Environmental Engineering and Management Journal

November 2018, Vol. 17, No. 11, 2537-2548
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

PREDICTION OF E-WASTE GENERATION BASED ON GREY MODEL (1,1) AND MANAGEMENT IN BOTSWANA

Daniel Mmereki[1,2]*, Baizhan Li[1], Md. Uzzal Hossain[3], Liu Meng[1]

[1]*Faculty of Urban Construction and Environmental Engineering, Chongqing City, 400045, P.R. China*
[2]*College of Civil Engineering, 174 Shazhengjie, Shapingba District, Chongqing University, Chongqing City, 400045, P.R. China*
[3]*Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong*

Abstract

This paper seeks to evaluate the quantities of e-waste in Botswana from 2000-2019, with a view towards formulating an effective and sound e-waste management system. Due to a lack of complete historical records on e-waste quantity and quality, this was achieved by the Grey Model GM(1,1) forecasting method. Our estimations indicate that an average weight of about 293.18 tons of e-waste will be generated in 2019 in the country. Considering an economic lifespan of between 3 and 10 years, more e-waste is expected to be produced annually in the country. This paper also highlights key societal factors influencing successful implementation of a sound e-waste management system. These include the introduction of legislation dealing specifically with e-waste, establishment of formal take-back systems, integration of the informal recycling sector into the formal recycling sector, innovative technologies and investment on e-waste management activities. An effective management system of waste from this sector should involve consideration of the toxicity and value of some of the components and materials of electrical and electronic equipment (EEE) and the prevailing inappropriate disposal practices for such potentially "toxic" materials.

Keywords: Botswana, e-waste, e-waste policy, Grey Model (1,1), value recovery

Received: March, 2014; Revised final: January, 2015; Accepted: January, 2015; Published in final edited form: November 2018

1. Introduction

E-waste is a complex waste category containing both valuable materials (e.g. non-precious metals: iron, steel, copper, aluminum, etc.; precious metals: gold, silver, palladium, platinum and plastics) (Amato et al., 2017) and hazardous substances (e.g. lead-containing glass, mercury, cadmium, batteries, flame retardants, chlorofluorocarbons and other coolants with heavy potential of negative environmental impacts) (Awasthi and Li, 2017; Ceballos et al., 2017). This type of waste encompasses a wide range of electrical and electronic devices such as large household appliances, including refrigerators, air conditioners, washing machines, microwave ovens, and fluorescent light bulbs, computers, mobile phones, television sets, stereo equipment that have been discarded by their first owners (Gramatyka et al., 2007). It is estimated that over 40 million tons of e-waste is generated per year. This e-waste causes adverse environmental impacts during the management stage, if it is not properly treated or disposed of (Ongondo et al., 2011). Data available from the European Union (EU) member states indicates that…"the volume and composition of e-waste varies from country to country depending on the level of technological advancement and how it is defined". It is often handled and disposed of by consumers and municipalities along with domestic wastes. However, the recent recognition of the potential for the diversion of materials from landfills has led to e-waste becoming a target of interest for recycling (Lee et al., 2000; Liu et al., 2005).

Recycling, one strategy of waste diversion from waste dumpsites and landfills, offers five main benefits: (i) conservation of natural resources; (ii)

* Author to whom all correspondence should be addressed: e-mail: dani.mmereki2@gmail.com; Phone:+86 15123964440; Fax:023 65120771

water pollution caused by hazardous disposal can be avoided; (iii) reduction of transport and solid waste management costs; (iv) reduction of space required for landfills and (v) reduction of greenhouse gas emissions (Alake and Ighalo, 2012; Del-Moral-Avila et al., 2016). Most significantly, in the United States, the state of California was the first to consider the problem of rising tides of e-waste and enacted legislation in 2003 to establish a broader landfill ban for e-waste (Electronic Waste Recycling Act of 2003) and funding for a system for collection and recycling of e-waste. The legislation is based on prevention of disposal of e-waste in landfills and its exportation overseas (United States Environmental Protection Agency) (USEPA, 2012). The volume of obsolete e-products in developing and transition countries is expected to exceed that of developed countries due to domestic consumption of EEE and trafficking of e-waste (Wang et al., 2012). Several researchers have highlighted that…"about two-thirds of e-waste is generated in developing and transition countries" (Nnorom and Osibanjo, 2007, 2008; Legler and Brouwer, 2003). The rising quantities of e-waste are driven by the demand for second-hand e-products and secondary resources by refurbishment and dismantling outlets as an income-generating opportunity for the people living in developing and transition countries (Gurauskiene and Stasiskiene, 2018; Wang et al., 2012).

