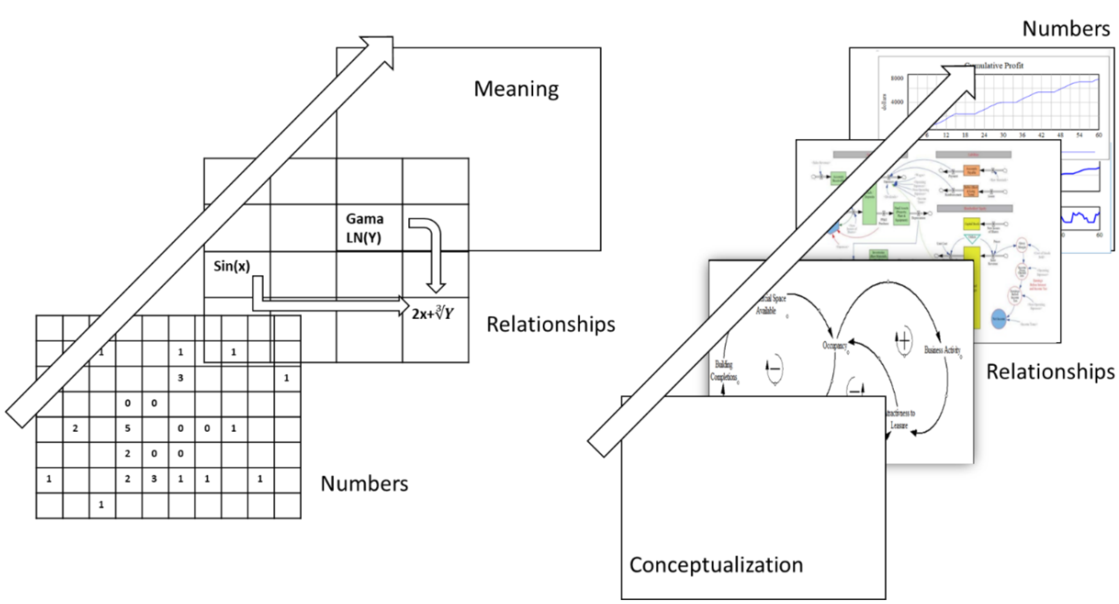

Figure 1. Standard data analytics approach on the left and system dynamics on right

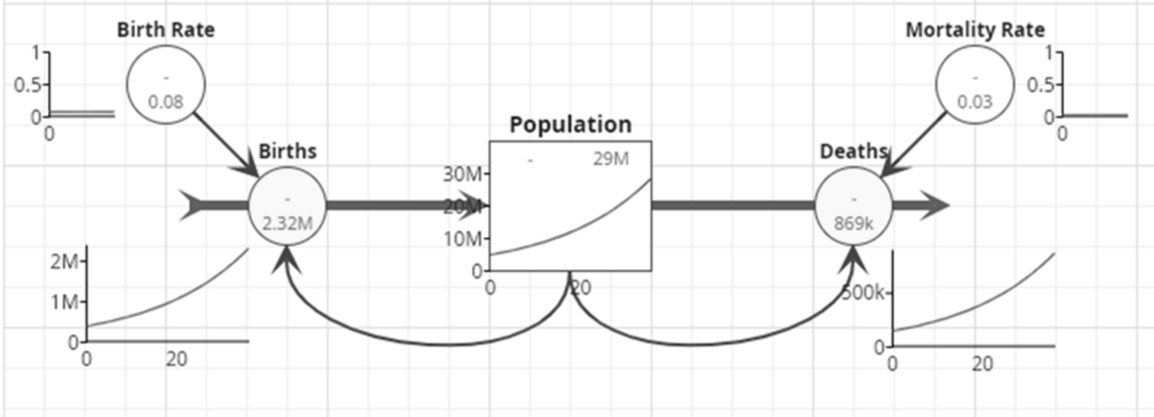

Figure 2. Simplified system dynamics population model

you can define any system from a supply chain to a biological ecosystem with a few visual tools as shown in Fig 2, and then you can derive a simulation model out of that. But the most important segment of system dynamics lies in the focus on modelling feedback loops (the positive and negative feedback loop) within the system and analysing the nonlinear behaviour of the system. A feedback system has a closed loop structure that brings results from past actions of the system back to control future actions (Angerhofer and Angelides, 2000). It should be acknowledged that real world complex systems function in this way and that they are nonlinear systems, when observed outside of controlled laboratory settings.

In managerial sciences standard approach in system dynamics is to simulate a specific part of a company like a production and inventory system, or to simulate a specific strategic initiative or a problem that is being solved (Snabe and Größler, 2006; Shafiei et al., 2015) with well-defined boundaries (Trimble, 2014). So it can be said that approach such as system dynamics modelling is not focused on modelling the whole system (whole economic system, industry or an entire company), but instead it is a specific goal and specific problem oriented. There are many reasons why this approach of isolation is sufficient, and one of the key reasons is complexity. If we chose to model all segments of an enterprise in great detail, we will get a highly complex mathematical model with an extremely large number of interconnections. One of the key elements of a successful modelling process is defining boundaries of the model, in other words deciding what to exclude from the model in some cases is of greater importance than deciding what to include. In system dynamics many use model boundary diagrams to optimize the scope of the model, and to avoid inconsistency due to complexity and bad data (Cihák, 2007; Moyano and Richardson, 2013).

3. Stress testing

As stated at the beginning of the paper, the focal point is risk, in particular stress testing, and the macro model of the enterprise needs to be adapted to this risk approach but also it should be applicable to other business analysis tools. The stress testing is a highly popular and essential risk assessment approach to financial enterprises, with an ever rising development of applications and capabilities. But this approach to risk has not been developed or used for the non-financial sector; a lack of research on optimal modelling approaches that can facilitate this approach is to be blamed. In this paper the focus will be placed on the model that can support this kind of risk approach. This kind of a model can be named the Macro Model of an Enterprise (MME) and this model would be intended for analysts, risk managers and top managers interested at observing the performance and analysing long term corporate strategies. The MME needs to have sufficient simulation capabilities (to adequately simulate the behaviour of the company), but more importantly, there has to be a level of agility to this model, where other models and analytical approaches can be built around the MME for different intended purposes.

There is a large demand for this type of models with the raise of novel risk approaches like stress testing (Forrester, 1995; Rogers et al., 2016) and managerial concept like resilience (Sheffi, 2007, 2017). Managers need a robust heuristics on the model development process and how to apply the risk assessment.

Stress testing is a concept that is used across many disciplines and it defines the stability and resilience of a particular system or an entity (Cihák, 2007). Stress testing should be characterized as a behavioural analysis of a system, and its reactions to shocks and different kinds of volatility. In years following the ‘08 financial crises, governments and financial institutions have recognize the importance of a more aggressive spending towards risk assessment technologies. Stress testing has seen a rapid growth in use by the financial institutions, where some of the largest institutions will invest anywhere between two hundred million to half a billion US Dollars. It can be said that this approach to risk leads the technological development for the world of risk management. However, the expenditure for financial institutions should not present this risk approach unattainable. A single financial institution will hire in many cases multiple consulting companies to conduct the stress testing, and many of these institutions have trillions of US Dollars of assets under management. There has been no development of this approach in the nonfinancial sector where stress testing can potentially bring more value in risk mitigation compared to the conventional approaches. A non-financial company can use stress testing to build redundancies, eliminate weaknesses in its operating model and combine stress testing with other analytical approaches.

Stress testing can potentially prove to be most valuable to energy, commodity, bricks, and motor companies. There are two main reasons why this approach has not been developed outside the financial world. Firstly, there are no state of the art theoretical heuristics for conducting stress testing for non-financial companies; and secondly, there are no best practices modelling technics developed to support the theoretical heuristics. As stated before, the paper will not focus on approaches on how to conduct a stress test as there can be multiple approaches, and in the case of nonfinancial enterprises, special customizations can be made to a particular industry. However, what kind of a model should be developed for this use will be examined.

4. Selecting the right model for stress testing

Borshchev and Filippov (2004) make a comparison of tree major modelling approaches: system dynamics, agent based, and discrete event modelling. All these approaches have their ideal domain of competence as shown in Fig 3. System dynamics is used for high abstraction, macro, and strategic level modelling.

However, you can use system dynamics for the operational and tactical level modelling, not just the strategic level. The model for the stress testing of non-financial enterprises would ideally include some data from the tactical and operational level. Such model will have parts that will be differentiated in abstraction and level of detail. We must recognize the diversity of data that would go into a model which will adequately simulate the behaviour of a particular company. This model could include data from different abstraction levels from Fig 3. Highly detailed low abstraction data from the financial reports can be included, and high abstraction and less reliable market and competitive forces data can be analysed in the model as well.

If the main analogy from Fig 3 is considered, of having micro level low abstraction and macro level high abstraction, and if we add a horizontal axis for reliability of the model, then a simplified segmentation in Fig 4 will be generated. There will be different kinds of models and data that we might want to include in our stress testing model, and the decision of what should be excluded must be made. Some would argue that if there is a need to simulate the behaviour of a non-financial company, a sub-model that generates the behaviour of a market, competition, or new technology diffusion should be included. It can be argued that from a strategic perspective companies have a reactive behaviour to these factors. However these models are highly unreliable by their nature, as they are mostly forecasts of highly volatile and uncertain phenomenon.

The focus should not be placed upon the top right corner, as it is unclear whether these models bring any value whatsoever, due to the fact that they are modelling highly uncertain and unpredictable events. The upper right corner models have proven to be highly unreliable, as there is no research for best practices modelling with a proven long term record of predicting market behaviour

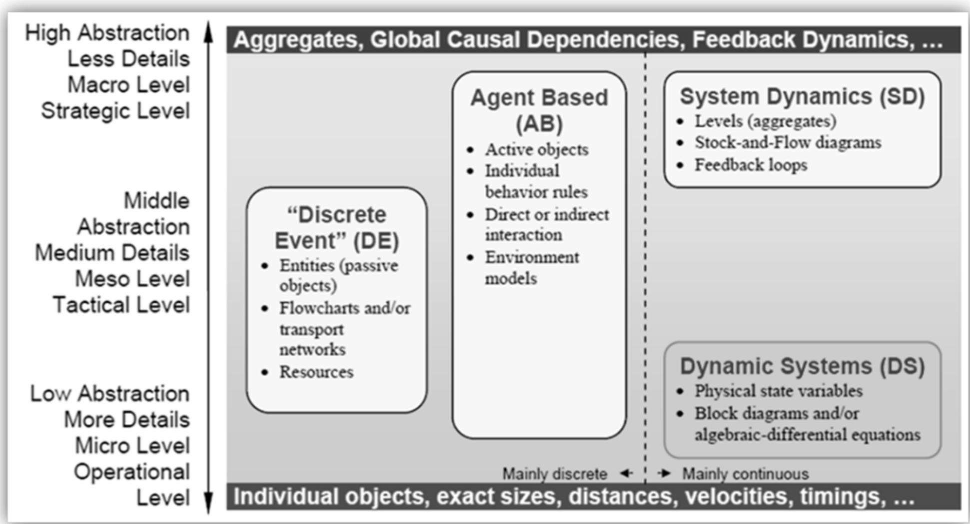

Figure 3. Simulations approaches and abstraction level scale (Borshchev and Filippov, 2004)

or robust behavioural analysis of new technologies or competitive forces. With that being said, the paper will mostly focus on modelling the bottom left part of the Fig 4, due to the fact that the main goal of our model is to be accessible to universal data like the financial statements data and the operational data. Process of gathering and using this data is well defined unlike in the case of the top right part of the diagram in Fig 4. Also it should be noted that it is possible to have a part of the model that simulates operations of the company derived from the financial statement data.

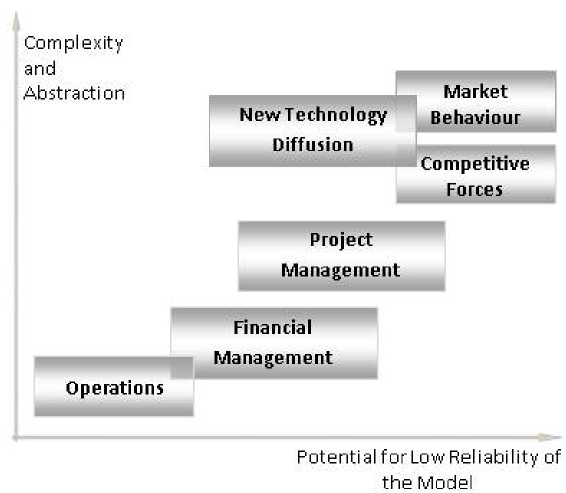

Figure 4. Different modelling segments and their characteristics

A question emerges whether or not system dynamics is suitable for modelling financial data, as this is not the main use of this simulations modelling approach and other approaches are more used for these endeavours. Modelling of the company's operations from micro to macro level, as shown earlier in the text, is highly functional in system dynamics, compared to alternative methods, but can this be said for financial data as well? System dynamics does not have structural limitation for this kind of financial data. There is a universe of specialized software for financial and accounting data management, modelling accounting data can pose difficulties and complexity due to the double entry book keeping system that accounting is based upon. Spread sheet modelling solutions are mostly used as they are uncomplicated and universally accepted, but system dynamics can accommodate these kinds of models in a more effective way. There is limited research on this topic in system dynamics. Melse (2006) defines the structure of a system dynamics financial accounting model, which can be integrated with other models, and the model is structurally coherent with the accounting equation and the double entry system.

The model that is required has to have a comprehensive use of the financial statement data: balance sheet, cash flow, and income statement data. More importantly it needs to integrate all tree parts of the financial statement in one coherent model. The reason for using all three parts of the financial statement is to have a robust overview of the enterprise, but also to allow the model to be extended in simulating operations. The model that integrates the whole financial report into a single model will be a large model with a large number of interconnections; however, it will be a highly calibrated and structurally reliable model, where there will be no uncertainty on how the parts are connected.

As pointed before there is limited research on this topic, nevertheless, there is a model and a modelling protocol that meets our early requirements. Yamaguchi (2003) outlines the modelling protocol for a comprehensive accounting model that combines the balance sheet, income statement, and the cash flow statement. The model is large and has multiple layers (sub-models), and has parts that cover production, inventory and sales, as these parts can easily be derived from the financial statement. In Fig. 5 a part of the model that covers the balance sheet is outlined. In the language of system dynamics all the elements from the balance sheet will be stocks (rectangular objects), and the elements from the income statement and the cash flow statement will be inflows and outflows.

The model has parts that simulate the operations of the enterprise in a superficial way, but the model can be easily extended to cover operations to a more sophisticated level. In Fig. 5 just one layer of the enterprise model is showed, which is derived by the modelling of the all three parts of the financial statement. This model fits the needs for the stress testing purposes of non-financial enterprises.

The examined model would need to go through smaller adaptation for stress testing analysis. These adaptations also depend on the industry that the enterprise originates from. There is no difficulty to adapt this model for other analytical approaches as well. The proposed model by Yamaguchi already has a sub model for some of the basic ratio analysis tools as shown in Fig. 6. Ratio analysis such as liquidity ratio, profitability ratio, and leverage ratio are used for stress testing purposes, but further analytical operations would need to be adapted around this model.

System dynamics offers a robust platform for conducting stress testing. However, stress testing modelling is at early stages in system dynamics as there are only two publications which have conducted a stress test of a financial institution (Anderson et al., 2011; Islam et al., 2013). Islam et al. (2013) outlines an advanced approach of using a system dynamics model supported by a machine learning algorithms, to conduct stress testing of a banking institution. The model proposed in this publication for stress testing of non-financial services by Yamaguchi (2003), aligns structurally with the model by Islam et al. (2013). The main difference between the models (Yamaguchi, 2003) and

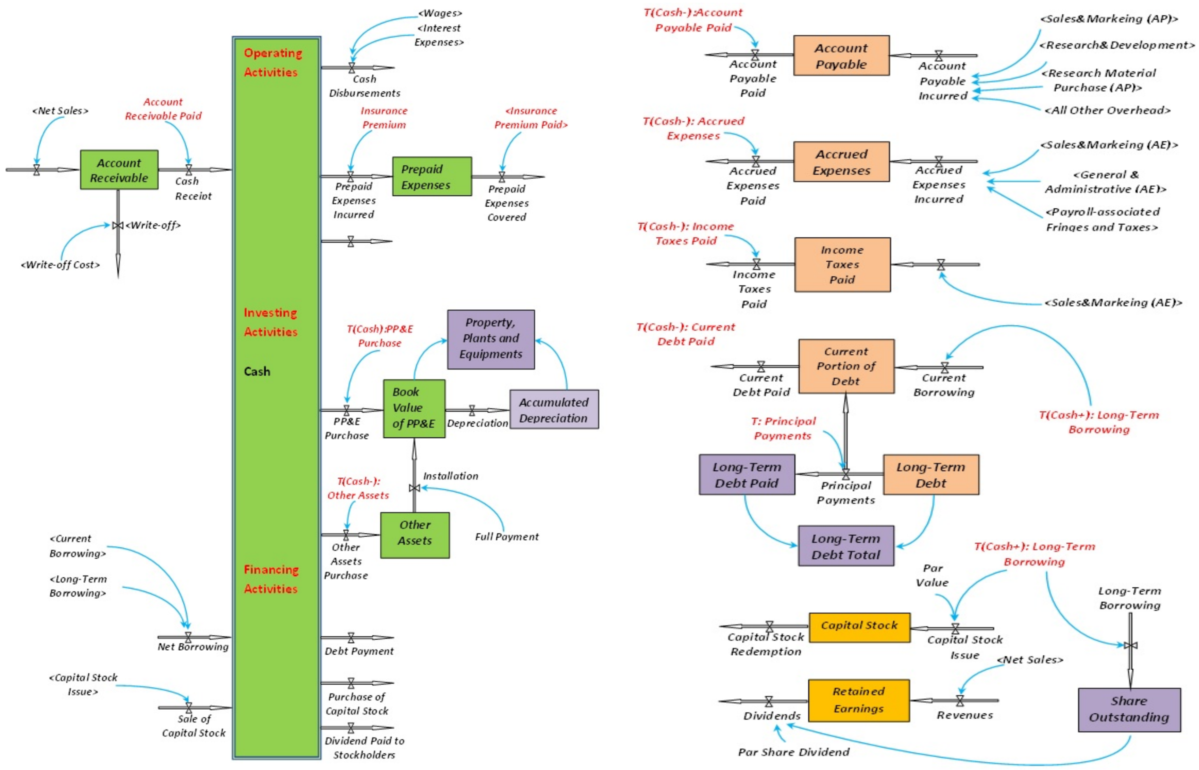

Figure 5. Balance sheet model (Yamaguchi, 2003)

(Islam et al., 2013) is that the model (Islam et al., 2013) is an in-depth balance sheet model that is specially adapted for a banking institution. As mentioned before, being able to adapt the model to the specific industry is of great importance. When it comes to financial institutions, the model should cover the inter-bank lending like in the case of Islam et al. (2013), as well as adding elements to the balance sheet which might not be present with a non-financial institution. In Fig 4 we have covered what kind of data should be potentially excluded from a stress testing model of a non-financial enterprises, the model proposed in this publication developed by Yamaguchi, leaves high optionality of how the model can be expanded to meet the stress testing needs of a specific industry. Publication by Islam et al. (2013) proves the versatility of the system dynamics modelling as a tool for stress testing as well as the proficiency of system dynamics to incorporate financial data.