In the EU countries …"the total quantity of e-waste arising will grow by at least 2.5-2.7% in 2020, reaching about 12.3 million tons". This represents 17-20 kg of e-waste produced annually by each EU citizen. Of this, 90% will be landfilled, incinerated, or recovered without any pre-treatment (Waste and Resource Action Programme) (WRAP, 2013). For the United Kingdom (UK), "e-waste growth rate is estimated to grow three times faster than the municipal solid waste (MSW)" (Savage et al., 2006). In 2010, over 80, 000 tons of e-waste was collected in Denmark (Danish Producer Responsibility System) (DPA System, 2011). Families in Hong Kong discarded more than 490,000 old televisions and computer monitors each year (So, 2011). South Africa produced some "2 million tons of e-waste annually" (Advanced Tropical Environment), (ATE, 2012). Based on a study on landfill forecasts in Australia… "75% of the 3 million computers bought every year end up in landfills" (Clean Up Australia Ltd, 2009).

Reducing and managing e-waste in developing and transition countries is becoming a critical challenge due to a general lack of strict environmental regulations, investment and technical know-how, basic infrastructure for e-waste management and technically skilled human resources (Kang and Schoenung, 2005; Khetriwal et al., 2007; Lee et al., 2000). This is because e-waste the current recycling and disposal methods cannot keep pace with the changing composition of e-waste. Most developed countries like the US (USEPA, 2012) and EU member states have framed strict regulations aimed at monitoring proper recycling of e-waste and safe disposal of the non-recyclable components (Wang et al., 2012), and have set up effective recycling systems (Stanislav and Branko, 2018). Also, the EU member states have implemented the "hierarchical principle", which is aimed at preventing the negative environmental impacts caused by e-waste (Bartolacci et al., 2017). Therefore, it is necessary to introduce innovative technologies and develop environmentally sound treatment systems aimed at fostering proper recycling of e-waste and safe disposal of non-recyclable components.

Botswana, a middle-income country, is a net importer of e-products such as televisions (liquid crystal displays (LCDs) and light emitting diodes (LEDs), personal computers (with cathode ray tube (CRT) monitors and LCD monitors), refrigerators, washing machines, cell phones and others (National Conservation Strategy (Co-ordinating) Agency/German Agency for Technical Cooperation, NCSA/GTZ, 1996). A very significant proportion of information and communication technology (ICT) international corporate organizations deal with e-products business in Botswana: Samsung, Nokia, Sony, Defy and others. These brand companies are quite familiar with the global e-waste directives and other environmental regulations.

However, in Botswana, the concept of Extended Product Responsibility (EPR) has not been widely applied to oblige producers of e-goods to control the environmental impacts of their products from the initiation of raw material production to the good's final disposal. A sizeable fraction of these ICT companies provide "informal" take-back system-*exchange-old-for-new* (Mmereki et al., 2012).

Over the recent years, Botswana has experienced rapid economic growth (Khupe, 1996; Mosha, 1996), rapid urbanization, accompanied with increasing proportion of total urban population, growing from 41% in 1990 to 53% by 2010, and expected to continue increasing (United Nations Population Division, 2012). Due to rapid urbanization and greater economic growth, research has noted that this has led to "the incorporation of computer-based technologies into the centerfold of public administrative reforms to digitize and optimize the delivery of services and the process of governance, which might ultimately result in increased generation of e-waste" (Mmereki et al., 2012). In recent years, the government of Botswana has launched several programs to make computers available in at all primary schools. Initiatives such as this, besides the advancement of the economy, are likely to lead to increased generation of e-waste Botswana in the near future. Fig. 1 reflects the imports of EEE between 2003 and 2011.

Although the proportion of EEE imported into the country was on the increase, in 2008 it decelerated. This deceleration may be explained by the three factors: (i) nowadays EEE such as computers, televisions and cell phones consist of embedded radios, (ii) recession and (iii) reduction of import "appetite".