As mentioned before, corporate transformations to a more environmentally sustainable business model, or a more profit driven one, carries a great deal of risks. Whether or not an enterprise is pursuing goals of sustainable development, goals of cutting costs and raising profits, or any form of high impact transformation, the probability for failure and value destruction is higher than the probability for success (Ward and Uhl, 2012).

Most of the companies pursuing innovative policies such as the circular economy shift or other policies defined in the area of sustainable development, should firstly observe how much up front, as well as later operational risks they can sustain. Focus on forecasting what risk will happen in the beginning stages or later stages of corporate transformations is highly insufficient. When transitioning to a circular economy system, operating the risk analysis needs to be focused on the up front losses which might occur, and there should be a sophisticated method like stress testing to see how much volatility the enterprise can take, and what redundancies should be built to better manage that volatility. It is important to note that with the operationally uncertain concepts like circular economy, there can be heavy volatility later when the company starts operating under this concept. With well-defined concepts like lean supply chains and agile supply chains, the types of volatility are well defined as these systems are implemented across industries. This is not the case with many emerging concepts with sustainable development and circular economy. The rise of machine learning and commercial data visualization tools may offer elimination of many bottlenecks in complex supply chains that need to facilitate better waste management, especially when it comes to material tracking and agile optimizations (Vujić and Milovanović, 2012). However these are tools that have a purpose of making the supply chain more efficient, the largest weight still falls on having an effective risk system to observe and analyse the durability of the overall system.

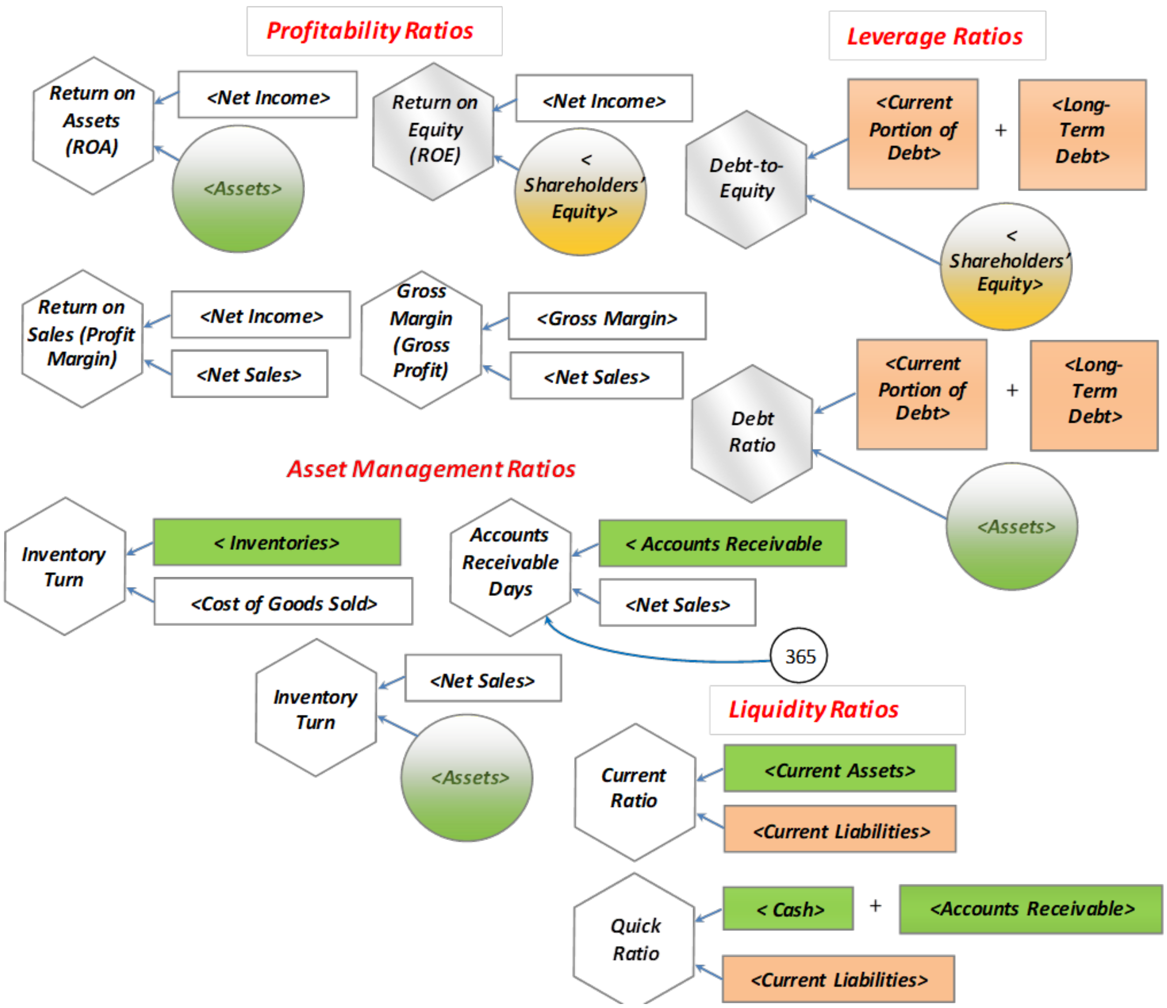

Figure 6. Ratio analysis part of the model (Richardson and Otto, 2017)

5. Conclusion

The paper has examined a contemporary and highly neglected approach to risk for non-financial enterprises, as stress testing outside of the financial industry has not been explored as a practical option for risk mitigation. It should be pointed out that there was a monumental increase in the analytical capabilities of companies and corporation from the end of 20th century and the beginning of the 21st century, however, the failure rate of projects and strategies within companies has not improved, and neither have the tools for risk planning. There is more data, along with higher than ever gathering and processing capabilities, but the tools for risk and planning that use this data need to evolve as well. This is the main reason for proposing stress testing development for the nonfinancial sector along with using system dynamics for it. New risk tools need to be explored, since new ways of operating, such as the sustainable development and circular economy, are emerging as the essential ways of managing the firm's assets. Considerable changes in the operating model of the company like the shift to circular economy model should be vowed as large up front stressor for the company, and this will be a huge barrier for implementing the circular concept with industries with high capital intensity. Stress testing can potentially aid in the development of these highly uncertain policies, as many standard risk techniques require large sets of previous data, and when it comes to circular economy and other similar policies that data is not available, due to the fact that these policies are not widely implemented.

The paper presents an early introduction to this unexplored topic, since, along with the stress testing, system dynamic has not been used for risk management problems. The paper has conducted the analysis of the state of current research, and proposed a well-grounded model that should be used for stress testing in the non-financial sector. Future research on the topic of stress testing in the non-financial sector needs to explore what are the insights and capabilities that stress testing offers, in comparison to the standard approaches to risk which are mostly anchored to forecast and prediction. The proposed approach for risk could have a notable effect on risk management in the non-financial sector, but this is only possible if the future research exemplifies the high standard of risk management research conducted in the financial sector.

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Stres test metoda za kompanije kroz dinamiku sistema: Predlog nove metodologije za upravljanje rizikom za tranziciju ka cirkularnoj ekonomiji i održivom razvoju

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I Z V O D

Cilj publikacije je da istraži trenutno stanje u objavljenim istraživanjima o optimalnim metodama kreiranja matematičkih modela koji simuliraju ponašanje preduzeća kao usklađene celine, sve to ka cilju analize rizika sa fokusom na stres test metodu. Stres test metoda može doprineti u procenama stabilnosti u visoko neizvesnim tranzicionim politikama, poput ostvarivanja više ekonomske cirkularnosti u kontekstu cirkularne ekonomije, kao i u analizi rizika visoko uticajnih aktivnosti u sferi održivog razvoja. Publikacija ima za cilj da istraži ovaj problem kroz matematičko modeliranje primenom dinamike sistema. Glavni cilj je sagledavanje univerzalne heuristike i teorije rizika koja se može primenjivati i u drugim oblastima. Pri predlaganju novog koncepta poput prelaska na cirkularnu ekonomiju, niz ekonomskih i drugih benefita se očekuje u dužem vremenskom periodu, međutim, ne treba zanemariti moguću pojavu kratkoročnih gubitaka. Ova publikacija istražuje inovativne pristupe na dva nivoa: u predlaganju matematičkog modela za ciljnu upotrebu metode dinamičkog modeliranja preduzeća, kao i u samom predlaganju stres test metode za koju se može reći da je zanemarena u upotrebi izvan finansijskog sektora.

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Landfill workers' proffesional education for protection against injury and damage

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ABSTRACT

Common practice in Southeast Europe (SEE) countries is that mostly low skilled workers work in waste management sector. In SEE countries there are no institutions specialized for educational training concerning safety of the employees who work in solid waste management system. It should be emphasized, that this specific type of profession, which is dealing with the high occupational health risks, needs legal basis for proper education and training, like it is defined for numerous professions in public sectors. Evidently, companies that provide the education and training for their employees will have direct benefits. The main focus of professional education is on workers on landfill, as this is the working place with the highest risk, but at the same time very important for operational practice and sustainability of a landfill. For these workers, there are following focus points: Professional training; Health and Safety protection; Fire protection; Landfill gas management; Leachate management. Well defined educational programmes for H&S, emphasizing safety precautions in handling with hazardous materials and fire protection, are good way to reduce injuries and to improve efficiency of employees as well.

1. Introduction

The poor employers' awareness of the complexity and benefits that the proper implementation of occupational safety and health (H&S) brings, represents the biggest problem at landfills and utility companies. Every injury in the workplace costs the employer much more than the expenditures related to the introduction of H&S.

The most important regulations in H&S area are acts of the International Labor Organization, World Health Organization, European Union and other European integrations whose regulations are accepted by EU Member State. EU laws are mandatory for Member States of this organization, and in good part also for countries that are preparing to join because this is one of the conditions for admission to the EU.

For safety and health at work most important are the directives of the general character to which have determined guidelines (frameworks) of national policy and national protection systems; and specific directives that determine the conditions of work and security measures in certain areas. In terms of defining the obligations and activities of the state at the national level and employer at the enterprise level, the most conclusive are the Convention no. 155 and General Directive no. 391/89. In the Republic of Serbia, right to health and safety as a fundamental right of employees, institutional organization, and mechanisms necessary for its

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realization are regulated by laws, by-laws, norms and standards, collective contracts, employer's act, and employment contract. Right to protection on work is guaranteed by the Constitution, and systemic issues, rights, obligations, and responsibilities are regulated by the relevant laws (Law on Safety and Health at Work, Labor Law, Laws on Social Insurance - health, pension and disability) and conditions for direct implementation by other legal acts. Harmonization of the Law and related by-laws in this area was conducted in such a manner that the majority of requirements stated therein was adopted in accordance with national market conditions. The Law on Health and Safety at Work set up all the activities intended for undertaking preventative measures for the purpose of preventing the risk of injury (Law on Safety and Health at Work, 2005).

Most companies in Serbia and countries in the region carry out regular training for workers in the field of occupational safety and fire protection, as imposed in the current legislation. Nevertheless, despite all the measures that are being taken, there were cases of lighter injuries, several cases of self-ignition of the waste at the landfills, as well as improper handling of the machinery. For that reason, professional education and H&S must be seriously considered. It is necessary to consider its introduction into every business system, and the final result would be safe workplace, as well as a higher productivity of employees (Thornton, 2002).

Incorrectly installed machines, poorly constructed landfills, improperly disposed or stored municipal waste, poor worker skills, and wrong working procedures inevitably lead to accidents. The variety of work, and in that sense a wide range of hazards, leads to a high level of injuries (Needham et al., 2004). It is indisputable that it is very difficult, almost impossible, to achieve completely safe working conditions in which there would be no accidents, especially if the work does not always occur in the same place and using the same means of work. Utility companies face precisely these difficulties. Well-defined professional education and H&S program are a good way to reduce injuries and improve efficiency of employees.

The goal of professional development is to acquire knowledge about waste management system and adequate operating procedures on landfill that will reduce number of accident situations, as well as to provide more efficiency in the municipal waste management sector.

Companies that provide H&S training for their workers will see benefits through improved and safer working conditions, which will further result in better motivation for employees.

2. Analysis of accidental situations at landfills

Hazardous emissions, dust, smoke, flies, odour, heat, cold, and long days in the cabin are not favourable conditions for most workers and drivers of machinery at the landfill (Bogale et al., 2014).

A large number of hours (32 hours per week) spent in the cabin during the day and in the cramped space can create discomfort and increase the likelihood of making a mistake (Pagano, 1964). People who do not have enough experience and knowledge with operating machinery often apply to work as drivers. In Republic of Serbia there is a lack of compaction and the daily corresponding landfill covers. Consequently, the approximate use of the working time for workers at the landfill is 800 hours per year.

The cause of lighter injuries at the workplace, for example during the landfill fire or improper handling of the machinery, is the fact that the company generates a lower level of income than required (Thakur et al., 2018).

This is usually the case when authorities do not approve the economic cost of utility services, and thus the utility companies need to reduce the expenditures, which directly negatively affects the procurement of H&S equipment. In order for utility companies to maximize savings in the process of the disposal of municipal waste, the application of a minimum or no layer of inert material on sanitary cells is applied, which does not provide adequate protection in the event of landfill fire. Also, the fact is that the sanitary waste disposal is new in the countries in the region, and that the work of mechanization in the handling of municipal waste is different from the work on the same mechanization on construction sites, quarries, excavations, etc.

This specificity is reflected in the fact that training of operators in the procurement of work machines is not adapted to specific conditions at the landfill (soft ground, heterogeneous composition of the ground, uneven load in manipulative work, etc.), and that general handling rules are not entirely sufficient for proper operations of machinery on landfills, thus leaving an extremely high possibility of damage to the underbody, engine, hydraulics, or other parts of mechanization.

The data taken from the Statistical Yearbook of the Republic of Serbia on work-related injuries in the period from 1977 to 2005 show that in the utility sector an average of 1170 work-related injuries occurred annually, i.e. three workers were hurt each day in this sector. In 2015, the total number of serious and fatal injuries in the following activities: industry, mining, forestry, construction, etc., was 729, out of which 43 injuries were in housing and communal activities (Ministry of Labour, Employment, Veteran and Social Policy, 2016). The work conditions in communal activities are quite difficult and specific, with a greater number of injuries at work, including death fatalities. According to the data from 2015, this activity includes 5.9 % of the total number of injuries at work in the Serbian economy (Ministry of Labour, Employment, Veteran and Social Policy, 2016).

Also, there are frequent injuries of workers at the municipal landfills (due to the frequent internal transport including vehicles bringing in the waste for klifts, compactors, bulldozers, and other heavy construction machinery), at the collection and sorting of waste, at the landfill working face, during landfill remediation, machinery maintenance, etc. The risk of injury from the machinery at the landfill is most often associated with the possibility of injury of workers operating in its vicinity, usually from parts of the machine itself.

According to an official 2009 Report from the New York Department for the assessment and control of mortality, a 49-year-old employee was fatally injured when he fell on the road from the rear of the truck on which he was standing. Since he suffered serious head injuries when hitting the ground, he died two days later. In order to prevent such accidents, workers should not stand outside of the cabin of vehicles moving faster than 10 km/h. Also, in 2008, the 69-year-old worker from the private sanitary sector died after being run over by a garbage truck. After compaction, the vehicle started to move, the worker ran for the vehicle, fell under the truck and died. In such situations, workers should turn on handbrake before leaving the vehicle (FACE, 2010; FACE, 2012).

3. Hazards which are present at a landfill and pose a risk for landfill workers

Health risk from working machinery is most often associated with the possibility of injury in the working space of the machine due to moving parts of the machine or the operator/driver of the mechanization. The risk of injury is also present when moving the machine. The landfill machines are being improved daily to achieve the following goals: the highest possible effects, simpler and easier handling by introducing the principle of automation, reducing operating costs per unit of production, simplifying supply and replacement of spare parts, easier and simpler maintenance, improving technical possibilities of movement, rotation, speed change, and operation in different climatic conditions (Thakur et al., 2018).

In many developed countries, the work of the driver/operator is simplified by the acquisition of modern machines. Modern working machines have better control, monitoring, and different operating modes. Any information that a driver can obtain in the vehicle cabin reduces possible accidents and makes safer and more efficient working environment.

However, despite all the information that a vehicle can provide, it is necessary to have trained workers to handle them. The machines have become simpler and easier to operate. Most people think that anyone can do such a job, but this is not the case, since training is required for all operations. For better performance, training and knowledge are needed to work safely and with higher efficiency. It is important to note that, in addition to modern mechanization, qualified drivers are in high demand all over the world. The technology has advanced, but all this comfort has no significant impact if the drivers/operators do not properly operate and maintain the machinery. Handling compactors, dozers, and loaders requires both skill and patience. These are the two qualities that the best drivers possess, and it is often difficult to find such drivers. Each landfill has unique layers and topography. The best drivers know which paths to avoid at the landfill.