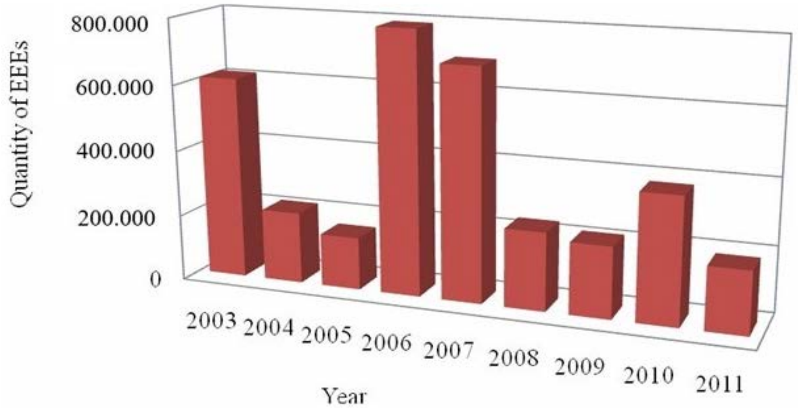

Fig. 1. The proportion and variations of different EEE imported into Botswana, 2003-2011 (Statistics Botswana, formerly Central Statistics Office (CSO), (Statistics Botswana, 2010)

Nevertheless, it can be said that the transition from televisions and cell phones embedded radios may not reduce the quantities of e-waste generated but enhance the complexity associated with its management. Presently, in Botswana, local authorities have no readily available or complete accurate data on e-waste quality and quantity (Mmereki, 2017; 2018). Fewer studies have been undertaken to determine the generation, characterization, disposal, and the emanating environmental risks and composition of e-waste in Botswana. However, many of these studies were ad hoc projects carried out for central and local authorities and have not been published.

The present paper builds on the past work and makes it up to date, by enumerating the quantities of e-waste generated in Botswana from 2000-2019 as an incentive for planning and designing of an efficient and cost-effective strategy for recycling e-waste and safe disposal of non-recyclable components of e-waste. Most significantly, the present study evaluates e-waste management practices and the existing environmental policies associated with the management of e-waste in Botswana. Additionally, this study aims to make practical recommendations to plan, change or improve e-waste management and disposal in Botswana.

2. Material and methods

In this initial study, five e-products were considered: televisions, tape recorders, radios, video players, and personal computers (PCs). E-waste resulting from these products is estimated by considering domestic e-waste generation during the period of 2000-2005. This inventory as compiled by NCSA is still the only available databank of e-waste covering the whole country. In such a situation, one has to rely on such data, for purposes of planning and development, and action plan for efficient e-waste management although it has relatively become obsolete. Imported electronic equipment was not included in the study (model), owing to the data gaps and uncertainty of the data. Mobile phones were not considered because the information is not available from the different stakeholders, particularly the local mobile networks in Botswana. The methodology used in this study to estimate the rate of e-waste generation was based on data collected from the National Co-ordinating Strategy Agency (NCSA/GTZ, 1996).

The annual e-waste generation (tons year^{-1}) was estimated based on the mass of the total of all items (single total-quantity of e-waste-total of all items to simplify the fitting of inputs into the model). In this paper, Grey Model GM (1,1) model was adopted for forecasting e-waste generation in Botswana.

2.1. Grey Model GM (1,1)

Deng et al. (1989) developed the Grey System Theory in the early 1980s. The GM (1, 1) uses a first order differential equation to characterize an unknown system. During the last two decades, the grey system theory has developed rapidly and caught the attention of many researchers. It has been widely and successfully applied in various systems (Mao and Chirwa, 2006). The theory is a truly multidisciplinary and generic theory that deals with systems that are characterized by poor information or for which information is lacking (Hsu and Wang, 2007; Farzana et al., 2014). It has advantages of a small sample data, computing convenience and short time forecast of high accuracy. Past research has noted that because of the ability of the GM (1,1) model to describe an unknown system and predict it efficiently based on a few data set, this has shown its practicality in utilizing insufficient database (Mao and Chirwa, 2006). The model was used because it doesn't need assumptions, and the extra measures for system planning of e-waste management are not required. The GM (1,1) model has three basic operations: 1) accumulating generating operation (AGO); 2) inverse accumulated generating operation (IAGO) and 3) grey modeling (Mao and Chirwa, 2006; Talebnejad and Nadaf, 2011). The description of the model building and the corresponding parameters used are shown in Fig. 2. Therefore, the archetypical process is as illustrated in Fig. 2.