Landfills can change their status from ‘controlled’ to ‘uncontrolled’ as a result of as serious landfill fire. Since landfill fire poses a threat to human health and the environment, the need to understand its mysterious nature is higher than ever. If some kind of a heat source contacts the surface, for instance deposits of hot waste, lightning, or arson, this can cause surface fire (Reinhart et al., 2002; Riquier et al., 2003).

For deep-seated fires (below 4.5 meters) the initiation mechanisms are quite different. Deep-seated landfill fires can expand in two different ways, which are known as ‘confined’ and ‘unconfined’ progression. Confined progression starts within multiple thin layers of waste which are pressed by a landfill compactor. The compactor realigns the waste in a way that it is more permeable horizontally than vertically. These thin layers of waste are located between layers of daily cover of inert material. In Serbia, daily cover is not used on any of the landfills, however on certain landfills compactors and buldozers conduct some sort of compaction. In this case, a fire will expand horizontally.

A confined fire might be indicated by a shallow collapse, surrounded by tension cracks at the surface, where operators of the heavy machinery may fall into. At unconfined landfills, fires occur in Construction and Demolition (C&D) sites. There are no horizontal constraints here and fire will progress vertically producing a dangerous sinkhole at the surface, where drivers of compactors, dozers, and buldozers may fall into (Sperling and Henderson, 2001; Reinhart et al., 2002). Surface fires are easy to detect, while deep seated fires may be predicted and often detected early on. The most cost-effective method of detecting a fire is through detections of the trained staff. Some detections include: barbecue-like odour; vertically unaligned gas wells; issues with landfill gas pipelines (breaks or softening); or an unplanned necessity to change the oil in landfill gas engines (Environmental Agency, 2002).

In addition to this, the operator should continuously monitor key properties to detect changes:

- In the topographic shape of the landfill;
- Greater rise of temperature of more than 3 °C, or when the temperature reaches 60 °C;
- Changes in a landfill gas analysis: i. changes in methane and carbon dioxide levels, ii. changes in nitrogen levels, iii. changes in hydrogen content, and iv. a change in carbon monoxide concentration;
- Changes in leachate analysis –increase in the level

of nitrogen, pH, conductivity, heavy metals, Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), and ash (ATSDR, 2001).

Frequently, during the extinguishing of landfill fire, the machinery may fall into the excavation. Due to the increased layer pressure from the water used to extinguish fire, the overload of the edge of the excavation and displacement of the bottom of the excavation leads to unstable geodetic conditions. Early detection and extinguishing of landfill fire are of utmost importance for minimizing the costs.

4. Training program for landfill workers

As part of the training of landfill and utility company workers, the employer should inform the employees of all the facts and circumstances that affect or could affect the safety and health of workers (organization of work, risks, and manner of carrying out work procedures) (Ministry of Environmental Protection, 2010). During training, the worker needs to be educated and trained for the practical application of occupational safety measures that he is obliged to apply during work, in accordance with the assessment of the risks, which he/she is exposed to at work and in connection with work. Training of workers is carried out in accordance with the training program, which must be based on risk assessment, and must cover all the hazards and risks identified by the risk assessment and the ways of eliminating danger and damage (EU-OSHA, 2001). It should be emphasized that this specific type of profession, dealing with high-risk jobs, requires a legal basis for adequate education and training, as defined for many other public sector professions.

Training of employees in the field of H&S consists of theoretical and practical work. Training is conducted for the following jobs:

- Drivers of the mechanization;
- Workers at the landfill.

Theoretical training of employees for safe work is carried out through oral lectures, discussions with employees, and passing on instructions for safe work, and it consists of a general and special part. Testing of the theoretical knowledge is carried out after the completed training by filling out the tests in written form.

The general part of the training includes the basics of waste management, vocational training, proper and efficient work with the means and processes of work, professional development, legal obligations and rights in the field of H&S, fire protection, the basics of handling hazardous substances, the rights of employees and their obligations regarding H&S and the manner of exercising these rights, as well as the procedures in case of violation of the rules, the technological process of work and the working environment, risk assessment, organizing, and the method of providing first aid in the event of accidents and other situations which can affect large number of employees.

Practical training of employees for safe work is carried out by direct introduction of the work process to the employee at his/her workplace, the manner of safe use of equipment for work with special attention to possible failures and risks if the equipment is not used in accordance with the instructions for safe operation, and proper use of personal protective equipment.

The assessment of the time required for theoretical training of the employees is 360 min, and for performing the practical work examination is 240 min.

5. Recommendations for safe work at the landfill

The Solid Waste Association of North America (SWANA) is dealing with HSE issues at landfills, and have tips/recommendations for landfill workers. The occupational health and safety education and training is one of the main priorities of SWANA, since it is revealed that thousands of employees in solid waste sector receive injuries each year (SWANA, 1988).

Recommendations for Landfill managers:

1. Develop a traffic control plan that can be used to monitor the movement of workers on the road, working machinery at the landfill, and garbage trucks;
2. Implant a policy that requires truck drivers to remain in the cabin during unloading;
3. Install additional safety devices on working machines that would alert drivers when someone is in the "dead corner";
4. Require that all employees at the landfill carry high visibility safety vests and all accompanying personal protective equipment.

Drivers often work in an unsafe manner, due to ignorance or other reasons, endangering themselves, as well as other people in the vicinity. This risk can be significantly reduced by appropriate work planning. In order to reduce the risk of possible incidents the recommendations are as follows:

1. Vehicles must be technically sound and equipped in accordance with existing regulations;
2. The work machine at the landfill must be handled by a person who is authorized to work with the machine and who has a medical certificate;
3. The machine driver/operator must comply with the manufacturer's technical instructions for safe working;
4. The driver/operator must have the skills and patience;
5. The driver/operator must be ready to react to

unexpected situations and be able to make quick decisions;
6. The driver/operator of heavy machinery should be aware at any moment of where other vehicles and workers at the landfill are located;
7. The driver must turn on the handbrake before exiting the vehicle;
8. The driver should be familiar with the specific waste streams at the landfill;
9. The driver should know which paths should be avoided due to the flow of process waters;
10. The driver/operator should wear the personal protective equipment at all times;
11. Workers should not stand outside of the cabin of a vehicle moving more than 10 km/h (NIOSH, 1998).

6. Conclusion

After the professional training, employees at the landfill are trained for safe work, as well as for better efficiency at work. Employees are able to recognize specific risks at their workplace, as well as to reduce health risks and more effectively fulfill their work assignments. Companies that provide safety and health training to their employees will benefit directly through a reduced number of injuries, which leads to a reduction in the cost of medical treatment and financial compensations for potential health and safety issues.

Education and training on H&S also imply harmonization with H&S legislation, and companies avoid penalties prescribed in legal acts for this type of offense. A special benefit for companies is the efficiency of employees, given that besides H&S training, employees are also provided with professional training which leads to better and more efficient skills. In this sense, the work process must be adapted to the physical and mental abilities of the employee. Working environment, tools for work and the personal protective equipment must be developed and manufactured so that they do not endanger the safety and health of the employee.

This paper offer perspectives for the future work of presenting the direct and indirect costs of providing such an education. This remains an open issue for further research.

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Profesionalna edukacija radnika na deponiji u cilju zaštite od povreda i oštećenja zdravlja

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Industrial waste materials as raw materials for the production of low heat hydration cement

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ABSTRACT

It has long been known that certain industrial waste can be used as a raw material or additive in the production of cement. European standards define waste materials that can be used as additives in the production of cement, which are, in particular, fly ash from thermal power plants, granulated blast furnace slag, silica fume, etc. In Bosnia and Herzegovina, there are certain energy and industrial plants that produce such waste materials, which are mostly deposited on open landfills. Such disposal of waste results in contamination of water, soil, and air. Therefore, the aim of this paper was to conduct a preliminary examination of the possibilities of increasing use of industrial materials (fly ash from TPP Kakanj and granulated blast furnace slag of ironworks ArcelorMittal Zenica). The basic parameter that is followed in the work is the heat hydration of cement with different percentages of the addition of industrial waste materials.

1. Introduction

1.1. General information about cement

Construction cannot be imagined without the key inorganic mineral binder - cement, which is used to prepare mortars and concrete, the leading building materials. Thus, cement production can be a measure of both the economic situation and the development of individual countries. Annual cement production in the world has reached an incredible figure of 4.18 billion tons in 2016. In order to have an image of the increase in the annual world production of cement, it is sufficient to know that in 1990, "only" 1.1 billion tons of cement were produced, which means that for 26 years, in the period of 1990-2016, cement production increased almost fourfold. By 2030, cement production is expected to reach 4.8 billion tons of cement per year (Bušatlić and Bušatlić, 2018).

Cement is a hydraulic mineral binder that mixed with water solidifies, both in the air and in the water. The cement production process consists of two stages. The first stage is sintering of limestone and clay in a mass ratio of 3:1, at a temperature of about 1450 °C, when Portland cement clinker is obtained. After that, during the second stage, the obtained Portland cement clinker is milled and mixed with raw gypsum and possibly with other additives that improve its physical and mechanical properties.

1.2. Industrial waste materials as additives to cement

As additives in the cement production, natural and artificial pozzolans are used. Natural pozzolans are volcanic tufts, aluminate and high silicon, amorphous SiO_2 such as diatomite, and trass. Artificial pozzolans are blast furnace slag, fly ash from thermal power plants, silica fume etc. Pozzolans in the cement production are

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used as the correction components of the raw material mixture for the cement production, and as additives to the milled cement clinker when their properties of latent hydraulic binders are used (Bušatlić, 2013).

Inorganic particles, present in fuel gases produced by combustion of coal in thermal power plants, are separated in electrostatic filters, resulting in a waste material known as fly ash. The fly ash, due to sudden cooling, retains the amorphous structure and as such has the pozzolanic properties. As a substitute for clinker, fly ash can be used up to 60 % by mass.

The characteristics of fly ash depend on the type of coal that burns and the combustion regime. Generally, the fly ash with a greater silica content is pozzolan, and if it prevails in calcium then it has latent hydraulic properties. Fly ash has been used as a mineral additive for cement since the 1930s and it can be used as a substitute material in cement for the purpose of environmental protection (Bušatlić, 2013).

Many research have shown that, when fly ash is used, in addition to economic advantages, cement-based composites with high strength and durability are obtained. Cement based concrete containing fly ash materials has a lower initial compressive strength.

Granulated blast furnace slag (GBS) is produced from molten blast furnace slag, which is obtained simultaneously with the iron as a byproduct (Lizarazo-Marriaga et al., 2011). By rapid cooling with water and air glassy granulated material with latent hydraulic properties is formed (Yoshitaka, 2015). It is used for cement, concrete, mortar and aggregates (grained stone of a certain size, e.g. sand, gravel). The above mentioned blast furnace slag that is obtained as a byproduct in iron production can replace up to 80 % of clinker in cement production. The molten slag is similar to the natural liquid lava. If it suddenly hardens, granulated blast furnace slag (GBS) becomes inorganic, glassy material. Glassy nature is responsible for its cement properties. The four basic components represented as oxides are CaO, SiO_2, Al_2O_3 and MgO. In addition, TiO_2 and MnO are also present and affect latent-hydraulic properties (Bušatlić, 2013).

1.3. Cement production and its influence on the environment

The process of cement production is highly energy intensive, and it is estimated that the energy makes up about 40-50 % of the production cost. This provides sufficient opportunities to reduce energy consumption, considering that many cement companies in developing countries consume more energy than the costs show for the developed countries. The theoretical consumption of heat energy for the production of one tonne of clinker is 1,700-1,800 MJ. The most modern cement production plants, which in addition to the rotary kiln have a multiphase cyclone pre-heater and a pre-calcinator, consume 3,000-3,300 MJ/tonne clinker of heat energy, while the outdated plants have consumed 6,000-6,500 MJ/tonne in a wet process (Bušatlić and Bušatlić, 2018).

Cement production is associated with the release of large amount of greenhouse gases, primarily CO_2. Countries that produce the largest quantities of cement, such as India and China, are blamed for increasing cement-related pollution. Cement production accounts for 5 % of the World's total CO_2 emissions in the atmosphere caused by human activity (Bušatlić and Bušatlić, 2018).

The concept of "green cement" was developed as a replacement for a current cement production methods. Green cement uses less natural raw materials, energy and water and appears as a substitute for Portland cement. Green cement is a cement that is produced with the lowest consumption of natural raw materials and fossil fuels, with the maximum use of industrial waste materials as a material for cement production and alternative fuels instead of fossil fuels. Research is ongoing on the development of innovative methods of green cement production in order to reduce and even eliminate emissions of gases that enhance the greenhouse effect and other toxic pollutants (Bušatlić and Bušatlić, 2018).

The basic ingredients of the Portland cement clinker are CaO (C), SiO_2 (S), Al_2O_3 (A) and Fe_2O_3 (F). The above mentioned compounds in cement do not appear as free, but they are always in the form of different complex compounds. In addition, some other ingredients are included in the composition of the cement (admixtures): Na_2O, K_2O, SO_2 (due to the presence of gypsum) as well as free CaO. These ingredients are generally harmful, but they are difficult to avoid because they usually incorporate basic raw materials that are never completely clean (Bušatlić, 2013).

At the sintering temperature, there are a number of chemical reactions from which the most important ones are those that lead to the formation of so called mineral clinker. Regarding the mineral composition of Portland cement, the following ratios are present:

- C_3S (alitte) 45 - 60 %
- C_2S (belitte) 20 - 30 %
- C_3A - 12 %
- C_4AF 10 - 20 %.

As can be seen, silicate minerals account for about 75 % of the total mass and their properties mostly determine the technical characteristics of Portland cement. However, other mineral components are also significant. For example, tricalcium aluminate (C_3A) is often a cause of sulphate corrosion of cement, and because of that in the cement which should be resistant to sulphate activity, the content of this mineral is limited to a maximum of 5 %. Mineral C_3S, on the other hand, has a very high heat of hydration, and thus so called low heat hydration cements tend to have the content of this component at the lowest possible level (Bušatlić, 2013).

1.4. Hydration of cement

Mixing cement with water results in a hydration reaction between cement constituents and water, i.e. hydration of cement. Hydration reactions of individual constituents affect one another and as a result a new chemical equilibrium in the liquid phase is established (Petrovski and Bušatlić, 2006).

All of this has a significant effect on the formation of hydration products. The hydration process of cement minerals is exothermic. The total heat of the cement hydration is equal to the sum of the heat developed during the hydration of certain clinker minerals (Merdić et al., 2012). The heat of hydration is not released at once, but gradually over a longer period of time. Low thermal conductivity of concrete prevents the radiation of heat from the interior of the concrete mass into the atmosphere, especially for large concrete structures such as dams, tunnels, bridges, massive foundations, piers, etc (Bušatlić and Karić, 2018). A large amount of heat released during hydration causes certain strain and formation of cavity and cracks in the cement composite which leads to reduced durability of the structure. With the formation of cavities and cracks, the path to the entry of chemical aggressive water into the concrete mass opens, which leads to the destruction of the entire structure even more rapidly, and which can be completed by demolition of the entire object.

Controlled heat of the cement hydration, which can be adjusted to mineral composition of cement, influences the formation of the hydration products and the density of the cement paste. The too low heat of the cement hydration results in very slow formation of hydration products (Karić, 2017).

Since cement is the only active thermal factor, i.e. the only component of the concrete that produces (releases) heat, by determining the heat of the cement hydration the amount of heat developed when the concrete is hardened, i.e. the temperatures to be reached during that process can be perceived.

Therefore, when constructing concrete structures of large masses, it is of crucial importance to know the characteristics of cement in terms of the heat of hydration or heat that these cements develop in the process of their hydration. Incorporating cement with unknown thermal properties can lead to the demolition of the entire building, due to the disturbed compactness of concrete under the influence of high heating of concrete masses and resulting cavities, cracks, and corrosive water penetrations.

2. Experimental part

At the beginning of the experiment, the chemical analysis of the starting materials was made. In the second part of the study it is examined the heat of hydration of ordinary Portland cement and cement with the addition of fly ash and addition of granulated blast furnace slag.

For the preparation of cement samples the following raw materials were used: cement clinker (produced in CF Kakanj), gypsum stone (Bistrica near Gornji Vakuf), fly ash (TPP Kakanj), and granulated blast furnace slag (ArcelorMittal Zenica).

2.1. Chemical analysis of the starting materials

In Table 1 are shown the results of the chemical analysis of the raw materials used for the preparation of cement samples examined by X-ray fluorescence method (XRF).

In the fly ash from the Thermal power plant Kakanj the highest mass percentage has SiO_2. However, according to BAS EN 197-1 it belongs to calcium ash (CaO content > 10 mass %), whereas according to the American standard ASTM C 618 it is classified as fly ash of class C, i.e. fly ash with high calcium content (CaO content between 5 and 40 mas %) generated by coal burning of lower quality.

Granulated blast furnace slag (ArcelorMittal Zenica) in its composition has the highest percentage of SiO_2 (41.86 %), and CaO (37.01 %).

2.2. Determination of hydration heat

The hydration heat of cement samples was determined according to the standard BAS EN 196-8, which describes the dissolution method for determining the heat of cement hydration using a calorimeter for dissolution (Figure 2).

The hydration heat was determined after 7 days of hydration, and is expressed in Joules per gram of cement.

Samples for determination of hydration heat were prepared by grinding in a laboratory ball mill to a specific surface area of about 3,000 cm^2/g (Figure 1).

Table 1
Chemical composition of materials

Material	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	Total (%)
Clinker	20.35	6.72	3.74	64.80	1.00	1.07	0.08	0.45	98.21
Gypsum	4.53	1.66	1.20	31.40	2.60	38.45			79.84
Fly ash	46.82	17.57	7.88	17.70	2.21	1.25	0.25	1.62	95.30
GBS	41.86	8.29	1.30	37.01	5.24	1.34			95.04

Figure 1. Laboratory ball mill

After grinding, the samples were sieved through a sieve of 1 mm. According to the standard BAS EN 196-8, the method for determining the heat of cement hydration consists of measuring the dissolution heat in a mixture of acids of unhydrated cement and cement hydrated under conditions prescribed by standard for a period of 7 days. The acidic mixture is obtained by adding 2.760 g of 40 % hydrofluoric acid to each 100.0 g of (2.00 ± 0.01) mol/l nitric acid, or 2.60 ml of hydrofluoric acid per 100.0 ml of nitric acid. The norm prescribed hydration conditions are:

- water/cement ratio 0.40,
- use of pure cement paste,
- curing the samples during the hydration process (until full 7 days after the preparation of the cement paste) at a constant temperature of (20 ± 0,2) °C.

Hydration heat *Hi* is obtained from the difference between the hydration heat of the nonhydrated cement, *Qa*, and the hydration heat of hydrated cement, *Qi*.

The calorimeter which is used for determination of the hydration heat consists of a dissolution vessel, a thermometer, a funnel, and a mixer (Figure 2).

Figure 2. Calorimeter

Four samples of cement were prepared for this examination. In the table 2 the cement mark and composition of the tested cement samples are shown, as well as specific masses and specific surface areas. As it can be seen from the table, the first reference cement sample (C) consisted only of clinker and gypsum.

To the second sample (CFA), 50 % of the fly ash was added to the cement in the grinding stage, while to the third sample (CBS) was also added, at the grinding stage, 50 % of the granulated blast furnace slag. To the fourth sample addition was made in the same way, 25 % of the fly ash and 25 % of the granulated blast furnace slag.

In the table 3 the heat of cement hydration (H_i) for all tested cement samples is given, and figure 3 shows the reliability diagram of cement hydration heat from cement content.

Table 2
Designations and composition of the cement samples

Cement mark	Cement mark according to BAS-EN 197-1	Mass content of individual components, (%)				Specific mass (g/cm^3)	Specific surface area (cm^2/g)
		Clinker	Gypsum	Fly ash	Granulated blast furnace slag		
C	CEM I	96	4	-	-	3.12	2,970
CFA	CEM IV/B-W	46	4	50	-	2.89	3,010
CBS	CEM III/A	46	4	-	50	2.85	2,950
CFABS	CEM V/A	46	4	25	25	2.87	3,090

Table 3
The hydration heat of cement samples

Cement mark	Hydration heat (J/g)
C	308.280
CFA	205.813
CBS	182.457
CFABS	204.736

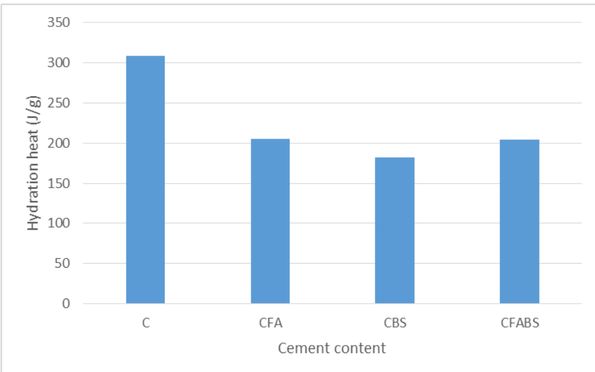

Figure 3. The reliability diagram of cement hydration heat from cement content

3. Discussion of results

Low heat hydration cements, according to the standard BAS EN 197-1, are cements that have hydration heat less than 270 J/g and their mark is LH (low heat), while cements of very low heat of hydration, according to this standard, are cements that have the hydration heat less than 220 J/g of and their mark is VLH (very low heat).

Based on the obtained results and in accordance with the above mentioned standard, the C cement sample, consisting of 96 % clinker and 4 % gypsum, cannot be used as low heat hydration cement.

Hydration heat of the other three cement samples, CFA, CBS, and CFABS, which besides clinker and gypsum consist of industrial waste materials, is less than 220 J/g, and these are cements of very low heat of hydration.

4. Conclusion

Based on the conducted examination, it can be concluded that the industrial waste materials, the fly ash from the Thermal power plant Kakanj and granulated blast furnace slag (ArcelorMittal Zenica), can be used for the production of low and very low heat hydration cement, which are used for the construction of large concrete structures such as dams, bridges, tunnels, massive foundations, piers, etc.

This way, a certain amount of these industrial waste materials can be used, instead of being deposited on a daily basis on the landfill, thus reducing soil pollution in and around the landfill, air pollution during transportation and disposal of the mentioned industrial waste materials, as well as the pollution of underground waters below and around the landfill.

By using the examined industrial waste materials, the use of cement clinker would be reduced, and in that way the emission of harmful gases (CO_2, SO_2, NOx) and the dust generated during the production of clinker would also be reduced.

Also, this would save a certain amount of energy consumed for the production of clinker, and thus the emission of harmful gases generated during the energy production would be reduced.

The subject of further research may be the examination of mechanical properties for the tested cement samples, such as flexural and compressive strength, as well as standard consistency, setting time, cement resistance to sulphate corrosion, etc.

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Korišćenje industrijskog otpada kao sirovine za dobijanje cementa niske toplote hidratacije

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I Z V O D

Odavno je poznata činjenica da određeni industrijski otpad može da se koristi kao sirovina ili aditiv u proizvodnji cementa. Evropskim standardima su definisani otpadni materijali koji se mogu koristiti kao adtivi u proizvodnji cementa, među kojima se nalaze leteći pepeo iz termoelektrana, granulisana visokopećna šljaka, silikatna prašina i drugi. U Bosni i Hercegovini postoje energetska i industrijska postrojenja koja dobijaju takav otpadni materijal koji se uglavnom odlaže na otvorenim deponijama. Odlaganje otpada na taj način dovodi do zagađenja vode, zemljišta i vazduha. Stoga, cilj ovog rada je bio da se izvrši preliminarno ispitivanje mogućnosti povećanja upotrebe industrijskog otpada (leteći pepeo iz Termoelektrane „Kakanj" i granulisana visokopećna šljaka iz kompanije za proizvodnju čelika ArcelorMittal iz Zenice). Osnovni parametar koji je ispitivan u radu je toplota hidratacije cementa koji sadrži industrijski otpad kao dodatak u različitim procentima.

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Technological characterization and utilization of recycled aggregate in the fine fraction in substitution to the fine natural aggregate for concrete production

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ABSTRACT

Civil Construction and Demolition Waste (CDW), after screening process, can go through benefication process which enables physical alterations obtaining samples with different granulometry. X-ray diffraction tests were performed in order to identify the mineral components present in the samples. The Scanning Electron Microscopy (SEM) analyzes showed that the samples had rough surface texture with grains present in different formats. The chemical properties are the conditioning factor of the affinity between the aggregate and the binder, and can contribute to the early degradation of the structures. The analysis of physical and mechanical properties is important because, in addition to assessing mechanical strength performance, it also analyzes the performance of CDW concrete. The compression tests and modulus of elasticity of an aggregate are not easy to measure because the particles cannot be tested alone. Test bodies were produced with fractions of 10 %, 20 %, 30 %, 50 %, and 100 % RCD. As a result of the mechanical tests performed in these test bodies it was observed that the fractions with up to 30 % recycled aggregate obtained good compressive strength ranging from 33 MPa to 46 MPa, with modulus of elasticity varying from 24.96 GPA to 31.54 GPA. However, the same result was not obtained for the fractions that had above 50 % recycled aggregate in the concrete trait that had compressive strength ranging from 10.8 MPa to 15 MPa, with modulus of elasticity varying from 11.82 GPA to 14.45 GPA.

1. Introduction

Brazil is a country rich in natural resources, which over the years has accompanied the disorderly growth of its great centers and cities. Due to this vector, the civil construction sector stands out with the extremely intensive use of natural resources. The CDW or rubble as it is popularly called, is all material coming from constructions, reforms, repairs and demolitions of civil works and those resulting from the preparation and excavation of land. These residues after sorting can be benefited by physical changes, becoming differentiated granulometry. About 90 % of the CDWs have recycling potential and can be applied in several areas of construction. Each granulometry is useful in civil construction, therefore, the products generated after the comminution can be used, in general, as sub-bases and non-structural concretes, according to the norms in force for the use of these materials. This study analyzed the behavior of recycled aggregates of fine granulometry of

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4.8 mm > 150 µm, which were submitted to the technological characterization that verified the diversified mineral composition of the samples, before the preparation of the test specimens and the mechanical tests performed to evaluate the behavior of these aggregates in differentiated fractions in the concrete trait. The variations were 10 %, 20 %, 30 %, 50 %, and 100 % of recycled fine aggregate, replacing the natural sand in the original trace of the concrete with high strength initial cement.

2. Material and method

The material was collected after the primary comminution process carried out at the private company Help Rio Entulho e Reciclagem de Materiais LTDA. A 250 kg sample was collected and bagged after the beneficiation process. The tests were carried out with material of granulometry passing through the opening sieve ø ≤ 4.8 mm and that were retained in the opening sieve 150 µm. Samples underwent characterization tests by SEM analysis, XRD, followed by granulometric composition tests, tests of unit specific mass and content of pulverulent materials, in accordance with ABNT standards.

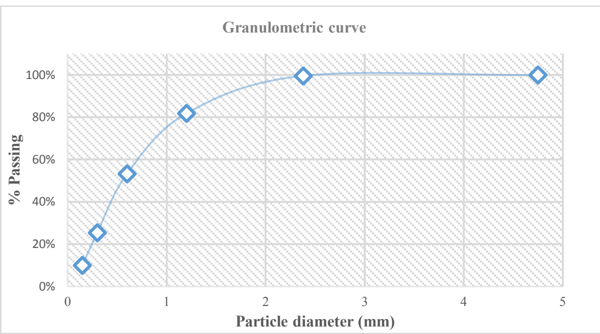

Figure 1. Representation of the granulometric curve of the CDW analyzed

The granulometric composition is based on the distribution of the particles of the granular materials in various dimensions. It is extremely important for a given choice of a viable aggregate because it exerts influence on important characteristics such as shrinkage, increased wear resistance, and changes in workability, costs, and mechanical strength. According to Carneiro et al. (2000), if sand has uniform granulometry, the shape of the grains does not influence, and yet the workability will be compromised. For Cabral (2007) the objective of determining the grain size was to establish the ideal composition that offers the highest possible compactness and also argues that the granulometry and the fine content influence the workability according to the cement dosage. Figure 1 shows the grain size curve of the analyzed material, and the particles are medium sized, with the maximum dimension of 2.38 mm.

Table 1
Composition of the CDW in the analyzed sample

Composition of the CDW sample			
	Sample 1	***Sample 2***	***average***
Rocks	28.43	26.89	27.66
Concrete	22.24	21.47	21.855
Mortar	12.8	16.6	14.7
Ceramic material	20.66	22.57	21.615
Gypsum plaster	4.3	3.2	3.75
Soil	7.9	5.02	6.46

The CDW was added to a predefined concrete trace. The same trait was used for the production of all test bodies used in this study, and only the percentage of fine aggregates underwent changes. After the curing time of the concrete the samples were submitted to tests of resistance to axial compression and modulus of elasticity.

3. Results and discussions

3.1. X-Ray diffraction analysis and scanning electron microscopy - SEM

The analysis of the X-ray diffraction samples of the recycled aggregate in the fine fraction is complicated due to the degree of heterogeneity. According to Figure 2 the presence of gypsum that is a component of Portland cement can be verified. Cabral et al. (2009) observed that the CDW sample in their study was composed mainly of quartz, muscovite, and manganite. According to Sinisterra (2014) the presence of quartz and calcite confirms that they have minerals characteristic of the composition of the limestone aggregates. The kaolinite is also present in the samples of this study and it was characterized by Sinisterra (2014) as clay that may be related to impurities during the

Table 2
Experiments and granulometric fractions

Material	%	Reference	10 %	20 %	30 %	50 %	100 %
Large aggregate	kg/m³	5.90	5.90	5.90	5.90	5.90	5.90
SAND	kg/m³	15.06	14.75	12.05	10.54	7.53	0.00
CDW	kg/m³	0.00	1.51	3.01	4.52	7.53	15.06
Cement	kg/m³	4.32	4.32	4.32	4.32	4.32	4.32
Water	kg/m³	2.13	2.13	2.13	2.13	2.13	2.13
Superplasticizer	g	43.2	43.2	43.2	43.2	43.2	43.2

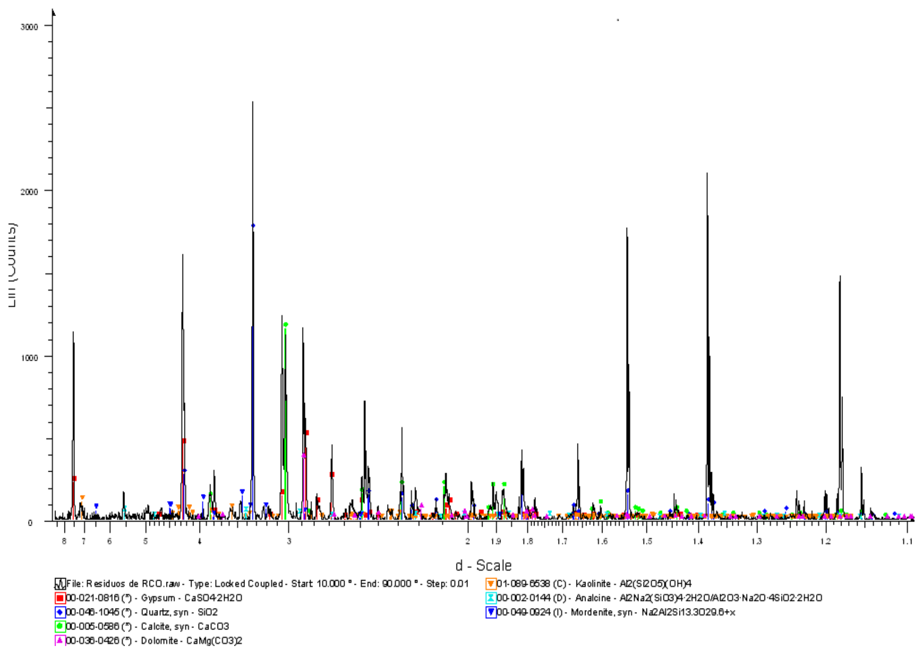

Figure 2. XRD analysis

production process of the aggregates, but may also be constituents of the aggregate of limestone itself. Silva (2014) observed in his study that the mineralogical composition of the CDW confirmed the presence of quartz (SiO_2), calcite ($CaCO_3$), calcium (Na, Ca) (Si, Al)$_4$O$_8$, and magnetite (Fe_3O_4).

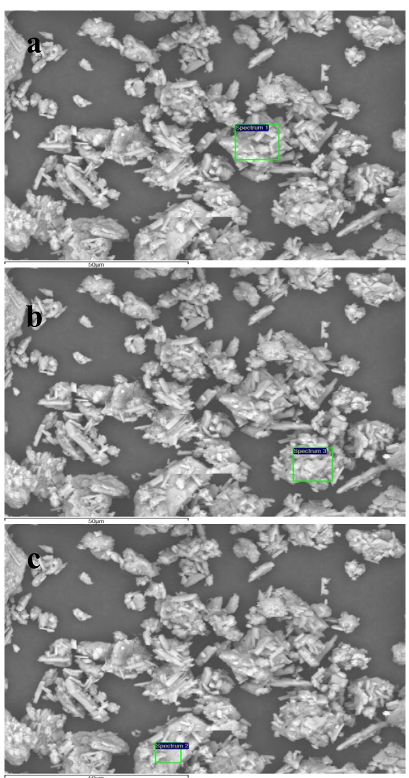

Figure 3. Analyze SEM of the sample

Araújo et al. (2016) pointed out in their study that Lima (1999), which included the physical and chemical variables common to different types of recycled aggregates, and the specific rules and rules for each of them, established a quality standard in the application of these wastes. To obtain a chemical sample of the samples analyzed in this study, it was necessary to submit them, not only to XRD, but to SEM analysis as well.

3.2. Compressive strength tests

Compressive tests and modulus of elasticity of an aggregate are not easy to measure because of the difficulty in testing the particles alone. Nematzadeh et al. (2012) evaluated that the compression test is one of the most important mechanical properties in the characterization of concrete quality. First, compression tests and modulus of elasticity were performed on the test specimens with 100 % and 50 % of fine recycled aggregate, and 100 % of natural aggregate, which was used like reference test specimen. Second, the sequence of compression tests and modulus of elasticity test bodies were tested with fractions of 10 %, 20 %, and 30 % of recycled aggregates, and the tests were repeated in order to establish the final results.