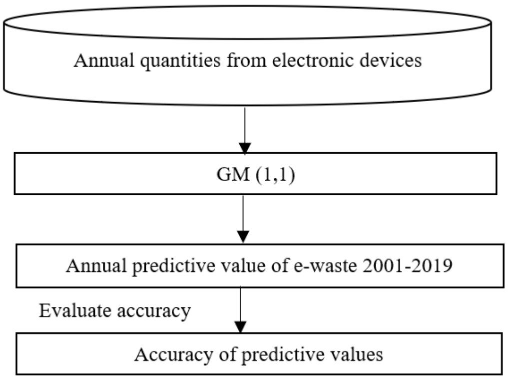

Fig. 2. Procedures for forecasting e-waste generation in Botswana

2.2. GM (1,1) prediction behavior and procedure design Stopped

The GM (1,1) has some procedures discussed as follows:

Procedure 1: Collect the original data with n samples (Eq. 1):

$$x^{(0)} = \{x^{(0)}(k)\} = \{x^{(0)}(1), x^{(0)}(2), \ldots\ldots x^{(0)}(i), \ldots\ldots x^{(0)}(n)\} \quad (1)$$

where $k = 1,2, \ldots \ldots, n$ and $x_i^{(0)}(k)$ represents the original data and negative values are not allowed. n is the number of years observed. The task is to forecast $x^{(0)}$(k).

Procedure 2: Establish the AGO. The main function of the AGO is to discover the potential regular pattern or trend of the original data sequence through the accumulation of data so that the prediction can be more accurate (Eq. 2):

$$x^{(1)} = (x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)) \quad (2)$$

where:

$$x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), \quad k = 1,2,3, \ldots, n \quad (3)$$

where: $x^{(1)}$ is monotonically increasing Eq. (3).

Procedure 3: Set-up the background model (Eq. 4):

$$Z^{(1)}(k+1) = \frac{1}{2}(x^{(1)}(k) + x^{(1)}(k+1)), \quad k = 1,2\ldots,(n-1) \quad (4)$$

Procedure 4: Establish the differential equation (Eq. 5).

$$\frac{dx^{(1)}}{dt} + + ax^{(1)} = b \quad (5)$$

where: *dx(1)/dt* is the derivative of the function *x*, *x* is the background value, and the parameters *a* and *b* are the development coefficient and grey input, respectively.

Procedure 5: Establish a whitening equation (Eq. 6).

$$x^{(0)}(k) + aZ^{(1)}(k) = b, \quad k = 2,3,4, \ldots\ldots, n \quad (6)$$

Procedure 6: Find the development coefficient *a* and grey controlled variable *b*. The parameters *a* and *b* are worked out by the least square method (Eq. 7):

$$\begin{bmatrix} a \\ b \end{bmatrix} = (B^T B)^{-1} B^T Y_n \quad (7)$$

In Eq. (8) the formula:

$$B = \begin{bmatrix} -Z^{(1)}(2) & 1 \\ -Z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(1)}(n) & 1 \end{bmatrix}; \quad Y_n = [x^{(0)}2, x^{(0)}3, \ldots . x^{(0)}]^T \quad (8)$$

Procedure 7: Establish the result (i.e. time response function) of the above differential equation as follows (Eqs. 9-10):

$$\hat{x}^{(1)}(k) = \left(x^{(0)}(1) - \frac{b}{a}\right) \times e^{-a(k-1)} + \frac{b}{a} \quad (9)$$

$$\hat{x}^{(1)}(k-1) = \left(x^{(0)}(1) - \frac{b}{a}\right) \times e^{-a(k-1-1)} + \frac{b}{a} \quad (10)$$

Procedure 8: Establish the inverse AGO value (IAGO) (Eq. 11):

$$\hat{x}^{(0)}(k) = \hat{x}^{(1)}(k) - \hat{x}^{(1)}(k-1) \quad (11)$$

where $k = 0,1,2,3,\ldots$

Eq. (11) is the total e-waste generation for the GM (1,1) of mathematical expressions and *K* is a one-time variable.

Procedure 9: Residual Test of GM (1,1) (Eq. 12):

(1) $x^{(0)}(k) - \hat{x}^{(0)}(k):$

$$\gamma^{(0)}(k) = x^{(0)}(k) - \hat{x}^{(0)}(k) \quad (12)$$

(2) Residual series by GM (1,1) model (Eq. 13):

t = 1

$$\hat{\gamma}^{(0)}(k) = \begin{cases} \gamma^{(0)}, & t \\ (1-e^{a}) \end{cases} \left[\gamma^{(0)}(1) - \frac{b}{a}\right] e^{-a(k-1)}, \quad t = 1,2\ldots,n \quad (13)$$

(3) Substitution (Eq. 14) $x^{(0)}(k)$ and $\hat{x}^{(0)}(k)$:

$$e(k) = \left| \frac{k^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)} \right| \times 100\% \quad (14)$$

where: Relate Percentage Error (*RPE*) is the absolute value of the error rate, $x^{(0)}(k)$ is the actual value and $\hat{x}^{(0)}$ is the predicted value.