The results show that the mechanical properties of concrete are more affected by the presence of large recycled aggregate fractions than by the small recycled aggregate fractions, which may justify the satisfactory performance of concrete with up to 30 % CDW tested in this research contrary to what Behnood et al. (2015) concluded that concrete with recycled aggregates should have compressive strength up to 25 % lower when

Table 3
Results of mechanical tests

Samples	Force (KN)	Strength (MPa)	Deformation Máxima (με)	Modules of Elasticity (GPa)
CP 10 %	363.03	46.22 ± 0.53	2699.60	31.54
CP 20 %	328.94	41.88 ± 1.9	1996.86	29.31
CP 30 %	262.86	33.47 ± 0.85	3290.64	24.96
CP 50 %	123.12	15.69 ± 2.7	2144.43	14.45
CP 100 %	84.8	10.8 ± 0.82	4173.78	11.82
Reference	276.21	37.46 ± 4.5	3265.1	29.64

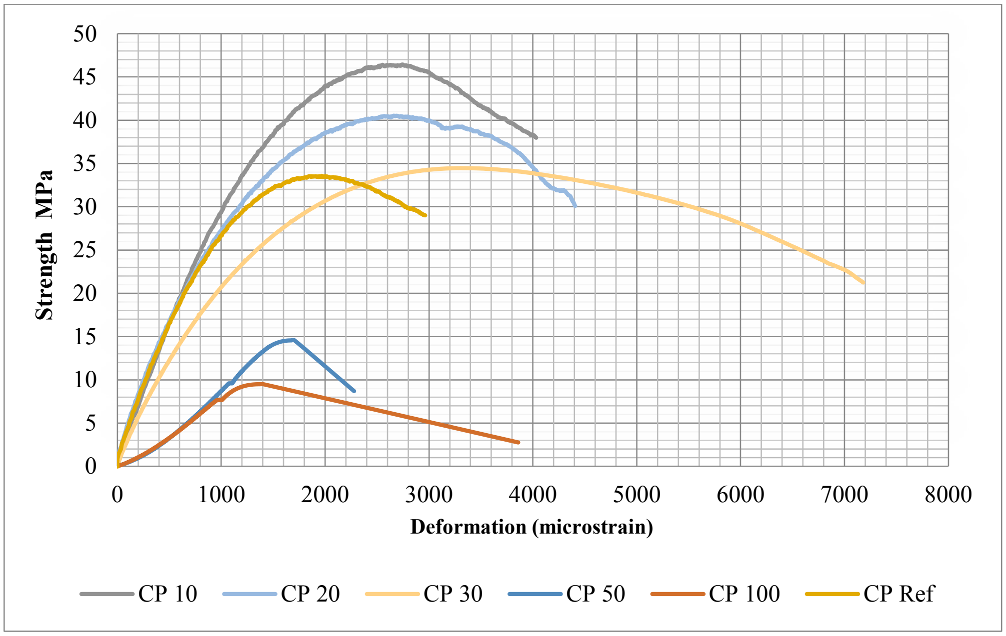

Figure 4. Results of the compression tests of the specimens

compared to concrete with natural aggregates. This lower performance was observed only in traces with fractions with 50 % CDW. In contrast, Pepe et al. (2016) evaluated that the limited use of the recycled aggregate in the structural concrete had insignificant consequences on technological aspects. This observation of the credibility of the results of compressive strength superior to the natural aggregate concrete presented by the concrete with and the results obtained in their research of Cabral et al. (2009), determined that the substitution of the natural fine aggregate for the fine recycled aggregate results in an increase in the compressive strength of the concretes produced, the same result was observed with the substitution of the coarse natural fraction for the coarse recycled fraction. The curves related to the compression tests can be observed in Figure 4.

3.3. Modulus of elasticity tests

Modulus of elasticity is an expression that determines stiffness, and the larger the modulus of elasticity, the more rigid the material (Tanaka et al, 2010). Nematzadeh et al. (2012) defined modulus of elasticity as one of the most important elastic properties of concrete from the point of view of the design and behavior of structures that is often expressed in terms of the compressive strength. For Liu et al. (2014), in addition to being important from the point of view of the design and behavior of structures, the modulus of elasticity is the parameter determined by the structural evaluation and adaptation of structures, also used to estimate structural deviations and to calculate deformation and seismic analysis.

Behnood et al. (2015) pointed out that concrete with CDW fractions must have modulus of elasticity reduced by up to 45 % when compared to concrete with natural aggregates. The author credits that these consequences are due to the fact that the recycled aggregate has a high absorption content of water and lower density besides having the presence of residual mortar on the surfaces of the particles.

According to the graphs presented above, we can point out that Behnood et al. (2015), are correct when they say that the modulus of elasticity of the concrete with CDW reduces abruptly when compared with the concrete with natural aggregates. However, the test specimens of this study with up to 10 % CDW had higher modulus of elasticity than that of the reference specimens, and the specimens with 20 % CDW showed elasticity moduli very close to the specimens which leads us to a conclusion that the presence of up to 20 % CDW does not significantly alter important mechanical properties such as modulus of elasticity and compressive strength. Although the specimens with 30 % CDW showed a lower modulus of elasticity compared to the reference specimens, the difference between the means was not discrepant.

Araújo et al. (2016) stated in their study that the modulus of elasticity was influenced by the substitution of the natural aggregate by the gross recycled aggregate, presenting a mean reduction of 6 % to 12 % in relation to the reference trait. The mean modulus of elasticity reduction presented in this study was higher than 12 % in relation to CP-50 and CP-100, as shown in Figure 5.

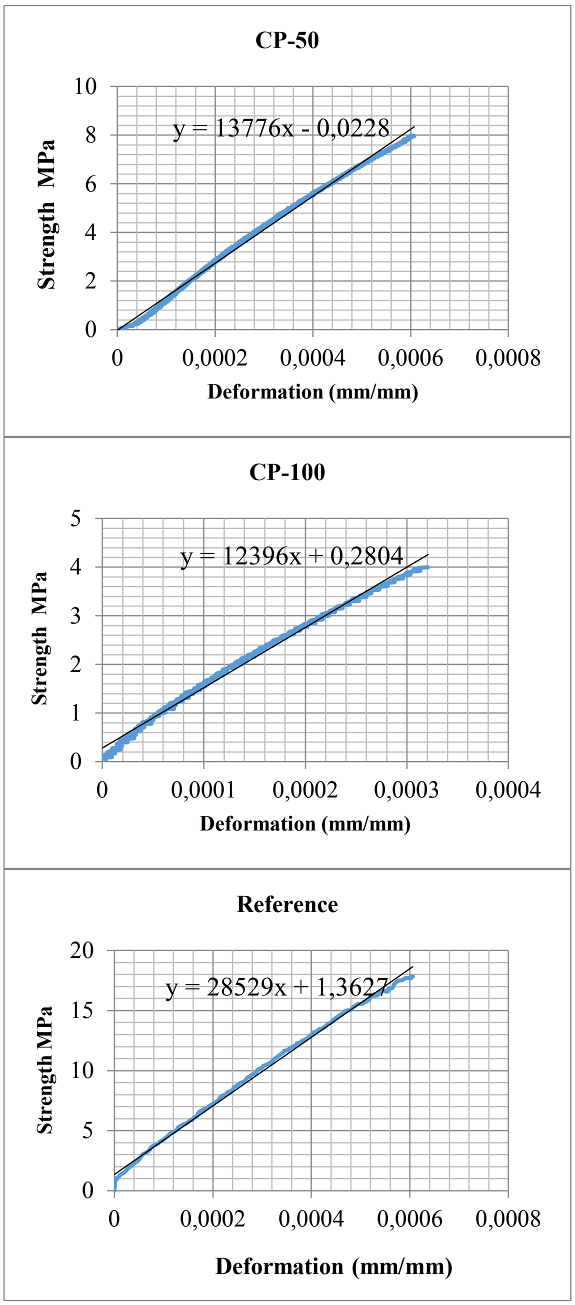

Figure 5. Graph of the modulus of elasticity

4. Conclusions

Recycling of construction waste is essential, either by adjusting the cost of general construction for large companies or preserving the environment. The fact is that it is no longer possible to coexist with these wastes and not take real steps to minimize their impacts.

This work characterized a lot of RCD and analyzed the behavior of the concrete with fractions of 10 %, 20 %, 30 %, 50 %, and 100 % of these recycled aggregates in the fine fraction. The fractions of 10 %, 20 %, and 30 % presented satisfactory behavior, taking into account the reference concrete. The concrete with these fractions of recycled aggregates presented high compressive strength, breaking with standard deformity and did not show a sudden rupture, after reaching the maximum point the compression process continued, they spread without breaking, that is, after the rupture crack was not abrupt, presenting characteristics of ductile material.

For concrete containing 50 % and 100 % recycled waste fractions, the behavior was far from the other fractions and the reference concrete, meaning that the high content of clay and friable materials changed the behavior of the concrete when it had high fractions of CDW.

The results lead to the conclusion that concretes with low fractions of CDW can be used with structural function taking into account that the compressive strength is one of the most important characteristics in the concrete and that the concrete usually has resistance from 15 MPa for foundations and 20 MPa, 30 MPa, 35 MPa, 40 MPa, and 50 MPa for structural concrete. This leads to a conclusion that the presence of up to 30 % CDW influences, but does not drastically reduce either the modulus of elasticity or the compressive strength of the concrete.

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Tehnološka karakterizacija i upotreba recikliranog agregata dobijenog finom frakcijom umesto prirodnog agregata u proizvodnji betona

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I Z V O D

Otpad od građevinskih konstrukcija i ruševina nakon procesa prosejavanja, može proći kroz postupak oplemenjivanja koje omogućava fizičke promene i dobijanje agregata različite granulometrije. Rendgenska difrakciona ispitivanja su izvršena da bi se odredili mineralni sastojci prisutni u uzorcima. Analize skenirajućim elektronskim mikroskopom (SEM) su pokazale da uzorci imaju grubu površinsku teksturu sa zrnima prisutnim u različitim oblicima. Hemijska svojstva predstavljaju bitan faktor za sposobnost sjedinjavanja agregata i veziva, a isto tako mogu doprineti ranoj degradaciji struktura. Analiza fizičkih i mehaničkih osobina je važna ne samo zbog procene svojstva mehaničke snage, već i zbog analize svojstva betona koji sadrži reciklirani agregat. Ispitivanje na pritisak i određivanje modula elastičnosti agregata nije lako izmeriti zato što se same čestiče ne mogu testirati. Dobijeni uzorci su sadržali 10 %, 20 %, 30 %, 50 % i 100 % recikliranog agregata. Kao rezultat mehaničkih ispitivanja izvedenih na ovim uzorcima, primećeno je da su frakcije koje su sadržale 30 % recikliranog agregata imale dobru pritisnu čvrstoću koja je iznosila između 33 MPa i 46 MPa, a modul elastičnosti je iznosio između 24,96 GPA i 31,54 GPA. Međutim, isti rezultat nije dobijen za frakcije koje su sadržale 50 % recikliranog agregata, gde je pritisna čvrstoća iznosila između 10,8 MPa i 15 MPa, a modul elastičnosti je iznosio između 11,82 GPA i 14,45 GPA.

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

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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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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.

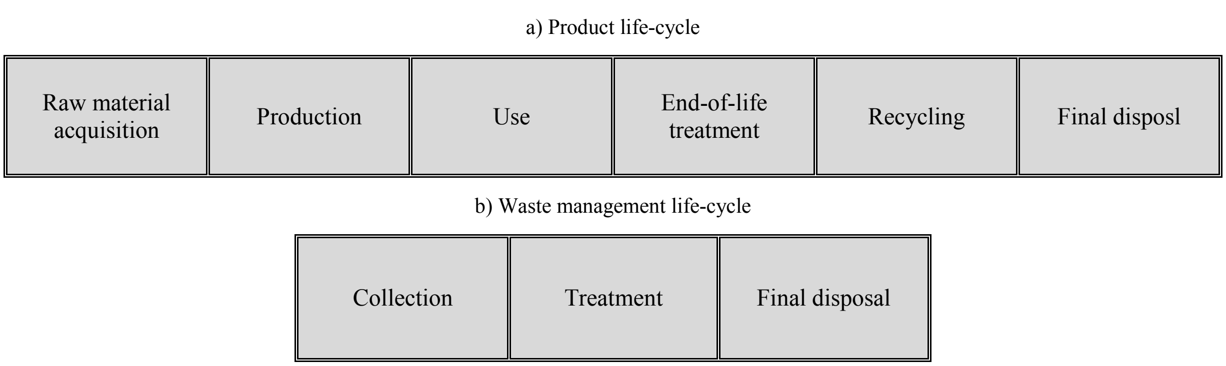

Figure 1. Product life-cycle stages (Figure a.) and waste life-cycle stages (Figure b.) (Merrild, 2009)

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.

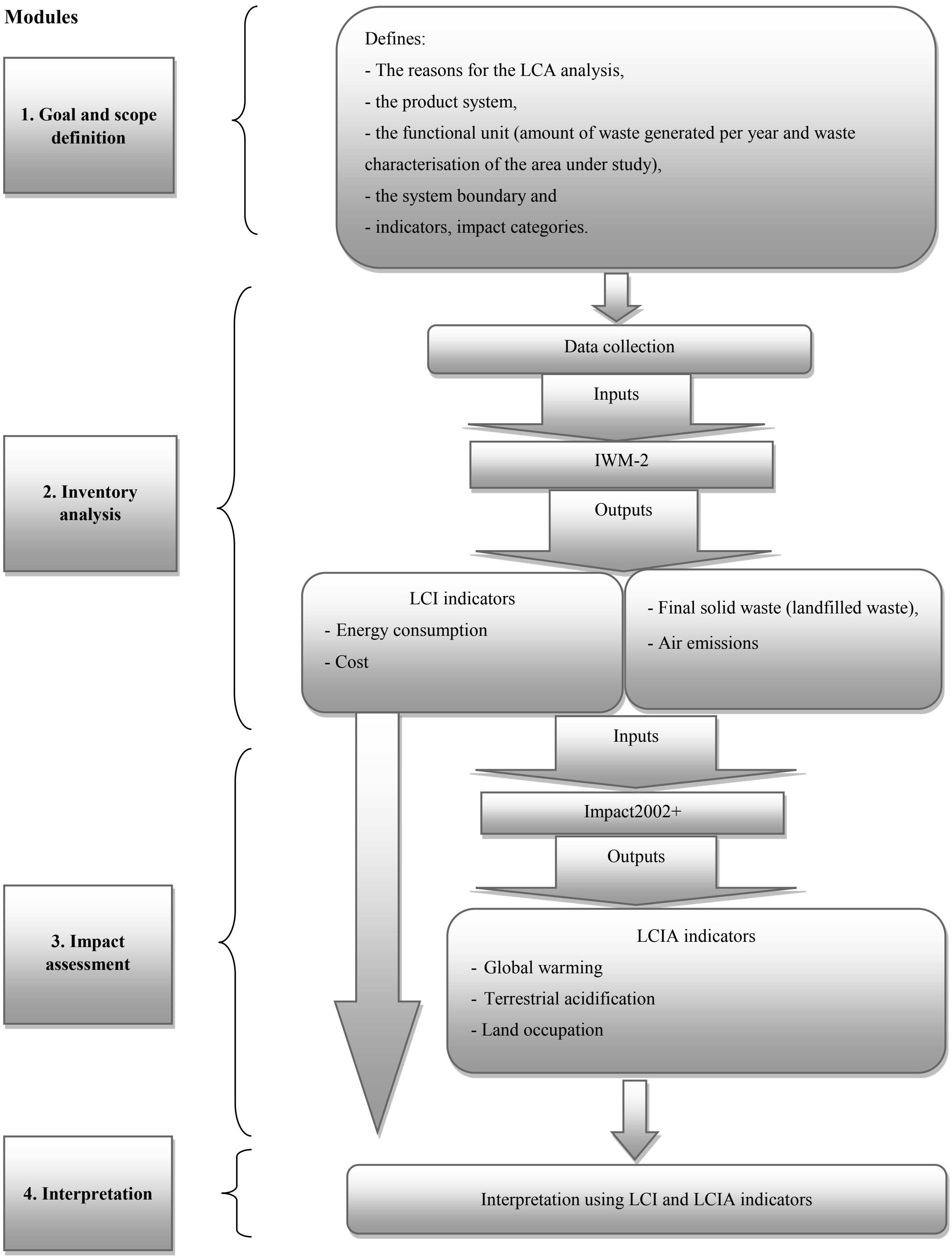

Figure 2. Modular structures of the model for evaluation of municipal waste management system using the method of life cycle assessment

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-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-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-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 $m^2 \cdot$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.

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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

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Pregledni rad

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

I Z V O D

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.

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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

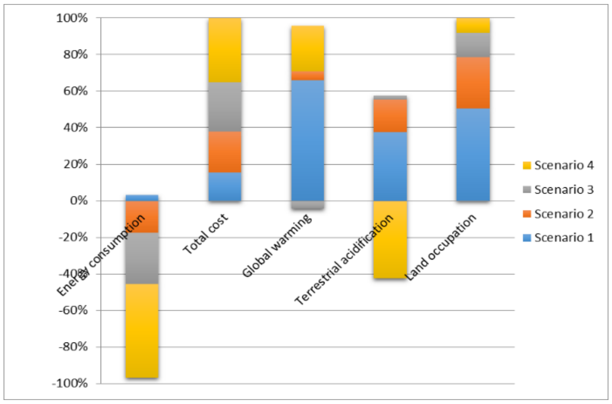

Figure 1. Comparison of scenarios

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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INFORMACIJE O RADU

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

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.

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Effect of SiO_2, Al_2O_3 and Na_2O content and fly ash fineness on the structure and mechanical properties of fly ash based geopolymer

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ABSTRACT

Nowadays, the geopolymer technologies using secondary raw materials are more and more widespread; however, some of them (for example fly ash) have originally low reactivity which can be tailored by a mechanical or chemical activation, or by the addition of various high reactive materials. This study investigates the effect of silica, alumina, and sodium oxide contents on the structure and mechanical properties of high calcium fly ash based geopolymers. Metakaolin (MK) was used as an additional alumina and silica source. It was added at various dosages (0; 5; 10; 15; 25; 50 and 75 % by weight) as a replacement of the fly ash (FA). The experimental results confirm that the compressive strength of the geopolymer is greatly affected by the SiO_2/Al_2O_3, Al_2O_3/Na_2O, and SiO_2/Na_2O ratio. The addition of MK improved the compressive strength of geopolymer by 92 %. In addition, the effect of mechanical activation of FA on the structure and strength of the geopolymer was investigated in case of a given MK content. Based on the results it can be stated that the mechanically activated FA resulted in higher compressive strength. The addition of MK and the fineness of FA changed the structure of geopolymers, which was detected using FT-IR spectroscopy method.

1. Introduction

Geopolymers are three-dimensional amorphous-to-semi-crystalline aluminosilicate materials (Davidovits, 1989), which can be produced from natural/synthetic aluminosilicate minerals or industrial aluminosilicate byproducts (for example fly ash, red mud, slag, metakaolin, perlite, glass, rice husk ash, clay, or a combination of them) mixed with an alkaline (potassium/sodium hydroxide, potassium/sodium silicate) or acidic solution (phosphoric acid) (Palomo et al., 1999; Komintsas and Zaharaki, 2007; Vaou and Panias, 2010; Mucsi et al., 2014; Tchakoute et al., 2017; Singh et al., 2018). Geopolymers possess good physical-chemical and mechanical properties like relative high strength, fire and chemical resistance, and thermal stability. Due to these properties geopolymers give an opportunity to replace conventional structural materials in the fields like road construction and building industry, metallurgy, mining industry, and high-tech industry (Davidovits, 2002). The properties of geopolymers are affected by the composition and reactivity of the material (Kumar et al., 2017; Singh et al., 2018), the composition of the activator solution (Fernandez-Jimenez and Palomo, 2005; Molnár et al., 2017; Tchakoute et al., 2017; Cheng et al., 2018; Singh et al., 2018), the curing condition (treatment temperature and time) (Palomo et al., 1999; Molnár et al., 2017), and the compression method (especially vibrating compaction or high-pressure compaction) (Wallah and Rangan, 2006; Živica et al., 2011). The alkaline solution

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plays an important role in dissolving Si and Al atoms to form geopolymer precursors and aluminosilicate material. The mechanical properties and microstructure of geopolymer are affected by the molar ratio of SiO_2/Al_2O_3.

Chindaprasirt et al. (2012) studied the effect of silica and alumina contents on setting, phase development, and physical properties of high calcium fly ash based geopolymers. The control of setting and hardening properties were investigated by changing SiO_2/Al_2O_3 ratio of the starting mix. SiO_2/Al_2O_3 content of the mixtures were changed in the range 2.87-4.79. They found that the increases in either silica or alumina content shortened the setting time of high calcium-based systems.

Chen et al. (2018) investigated the effect of sodium polyacrylate (as organic polymer) on the mechanical properties and microstructure of metakaolin-based geopolymer with different SiO_2/Al_2O_3 ratio (2.0-4.0). They found that the toughening effect of organic polymer on geopolymer depended on the SiO_2/Al_2O_3 ratio of geopolymer, and the geopolymer with lower SiO_2/Al_2O_3 ratio (no more than 2.5) can be significantly toughening modified by organic polymer.

He et al. (2016) investigated the effect of Si/Al ratio on the structure, mechanical properties and chemical stability of metakaolin based geopolymers. Geopolymers with Si/Al ratios of 2 and 2.5 showed similar structure and property and geopolymers with Si/Al ratios of 3, 3.5 and 4 were similar. Geopolymers with Si/Al of 4 showed much higher mechanical properties than geopolymers with Si/Al of 2, which was due to the increased Si-O-Si bonds and residual silica as reinforcement. However, geopolymers with Si/Al $\geq$ 3 showed worse chemical stability than those with Si/Al $\leq$ 2.5, with the presence of efflorescence on the surface, which was attributed to their higher residual free K^+.

Several studies (Criado et al., 2007; Silva and Crenstil, 2008; Vargas et al., 2011; Tchakoute et al., 2013; Bignozzi et al., 2014; Gao et al., 2014; Khedmati et al., 2018) have reported that, in addition to SiO_2/Al_2O_3 molar ratio, the Na_2O/SiO_2 and Al_2O_3/Na_2O ratios also play an important role in the morphological, microstructural, and mechanical properties of fly ash based geopolymer.

Vargas et al. (2011) investigated the influence of different Na_2O/SiO_2 molar ratio, curing temperature and age on the mechanical and microstructural properties of fly ash based geopolymers. The results showed that the Na_2O/SiO_2 ratio played an important role in the mechanical and morphological characteristics of geopolymers. Geopolymer with higher Na_2O/SiO_2 ratio showed higher compressive strength and more compact structure.

Khedmati et al. (2018) received similar results. They found that the higher Na_2O/SiO_2 molar ratio showed more N-A-S-H (sodium aluminosilicate hydrate) gel formation, which increased the bonding strength between the geopolymer binder and the aggregate.

Tchakoute et al. (2013) investigated the effect of Al_2O_3/Na_2O molar ratio of soda-volcanic ash. Based on the results, they found that the optimal Al_2O_3/Na_2O molar ratio of volcanic ash to produce geopolymer mortars ranged between 0.13 and 0.18.

The aim of the present research reported in this paper is primarily to study the effect of SiO_2, Al_2O_3 and Na_2O contents on the structure of geopolymer and to examine the relation among silica, alumina and sodium oxide content and geopolymer compressive strength. The additional goal was to investigate the dependence of strength on the fly ash fineness.

2. Material and methods

For the experiments FA from the lignite burned power plant (Visonta, Hungary) and MK (IMERYS Ltd.) were used as solid. FA was replaced with MK in various amounts (0; 5; 10; 15; 25, 50 and 75 wt %) in the solid part. The mixture of sodium-hydroxide (8 M) and sodium-silicate (waterglass) solutions was applied as alkaline activator. NaOH solution was prepared by dissolving sodium hydroxide pellets with a purity of 99 % in distilled water. The chemical composition of the sodium silicate solution was as following: 25.3 % SiO_2, 13.7 % Na_2O, 2.7 % K_2O of and 58.3 % H_2O.

The particle size distribution of the raw materials and the ground FAs was measured by HORIBA LA-950V2 laser diffraction particle size analyzer in wet mode using distilled water as dispersing media and sodium-pyrophosphate as dispersing agent, applying the Mie-theory as evaluation method. The geometric (outer) specific surface area (SSA) was calculated using PSD data by the laser sizer software, the shape factor was 1. The particle density (ρ_p) was determined by pycnometer method using alcohol as media. The chemical composition of FA and MK was determined using X-ray fluorescence spectroscopy analysis (XRF). The structure of raw materials and geopolymers was detected by Fourier Transform Infrared Spectroscopy (FT-IR) in reflection mode with diamond ATR. The main physical properties and chemical composition of FA and MK are found in Table 1 and Table 2.

Based on Table 2 it can be stated that the SiO_2 content of FA and MK was similar, but the Al_2O_3 content was rather different. The Al_2O_3 content in MK was three times higher than in FA. The Na_2O content was low in both materials (under 0.4 wt %), but in FA was higher than in MK.

Table 1
Physical properties of raw materials

	Fly ash	Metakaolin
particle density (g/cm^3)	1.93	2.73
x_{10} (μm)	10.8	1.8
x_{50} (μm)	52	5.2
x_{80} (μm)	119.3	8.5
SSA (cm^2/g)	1,152	11,307

Table 2
Chemical composition of starting materials

Component (wt %)	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	SO_3	L.o.I.*
Fly ash	48.1	14.42	11.76	10.97	3.34	0.37	1.66	0.492	0.264	0.171	0.575	2.2
Metakaolin	51.4	45.9	0.4	1.12	0.26	0.05	1.34	0.05	0.064	0.033	< 0.013	-

*L.o.I. = Loss on ignition (at 950 °C)

3. Experimental

The mechanical activation experiments of FA under dry condition were carried out in a conventional tumbling laboratory ball mill with the size of Ø305×305 mm (smooth walled), with steel balls (minimum and maximum ball size was 12 mm and 50 mm, respectively) as grinding media. The mill filling ratio of the grinding media was 30 volume %, the material filling ratio (compared to the pore volume among the grinding media) was 110 volume %. The operational revolution number to the critical revolution number was 80 %. The residence time of mechanical activation was 5, 10, 20, 30, 60, and 120 minutes.

As a first step, the raw or ground FA (and MK) and alkaline activator (mixture of 8 M NaOH and waterglass) were mixed together using 0.82 liquid/solid ratio (L/S ratio). Then the paste was placed to pre-oiled moulds and compacted by vibration for 1 minute. The compacted mixture was kept in moulds for 24 hours in sealed condition in a climate chamber at 23 °C, before removing the specimens. It was followed by heat curing at 30 °C for 6 hours. After the heat treatment, the specimens were stored in a climate chamber at 23 °C and 90 % relative humidity until the measurement of compressive strength. Five specimens of geopolymer were prepared in all cases for the strength investigations. The mechanical test was carried out by Compression Testing Machine for 7 days.

4. Results

4.1. Mechanical activation of FA

The effect of the grinding on the particle size and SSA of the raw and ground FA is summarized in Table 3. The 50 percent particle size (median) of the raw FA was 48.4 µm. During the grinding the particle size was significantly decreased and SSA increased. After 120 min grinding in a ball mill 8.4 µm median particle size was achieved from the initial value of 48.4 µm, indicating a 5.76 size reduction rate. Particles with smaller size than 1 µm also appeared in a significant amount (more than 10 %). Additionally, the "outer" specific surface area increase was significant; from 1,140.9 cm^2/g it reached 12,228.8 cm^2/g due to ball milling.

4.2. Effect of SiO_2/Al_2O_3, SiO_2/Na_2O and Al_2O_3/Na_2O molar ratios

The use of MK had a beneficial effect on the compressive strength of geopolymers. Based on the Figure 1, it can be seen that the increasing amount of MK in the solid part of mixture increased the geopolymer strength and density. Geopolymer with the highest strength and density was produced by 50 % MK content in the solid part. These values were 22.1 MPa and 1.61 g/cm^3. However, it is important to note that the increasing amount of MK reduced the workability of the mixture. It was not workable by 75 % MK content. In this case the fresh paste had a short setting time resulting in the paste quickly bound forming granules during the mixing.

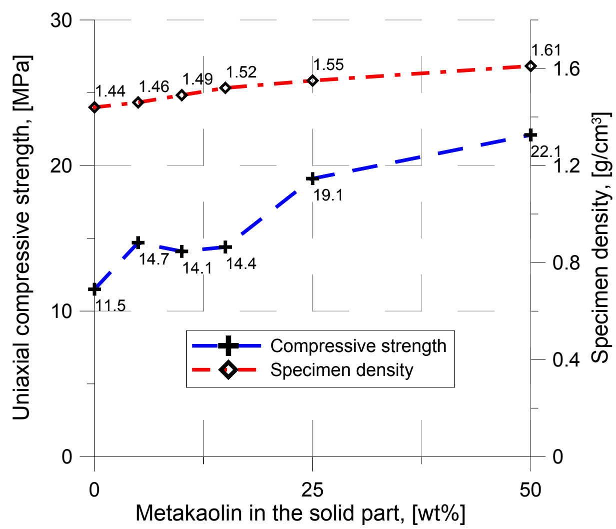

Figure 1. Effect of metakaolin dosage

The relation between the SiO_2/Al_2O_3 molar ratio of

Table 3
Characteristic particle size and SSA of FA after various grinding time

Material properties	Grinding time (min)						
	0	5	10	20	30	60	120
x_{10} (µm)	10.3	9.7	8.4	6.5	5.8	4	0.5
x_{50} (µm)	48.4	41.1	29.6	19.5	16.4	12.3	8.4
x_{80} (µm)	112.6	89.5	68.1	45.9	33.7	22.6	16.1
SSA (cm^2/g)	1,140.9	1,219.3	1,417.9	1,807.4	2,056.5	2,937.9	12,228.8

mixture and the compressive strength is shown in Figure 2. The SiO_2/Al_2O_3 ratio was changed in the range 3.67 and 7.49, which was modified with MK content in the solid part of mixture. The SiO_2/Al_2O_3 ratio decreased with the content of MK in solid part (due to higher Al_2O_3 content of MK). Based on Figure 2 it can be stated that increasing the SiO_2/Al_2O_3 ratio decreased the geopolymer strength. The figure shows that the maximum compressive strength (22.1 MPa) was obtained when SiO_2/Al_2O_3 was 3.67. Furthermore, it can be observed that the geopolymers had almost the same strength (14.1 - 14.7 MPa) between SiO_2/Al_2O_3 of 5.68 and 6.77.

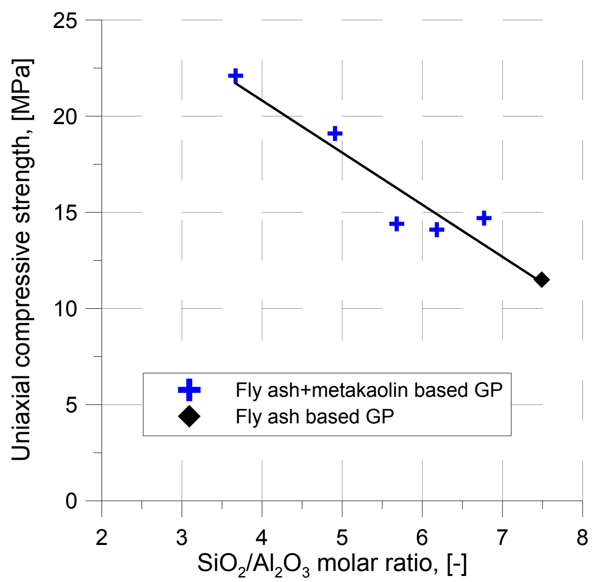

Figure 2. Effect of SiO_2/Al_2O_3 molar ratio

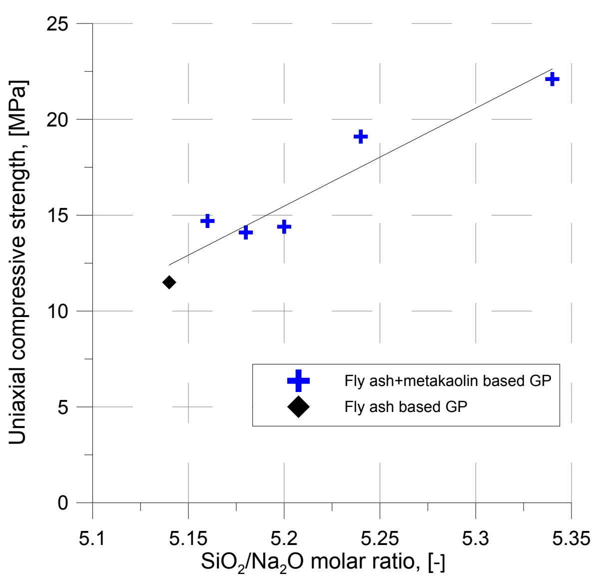

Figure 3. Effect of SiO_2/Na_2O molar ratio

Figure 3 shows the compressive strength of geopolymers at various SiO_2/Na_2O ratios. The ratio was changed in the range of 5.14 and 5.34. The results show that the strength of geopolymers increased with SiO_2/Na_2O. The highest compressive strength (22.1 MPa) was obtained when SiO_2/Na_2O was 5.34.

A similar conclusion can be drawn from Figure 4 as shown in Figure 3. Increasing Al_2O_3/Na_2O ratio increased the geopolymer strength. The ratio was changed in the range 0.69 - 1.45. Based on the result it can be stated that not only the SiO_2 content plays an important role in geopolymerization, but also the Al_2O_3 content.

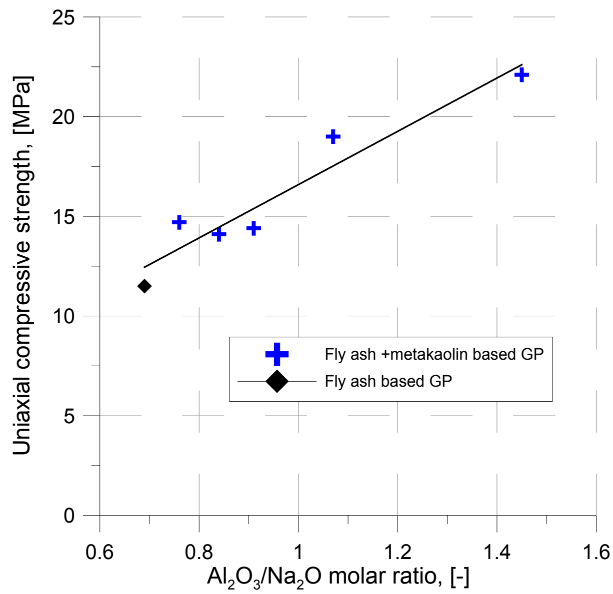

Figure 4. Effect of Al_2O_3 /Na_2O molar ratio

4.3 Effect of grinding fineness of FA

The effect of grinding fineness of FA was investigated by metakaolin content of 25 % taking into the workability of mixture. Based on Figure 5 it can be stated that increasing the grinding time (by changing of FA fineness) increased the density and the compressive strength of the geopolymers. While the raw FA based geopolymers (SSAFA=1,141 cm^2/g) had compressive strength of 19.1 MPa and specimen density of 1.54 g/cm^3, the geopolymers which were made using SSAFA of 12,229 cm^2/g (grinding time of 120 min) had compressive strength of 25.2 MPa and specimen density of 1.64 g/cm^3. As a result of the milling, the specific surface of the material was increased as well, resulting in more Al and Si solved by the alkaline solution from the FA, and it was advantageous for the emergence of the geopolymer gel. Another explanation of the increasing compressive strength (and specimen density) can be that the finer particles resulted in more compact microstructure.

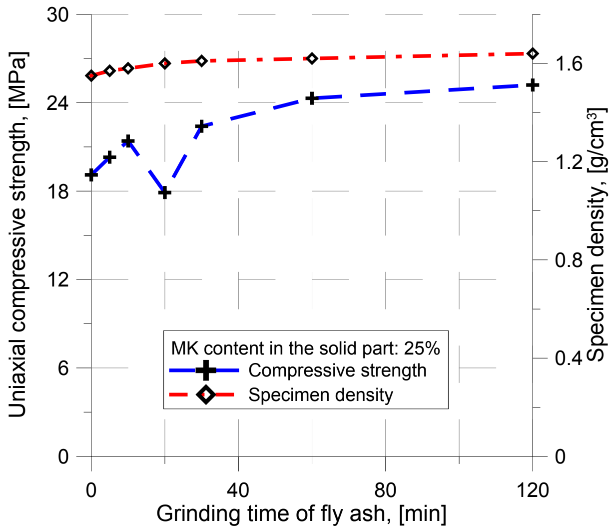

Figure 5. Effect of fineness of FA on the compressive strength and specimen density

4.4. FT-IR results

The FT-IR spectra of raw materials (FA and MK) can be seen in Figure 6. The IR spectrum of MK contains one very intense band characteristic of the internal vibrations in TO_4 tetrahedral (T=Al, Si). This peaks at around 1,064 cm^{-1}, and is associated with T-O-Si bond (T= Al, Si) asymmetric stretching vibrations. In case of FA this peak appeared at around 1,100-1,009 cm^{-1} in the form of a double band. At 800 cm^{-1}, a band appeared corresponding to Al-O bending of tetrahedral Al (Granizo et al., 2000). The peak at 1,457 cm^{-1} corresponds to O-C-O stretching vibration, symmetrical stretching vibrations of Si-O-Si and Al-O-Si bonds are observed at 677 and 598 cm^{-1} (Swanepoel and Strydom, 2002; Panias et al., 2007).

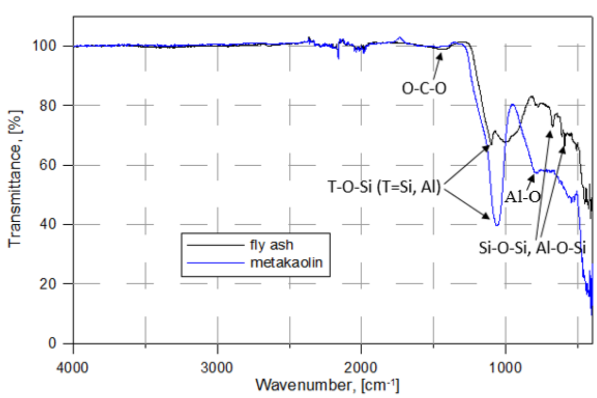

Figure 6. FT-IR spectra of raw materials

FT-IR spectra of geopolymers with various metakaolin content can be seen in Figure 7. The most characteristic difference was observed between the IR spectra of geopolymers and FA at the band of T-O-Si bonds. This band that appeared as a broad band between 1,100 and 1,009 cm^{-1} in the FT-IR spectrum of FA became sharper and shifted to lower wavenumber (~ 943 cm^{-1}) in the FT-IR spectrum of FA based geopolymer, indicating the formation of a new product (the amorphous aluminosilicate gel phase), which is associated with the dissolution of FA amorphous phase in the strong alkaline solution (Swanepoel and Strydom, 2002; Panias et al., 2007). This bond is often used to determine the degree of polymerization. This peak observed between 951 and 973 cm^{-1} in the FT-IR spectra of MK containing geopolymers. The peaks that were observed in IR spectra of FA and MK between 800 and 598 cm^{-1} disappeared after geopolymerization, which is associated with the dissolution of Al and Si in the NaOH solution.

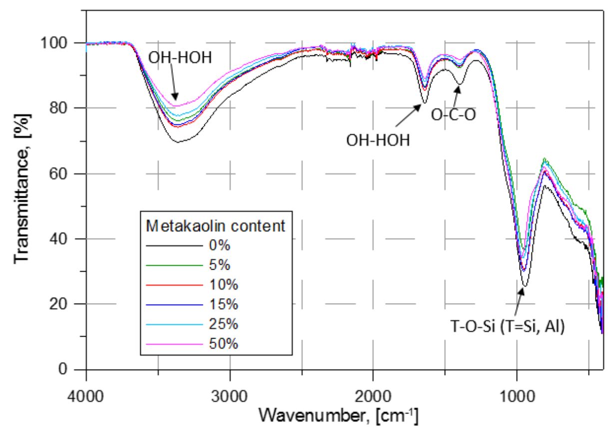

Figure 7. FT-IR spectra of geopolymers with different MK content

The broad bands which appeared in all FTIR spectra in the region of 3,370 and 1,640 cm^{-1} are assigned to stretching (-OH) and bending (H-O-H) vibrations of bound water molecules, that were either surface absorbed or caught in the structure cavities (Swanepoel and Strydom, 2002; Panias et al., 2007; Ozer and Soyer-Uzun, 2015). The intensity of these bands decreased by higher MK content, which could be correlated with higher mechanical strengths.

The peak observed at 1,457 cm^{-1} in case of FA shifted a lower wavenumber (approximately 1,400 cm^{-1}) in all the FTIR spectra of geopolymer, which are attributed to stretching vibrations of O-C-O bond. This band is related to carbonate formation because of alkali sodium hydroxide reacting with the atmospheric CO_2, which is diffused on the geopolymeric materials surface (Swanepoel and Strydom, 2002). The intensity of these bands decreased by higher metakaolin content, which could be correlated with increased mechanical strengths. It is associated with higher proportion of Na^+ ion built into the geopolymer structure.

Figure 8 shows FT-IR spectra of geopolymers with different fineness of FA and MK content of 25 %. Based on Figure 8 it can be stated that the spectrum of raw FA based geopolymer is separated from the other FT-IR spectra. In case of the ground FA based geopolymers, the peak intensities were higher than by the raw FA based geopolymer. It can be also observed that the different FA fineness did not cause a significant change in the structure of the geopolymers. The position and intensity of the absorption bands were almost the same.

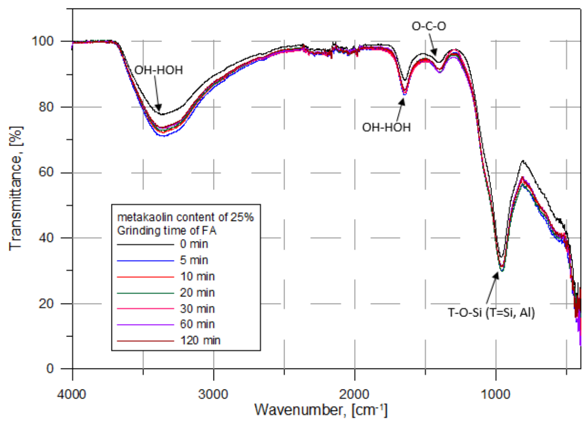

Figure 8. FT-IR spectra of geopolymers with different fineness of FA

5. Conclusions

In this work, the effects of SiO_2/Al_2O_3, SiO_2/Na_2O and Al_2O_3/Na_2O molar ratios and FA fineness on the structural and mechanical properties of geopolymers are studied and the following results are drawn:

- MK had a positive effect on the compressive strength of FA based geopolymers. Increasing the MK content improved the strength. Geopolymer with the highest strength (22.1 MPa) and density (1.61 g/cm^3) was made by 50 % MK content in the solid part.
- Higher MK content resulted in lower SiO_2/Al_2O_3 ratio of the mixture. There is a relationship between SiO_2/Al_2O_3 ratio and compressive strength. The lower SiO_2/Al_2O_3 molar ratio resulted in a higher compressive strength.
- The strength of geopolymers increased with SiO_2/Na_2O and Al_2O_3/Na_2O ratios. The highest compressive strength was obtained when SiO_2Na_2O was 5.34, and Al_2O_3/Na_2O was 1.45.
- Not only did the MK content significantly influence the strength of geopolymer, but also the FA fineness. The mechanical activation of FA enhanced the reactivity and consequently the properties of the resulted geopolymer, i.e. the compressive strength was improved and specimen density increased as well. Geopolymer with the highest compressive strength (25.2 MPa) was made using SSAFA of 12,229 cm^2/g (grinding time of 120 min).
- Based on the FT-IR results, it can be stated that the intensity of O-C-O bonds in IR spectra of geopolymers decreased by higher metakaolin content, which could be correlated with the increased mechanical strengths. The higher alumina content resulted in a higher degree of Na^+ incorporation into the geopolymer structure.
- FA fineness did not cause a significant change in the structure of the geopolymers. The position and intensity of the absorption bands were almost the same.

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Uticaj sadržaja SiO_2, Al_2O_3 i Na_2O i finoće letećeg pepela na strukturu i mehaničke osobine geopolimera na bazi lebdećeg pepela

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Al_2O_3/Na_2O molarni odnos

Proširena i recenzirana verzija rada - rad prezentovan na simpozijumu XIII IMPRC

I Z V O D

U današnje vreme, tehnologije geopolimera na bazi sekundarnih sirovina se sve više koriste. Međutim, neke od njih (na primer na bazi lebdećeg pepela) imaju na početku nisku reaktivnost koja se može promeniti mehaničkom ili hemijskom aktivacijom, kao i dodavanjem različitih visoko reaktivnih materijala. U ovom radu je ispitivan uticaj sadržaja silicijum, aluminjum i natrijum oksida na strukturu i mehaničke osobine geopolimera na bazi lebdećeg pepela sa visokim sadržajem kalcijuma. Metakaolin (MK) je korišćen kao dodatni izvor aluminijuma i silicijuma. Dodavan je u različitim dozama (0; 5; 10; 15; 25; 50 i 75 % mase) kao zamena za lebdeći pepeo. Rezultati eksperimenta potvrđuju da na pritisnu čvrstoću geopolimera značajno utiče odnos SiO_2/Al_2O_3, Al_2O_3/Na_2O i SiO_2/Na_2O. Dodavanje metakaolina je povećalo pritisnu čvrstoću geopolimera za 92 %. Osim toga, ispitivan je i uticaj mehaničke aktivacije lebdećeg pepela na strukturu i čvrstoću geopolimera u zavisnosti od sadržaja metakaolina. Na osnovu dobijenih rezultata, može se zaključiti da se mehaničkom aktivacijom lebdećeg pepela postigla veća pritisna čvrstoća. Dodavanje metakaolina i finoća lebdećeg pepela su promenili strukturu geopolimera, što je utvrđeno metodom FT-IR spektroskopije.

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Production of sustainable energy from solid waste by pyrolysis - a review

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ABSTRACT

Environmental pollution is the major problem of the modern society associated with rapid urbanization and industrialization. The thermal technologies such as pyrolysis have been developed for waste reduction and environmental protection. Pyrolysis processes are optimized for fuels (liquid, gases, and char) production by thermal degradation of solid waste, in the absence of air.

This study involved a brief review of waste pyrolysis potential. The pyrolysis as a thermal technology is used at commercial scale, predominately in Europe and Japan. The focus of this paper is on the types of pyrolysis technologies which include amounts and products type, reactor design, and economics. Advantages and disadvantages of pyrolysis are also discussed and compared with incineration as a very similar thermal process.

1. Introduction

The primary aim of the waste management system in developed countries is resource recovery from waste. Waste-to-energy technologies, such as thermal technology of pyrolysis, incineration, or gasification have been implemented for managing municipal solid waste in many countries all over the world for many decades. These thermal technologies are energy-intensive processes that attempt to reduce the volume of waste by converting it into fuel or energy. Most of the thermal technologies attempt to treat large quantities of heterogeneous mixed municipal solid waste (Tangri and Wilson, 2017).

One of the greatest challenges for future generations is understanding and sustainable managing with large quantities of waste, as an inevitable product of society. Each person consumes a certain different amount of products, and more important, produces a large amount of waste. The disposal of waste became a world huge problem. In our modern societies, the amount of waste generated by the average consumer constantly increases. It is estimated that the statistical inhabitant of Western Europe produces more than 450 kg of garbage per year, or each person produced 475 kg of municipal waste only in 2014 (Hauser and Blumenthal, 2016). *World Energy Council, waste-to-energy*, estimated that global waste generation will double to over 6 million tons of waste per day by 2025, and the rates are not expected to peak by the end of this century (World Energy Council, 2016). The treatment, management, and disposal of municipal solid waste (MSW) are common concerns in every country. Different system analysis tools (Finnveden and Moberg, 2005) are available at the present time, but the most commonly applied tool to analyze environmental burden for waste management technology, as well as a system, is life cycle assessment (LCA). According to this data, the waste management sector faces a problem that cannot be solved on its own. The Kyoto Protocol predicted a reduction of greenhouse gas emissions because the global warming situation would likely be increasing day by day. These concerns have boosted the importance of research for alternatives to petroleum fuel because the global energy supply is based on fossil fuels (oil, natural gas, coal), of which the reserves are finite (Albrecht, 2015).

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Waste is defined as an unusable or undesired product of society, but a valuable energy resource as well. Different waste treatment options are available now, there is not a single technology that can solve the waste management problem (Zaman, 2010). Different countries choose different strategies, depending on their social, economic, and environmental criteria. These decisions can help improve future energy security and environmental sustainability (Tehrani et al., 2009). The energy sector can be a perfect match for waste reduction because of its need to continuously meet growing energy demand. If waste-to-energy (WTE) technologies are developed and implemented, then a correct waste treatment strategy and an environment-friendly energy production can be achieved. Energy recovery from waste can solve two problems at the same time in the waste management and energy sectors. First, there is a reduction and treating of non-recyclable amounts of waste and second, generation high energy amount which can be included in the energy production in order to satisfy the consumers' needs (Chen et al., 2014).

The pyrolysis is considered to be an innovative alternative for treating municipal solid waste (MSW) that obtains different chemicals and fuels. Pyrolysis processes are better than conventional MSW incineration because energy can be produced in a cleaner way. Also, there are lower productions of nitrogen oxides (NO_x) and sulphur oxides (SO_2) and better quality of solid residues can be expected from this thermal technique for MSW (Saffarzadeh et al., 2006). The MSW pyrolysis is more flexible technology than conventional incineration and it's more interesting for small cities and towns. There is growing difficulty in finding new sites for incinerators and landfills in the cities, so the pyrolysis is the technology for long-distance transport prevention. All MSW treatment facilities, due to capital cost limitations that are unsatisfactory, ensure environmental safety, but the pyrolysis plants of proper capacity with energy products output could be a suitable alternative (Chen et al., 2014).

The focus of this paper is pyrolysis, a waste thermal technology, as a potential solution for municipal solid waste reduction. The primary aim of this paper is the identification of challenges, and potential solutions for municipal solid waste reduction and achieving greenhouse gas using thermal technologies. The MSW thermal processes discussed in this paper are thermochemical processes. Pyrolysis, as a highly effective way of waste recycling and disposal, is a thermal process of degradation of MSW that generates energy in the form of fuel.

2. Types and sources of waste as an energy resources

Waste is an inevitable product of society. The term solid waste is usually used to describe non-liquid materials arising from domestic, trade, commercial, agricultural, and industrial activities, and from public services (Sasikumar and Krishna, 2009). Figure 1 illustrates the composition of solid waste worldwide, but specific waste products deriving from construction, industrial, and commercial waste are not specified in this figure.

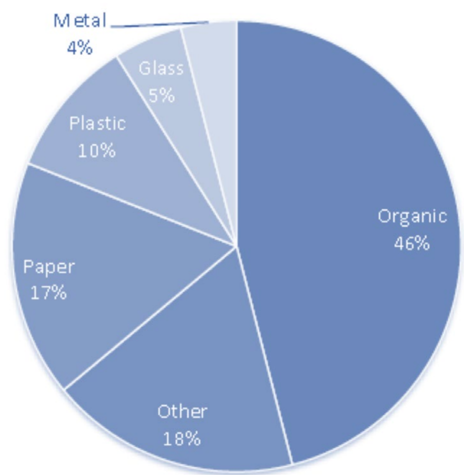

Figure 1. Composition of global MSW (Hoornweg et al., 2013)

The components that constitute MSW are mainly paper, textile yard waste (including fallen leaves and branches, etc.), food wastes, plastics, and a small amount of leather and rubber, metals, and glass. The most dangerous solid waste is the waste that does not degenerate or it needs a long time to degenerate. The time of degeneration of different types of solid waste are shown in Table 1 (Hoornweg et al., 2013).

Table 1. Approximate time for degeneration of some solid waste

Organic waste such as vegetable and fruit	**A week or two**
Paper	10 - 30 days
Cotton cloth	2 - 5 months
Wood	10 - 15 years
Woolen items	1 year
Tin, aluminum and other metal items such as cans	100 - 500 years
Plastic bags	Million years
Glass bottles	Indefinite

MSW from residential, industrial, and commercial sources is the most common waste stream used for energy recovery. The composition of different types of available waste is very important when waste is used as an energy resource. The calorific value of the waste, or the energy content, is a key factor which determines a possible extracted energy. Table 2 shows approximate net calorific values for common fractions of MSW (Auckland Council, 2011).

Table 2. Calorific values of selected fuels and fractions of MSW

Fuels	Q, MJ/kg	Fraction of waste	Q, MJ/kg
Natural gas	36 - 50	Paper	16
Diesel	46	Organic material	46
Black coal, various types	29 - 32.7	Plastic	36
Lignite briquettes	21	Glass	0
RDF fuel	13 - 23	Metal	0
Wood	15	Textile	19
Crude lignite	10	Other materials	11
Residual waste, unsorted, (Austria)	8 - 12	Residual waste, unsorted (China)	3.5 - 5

3. Modern methods of processing municipal solid waste

The choice of WTE technology will be largely dependent on the nature and volume of the incoming waste stream. Waste is now treated as a resource, not as the valueless garbage. Resource recovery is one of the prime objectives in a sustainable waste management system. There are different methods and generally accepted classification of technologies for the treatment of MSW. Some pathways of MSW processing are depicted in Figure 2.

Highly wet food wastes should be processed by biochemical/biological treatment. The MSW fractions such as plastics, paper, cloth, wood, and yard wastes should be processed using thermal technology (Chen et al., 2014).

4. Advanced Thermal Treatment - Pyrolysis

There are differences between Advanced Thermal Treatment and traditional Incineration technologies. Pyrolysis, in contrast to combustion, is the process of thermal degradation of a substance in the absence of oxygen that produces recyclable products, including char, oil/wax, and combustible gases (Figure 3). This process is endothermic and requires about 1 to 1.5 GJ of thermal energy per ton dried MSW (Zaman, 2010). An external heat source is essential to maintain the temperature, usually between 300 °C to 850 °C in the reactor.

The aim of using thermal methods, such as pyrolysis in the waste management sector is a reduction of MSW volume, the conversion of waste into harmless materials, and the utilization of waste hidden energy as fuel, heat,

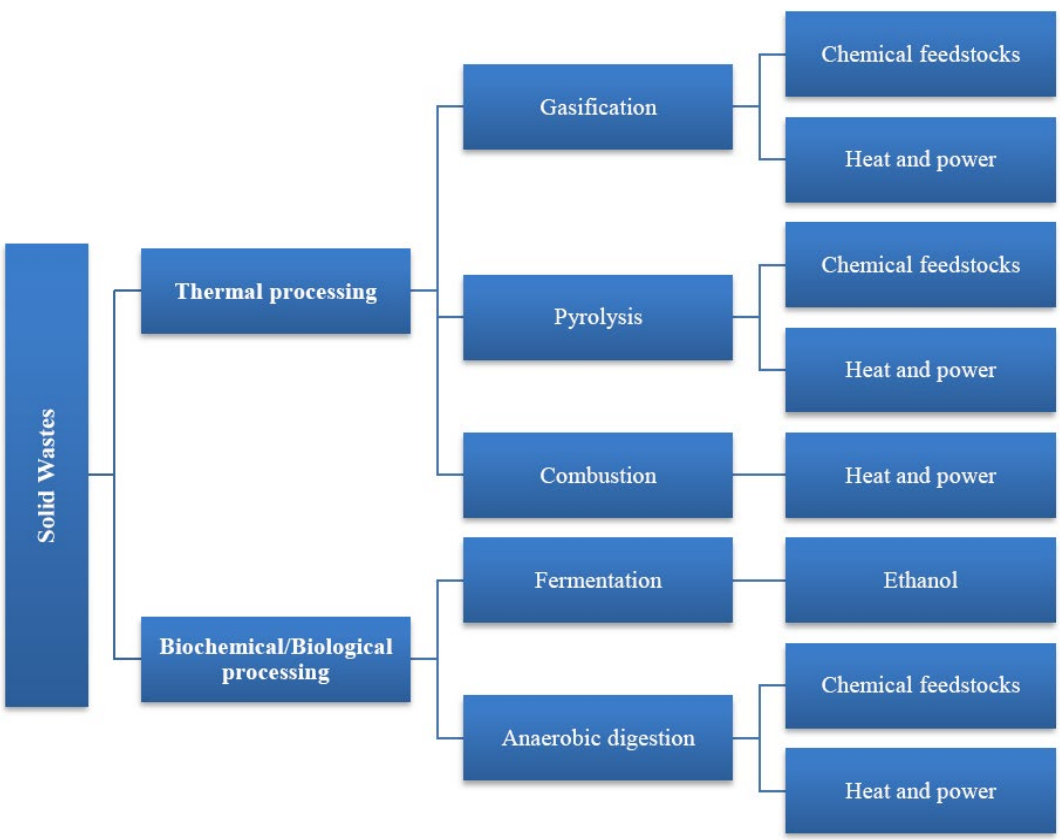

Figure 2. Solid waste to energy pathways (Auckland Council, 2011)

or electrical energy (Moustakas and Loizidou, 2010). Most of the facilities for MSW treatment do not ensure environmental safety due to capital cost limitations; but pyrolysis plants of proper capacity with energy products output are a suitable alternative when the quality of char, oil/wax, and combustible gases is under fine control (Chen et al., 2014). There are numerous pyrolysis plants that are being developed around the world. Globally in 2001, there were 100 small-scale pilot plants processing more than 4,000 tons of residue per year. Many plants are designed for specific processes such as separation and recovery services, and specific organic materials such as industrial by-products or residuals (Caruso et al., 2016).

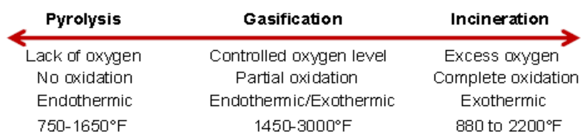

Figure 3. Thermal treatment of the MWS (Bridgwater, 1994)

Pyrolysis of biomass is an age-old technology and its application to MSW is a relatively recent development (Bridgwater, 1994). The feedstock (MSW) during pyrolysis will not thermally decompose before its moisture is vaporized. The total heat required for water vaporization is calculated according to the following equation:

$$Q = W \cdot 2260, [\text{kJ/kg}] \quad (1)$$

where: W is the water content [%] of the feedstock to the reactor (Raveendran et al., 1996).

This is the reason that raw MSW feedstocks should be consistent, and it is usually not appropriate for pyrolysis. The MSW components with high moisture content such as food wastes, biomass are suggested to be separate before pyrolysis, therefore, the MSW needs mechanical preparation and separation of glass, metals, and inert materials (such as rubble) prior to processing the remaining waste (Scheirs and Kaminsky, 2006).

The reaction of thermal degradation of organic material that take place in pyrolysis process can be expressed as:

$$C_xH_yO_z + Q = Char + Liquid + Gas + H_2O \quad (2)$$

where: Q is the heat that needs to be input to the reactor for the reactions to take place.

The pyrolytic products of degradation of organic part of the waste are 75 - 90 % volatile substances and solid residue (coke) by 10 - 25 %. Humidity and inorganic substances present in the MSW decrease the volatile products and the quantity varies from 60 to 70 %, but increase the coke formation from 30 - 40 % (Chakraborty et al., 2013).

Pyrolysis processes have significantly lower pollutant emissions compared to normal combustion in the incinerator (Rumyantseva et al., 2017). It is necessary to prepare MSW for the process of pyrolysis, and needed stages include the following:

1. Sorting,
2. Size reduction,
3. Drying up to a certain moisture degree at 100 - 200 °C,
4. Pyrolysis process itself,
5. Separation and refining of volatile products and
6. Gasification.

The most important parameters affecting MSW pyrolysis are types of MSW, reaction temperature, heating rate (HR), residence materials' size, the usage of catalyst, the type of reactor and etc. There are different types of pyrolytic processes in accordance with the pyrolysis temperature (Rehraha et al., 2016; Rumyantseva et al., 2017):

- **Low-temperature pyrolysis is carried out** in the temperature range of 450 - 500 °C. The yield of different oils, tars or resins, and solid residue is maximum, and the lowest amount of gases is formed;
- **Medium temperature pyrolysis** is performed up to 800 °C. This type of pyrolysis increase the gas and oils formation and the volume of resins, but the residue is reduced;
- **High-temperature pyrolysis** treats unsorted MSW at temperatures above 800 °C and it is limited to 1050 - 1100 °C because residues (slag) melt and that can complicate the work of slag removal system. The maximum degree of gases is generated, but formation of resins, oils, and solid is minimal. Efficiency reaches up to 95 % (Bugayan, 2015);
- **Plasma pyrolysis** is used for hazardous waste disposal at a very high temperature, over 1000 °C, using plasma torches, where the synthetic gas with the optimum composition (mainly CO and H_2) and other end-products, such as a vitrified matrix, are formed (Miandad et al., 2016). This process needs lower reaction volume, but a large amount of secondary energy (example: 1 kWh/kg for arc plasma (Hauk et al., 2004)).
- **Microwave pyrolysis** is performed for homogenous MSW wastes (sludge, plastics, and tires) with very fine particles. The main advantages are rapid heating, easy control of the process, and maintenance of the desired temperature for desired product raising. The disadvantages are small treatment capacity, and impossibility to apply it on heterogeneous MSW, because accurate dielectric data in the microwave frequency range is a function of temperature, and

it is not available for most of the waste components (Yin, 2012).

The most MSW pyrolysis processes have been conducted at atmospheric pressure in typical fixed-bed reactors with a slow heating rate (HR). Vacuum pyrolysis has only been reported in studies of special wastes, such as printed circuit board (Pan, 2012). Another frequently used reactor is the more efficient rotary kiln for conventional (slow) pyrolysis with slow heating rate up to 100 °C/min and 1 h residence time. This type of reactor has good mixing of MSW, the flexible adjustment of residence time, simple maintenance, and larger channel for the entrance of waste, so extensive pre-treatment of wastes is not required (Li et al., 2005). Fluidized bed reactors with high HR and good blending of MSW are more frequently used for fast pyrolysis, and some innovative reactors are used as well (Dai et al., 2001).

The pyrolysis technology for MSW treatment with rotary kiln as pyrolysis reactor can be represented as shown in Figure 4. This is typical energy efficiency, commercially available technology in Europe.

4.1. Pyrolysis products as an energy source

All pyrolytic products often have good properties as a fuel, so they are desired easy to sell products because of their possible conversion to electricity or incineration. The formation of different products is very dependent on the reaction temperature. In a typical pyrolysis process the following reaction takes place: Initial decomposition of substances starts at 250 °C, and also decomposition of H_2S and CO_2. Decomposition of aliphatic bonds and separation of CH_4 and other aliphatic substances start at 340 °C. Enrichment of the produced material in carbon is at 380 °C. Breaking of C-O and C-N bonds occurs at 400 °C. In temperature range of 400 - 600 °C, a conversion of coal tar into fuel and tar happens. Higher temperature (> 600 °C) results with aromatic substances formation and hydrogen removal (Moustakas and Loizidou, 2010).

The composition, yield, and gas heating value of pyrolytic products are strongly dependent on the pyrolysis temperature, feedstock, and heating rate. Increasing the temperature causes increasing of gas yields, due to the second reaction and partial char decomposition (Dai et al., 2001). The gas heating value varies from 10 - 15 MJ/Nm^3 for slow and 14 MJ/Nm^3 (CO, H_2) for fast pyrolysis of biomass, where PP and PE is in range of 42 - 50 MJ/kg (H_2 and light hydrocarbons), and the pyro-gas from MSW consists of CO_2, CO, H_2, and other light hydrocarbons with average heating value around 15 MJ/Nm^3 (Jung et al., 2010). The liquid fuel can be used for the production of heat, electricity, synthesis gas, or chemicals. The heating value of pyrolytic oil from biomass is around 15 - 20 MJ/kg and 30 - 45 MJ/kg from a plastic polymer, and it contains less aqueous fraction (Adrados et al., 2012). In general, the liquid products of co-pyrolysis of biomass and synthetic polymers have the greatest heating value in the range of 41.33 - 46.4 MJ/kg, so they could be a valuable fuel resource (Rutkowski and Kubacki, 2006). The solid product or char is a carbon-rich matrix that contains almost all the inorganic compounds present in MSW, and it has around 33.6 MJ/kg heating value, which is comparable with typical coal (Chen et al., 2014).

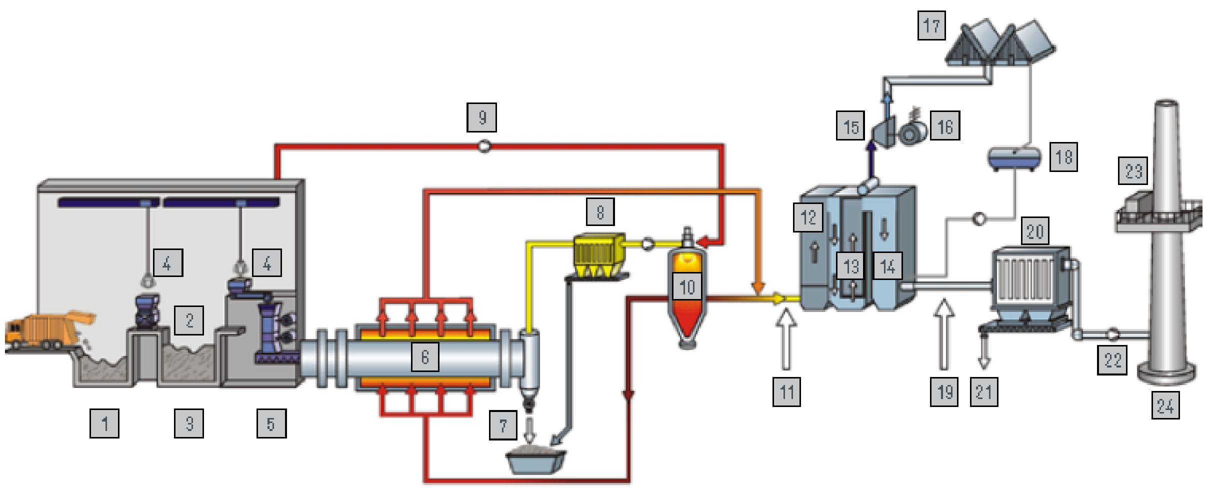

Figure 4. Schematic flow sheet of pyrolysis plant for special solid waste treatment

Agenda: 1. Coarse refuse bunker; **2.** Rotary shears; **3.** Fine refuse bunker; **4.** Overhead crane; **5.** Feeding system; **6.** Pyrolysis kiln; **7.** Discharging system; **8.** Hot gas filter; **9.** Combustion air fan; **10.** Combustion chamber; **11.** Selective non catalytic reduction; **12.** Evaporator; **13.** Super-heater; **14.** Economizer; **15.** Turbine; **16.** Generator; **17.** Condenser; **18.** Feed water tank; **19.** Additive metering hopper; **20.** Fibrous filter; **21.** Filter dust discharging; **22.** Induced ventilator; **23.** Emission monitoring system; **24.** Stack

4.2. Advantages and disadvantages of pyrolysis

There are many advantages of pyrolysis in comparison to incineration, seen as two different thermal technologies. The lower temperature is requisite and the decomposition takes place in the inert or reducing atmosphere, so there are fewer air emissions in the case of pyrolysis. The ash content in carbon is much higher than in incineration, and the metals in the ash are not oxidized, so they have a higher commercial value. The initial waste volume is reduced at a higher level in comparison to the incineration. Low demands for land for their installation and easy control of the process are also seen as advantages for the pyrolysis process (Malkow, 2004).

The main disadvantages of pyrolysis include the necessity of MSW pre-treatment, cleaning of gases, and wastewater treatment, which increase the cost of pyrolysis plants. The pyrolysis products cannot be disposed without further treatment, and the application of this method is limited to large scale. Demand for high quantities of waste, especially for incineration, and need for specialized personnel are also viewed as disadvantages (Chen et al., 2014).

4.3. Economic aspects

Pyrolysis and gasification as a thermal technology are the most expensive processes due to their high costs of investment, operation, and maintenance. The payback period for the investment is long, but the investment in the future in terms of achievements of the current and deferred environmental impact for future generations is also needed. Table 3 offers an orientation on the costs for an alternative technology plant with an annual input of 150,000 - 200,000 tons.

The analysis of the economic efficiency of high-temperature pyrolysis and gasification for MSW processing is attractive and appropriate for implementation due to environmental benefits. The main environmental benefit is the recycling of accumulated and newly generated waste and prevention of environmental damage. The economics of these technologies can only be considered as acceptable if the result of process is fuel (gas, liquid and, coke), which has a good market value. This depends very much on market conditions. The combined pyrolysis & gasification technology is a good choice for MSW treatment method in cities that can afford it. Pyrolysis alone, in general, is cheaper and may be adapted to the undeveloped places (Rumyantseva et al., 2017).

4.4. Comparison among thermal technologies

Thermal MSW processing is a part of a sustainable waste management system. Today, combustion is still the main thermal technology used for waste to energy conversion. Pyrolysis and gasification processes have many advantages, but they are more costly and more complicated processes. Thermal waste management methods should be applied together in order to maximize material recovery from waste. Summarizing the main characteristics of the common thermal techniques for waste management, Table 4 presents the basic products and the main operating conditions.

Table 3. Example of comparative individual cost elements of pyrolysis plant in Germany (Tangri and Wilson, 2017)

Cost estimates of a pyrolysis/gasification plant in developing countries - figures are a rough orientation only						
Initial Investment	Capital costs per ton and year of waste input	O&M costs per ton	Total cost per ton	Revenues* per ton	Cost** per ton waste input	Remark
80 - 120 Million EUR	35 - 45 EUR/t	30 - 40 EUR/t	65 - 80 EUR/t	2 - 5 EUR/t	63 - 80 EUR/t	Capacity 250,000 t/a, 20 y operation, 6 % p.a. IR

* From the sale of end-products ** Costs to be covered by gate fee, subsidies etc.

Table 4. Parameters of typical operation conditions & products of the common thermal management practices (Moustakas and Loizidou, 2010)

	Combustion	**Gasification**	**Pyrolysis**
Temperature (°C)	800 - 1450	500 - 1800	250 - 900
Pressure (bar)	1	1 - 45	1
Atmosphere	Air	O_2, H_20	Inert, N_2
Stoichiometric ratio	> 1	< 1	0
Products			
Gas phase	CO_2, H_2O, O_2, N_2	H_2, CO, CO_2, CH_4, H_2O, N_2	H_2, CO, H_20, N_2, HC
Solid phase	Ash, slag	Ash, slag	Ash, coke
Liquid phase			Pyrolysis oil, water

5. Conclusions

The global growth of municipal solid waste makes the urgent need to develop new and better methods of disposal. Different waste treatment options have different environmental impacts. Traditional methods like landfilling, composting, and incineration should be replaced by modern technologies due to their impact to the socio-economic and environmental issue. Thermal MSW technologies allow energy recovery, volume reduction, and conversion of hazard into non-hazard components of MSW, which makes these technologies environmentally friendly. The pyrolysis is thermal technology with the greatest potential. There are numerous successful commercial waste pyrolysis facilities operating worldwide, predominately in Europe and Japan.

The composition of MSW determines the technical efficiency of the pyrolysis technology. A good raw material for the pyrolysis process is basically any material, which includes organic carbon. A process parameters and type of reactor influence the yield and types of generated products. The obtained products of thermal treatment have high calorific value and are absolutely free of pathogenic factors due to the high temperatures process. Pyrolysis reduces the weight and volume of the treated waste and also, there is low requisite for land for installation of their units. In general, pyrolysis is characterized by relatively high operation cost, but they substantially decrease as the capacity of the plant increases.

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Proizvodnja održive energije iz čvrstog otpada putem postupka pirolize - pregled

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INFORMACIJE O RADU

Primljen 01 jun 2019
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Pregledni rad

Ključne reči:
Termički postupak
Komunalni čvrsti otpad
Razgradnja
Savremena tehnologija

I Z V O D

Zagađenje životne sredine predstavlja glavni problem savremenog društva i povezan je sa brzom urbanizacijom i industrijalizacijom. Termički procesi, kao što je piroliza, razvijeni su da bi se smanjila količina otpada i da bi se zaštitila životna sredina. Postupak pirolize je optimizovan za proizvodnju goriva (u tečnom i gasovitom stanju, kao i ugalj) termičkom razgradnjom čvrstog otpada, bez prisustva vazduha.
Ova studija uključuje kratak pregled potencijala pirolize otpada. Piroliza se, kao termički proces, sa komercijalnog aspekta koristi u Evropi i Japanu. Fokus ovog rada su postupci pirolize koji uključuju količinu i vrstu proizvoda, konstrukciju reaktora, kao i ekonomičnost postupka. Prednosti i nedostaci postupka pirolize su takođe razmatrani u upoređivani sa postupkom spaljivanja koji se smatra sličnim termičkim postupkom.

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