Data on the growth domestic product (GDP) and population growth were not included in the model building because it is assumed that the figures do not signify/reflect any strong correlation between them or signify/reflect a weak or non-existent link between them in Botswana. Virtually, accurate and formal data showing the relationship is not available from the Ministry of Trade and Industry and Statistics Botswana. It is almost impracticable to include these factors in the model building, as the years covered are different. Generally, information on the average lifespan of e-products is not available or inadequately understood. Hence, this was not considered in the study. Refurbished and repaired electronic equipment was not included in the study, owing to insufficient data from these activities. Given the difficulty to determine the actual quality and quantity of recycled e-waste, and the "informal" status of recycling in the country, this was not considered in the model building.

Botswana is a country with a present population of approximately 2,065,000 (Central Intelligence Agency, CIA World Factbook, 2011). To assess the current e-waste management situation, the evaluation was performed in the cities of Gaborone and Francistown. Gaborone, the capital city, is the largest urban centre in terms of population size, which was over 231,000 people in 2011, and is the principal centre of attraction to migrants and investors in Botswana. Francistown, with a population of more than 98,000 people, is the second-largest city in the country and the largest in the northern part of Botswana (Statistics Botswana, 2011).

To assess the stakeholders and the factors influencing the performance of e-waste management in Botswana, mixed methods were used in this study. Data was collected from scientific literature, existing databases, together with extensive field observations made during site visits in the two urban areas and interviews with relevant key professionals. In addition, existing environmental policies, e-waste management and disposal activities were assessed. Finally, the e-waste flows in Botswana were generally generated based on the information obtained through literature reviews and interviews with the waste management professionals.

Based on the prevailing condition in the country, and with reference to other countries' successful experiences, some applicable management strategies were suggested to plan, change and improve e-waste management and disposal in Botswana.

The simulation data (from 2000 to 2005) was presented to create the original data sequence $x^{(0)}(k)$, that is (Eq. 15):

$$x^{(0)}(k) = \left[x^{(0)}(1), x^{(0)}(2), \ldots\ldots\ldots, x^{(0)}(5)\right] = (1346, 861, 790, 735, 646, 710) \quad (15)$$

Furthermore, the AGO series $x^{(1)}$ can be obtained Eqs. (16-17):

$$x^{(1)}(k) = \left[x^{(1)}(1), x^{(1)}(2), \ldots\ldots\ldots, x^{(1)}(5)\right] = (1346, 2207, 2997, 3732, 4378, 5088) \quad (16)$$

where:

$$x^{(1)}(1) = x^{(0)}(1)$$
$$x^{(1)}(2) = x^{(1)}(1) + x^{(1)}(2) \quad (17)$$
$$x^{(1)}(3) = x^{(1)}(1) + x^{(1)}(2) + x^{(1)}(3)$$

....

(1346, 2207, 2997, 3732, 4378, 5088)

Therefore, Columns [a,b] are parameters of the least-square estimation:

$$\begin{bmatrix} a \\ b \end{bmatrix} = (B^T B)^{-1} B^T Y_n = \begin{bmatrix} -0.0614592 \\ 951.4201851 \end{bmatrix} \quad (18)$$

So, reflecting on $x^{(1)}$ and $x^{(0)}$, the values of the parameters are as follows: a is -0.0614592, and b is 951.4201851.

A forecasting equation was obtained as Eq. (19):

$$\hat{x}^{(0)}(k) = \hat{x}^{(1)}(k) - \hat{x}^{(1)}(k-1) = \\ = \left[\left(x^{(0)}(1) - \frac{b}{a}\right) \times e^{-a(k-1)} + \frac{b}{a}\right] - \\ - \left[\left(x^{(0)}(1) - \frac{b}{a}\right) \times e^{-a(k-1-1)} + \frac{b}{a}\right] = \\ = 943.21\ e^{(0.06146k)} \quad (19)$$

where: k = 0,1,2,3,…

Eq. (19) sets up the forecasting model, the forecast value for the total e-waste generation for GM (1,1) which can be elicited in Fig. 3.

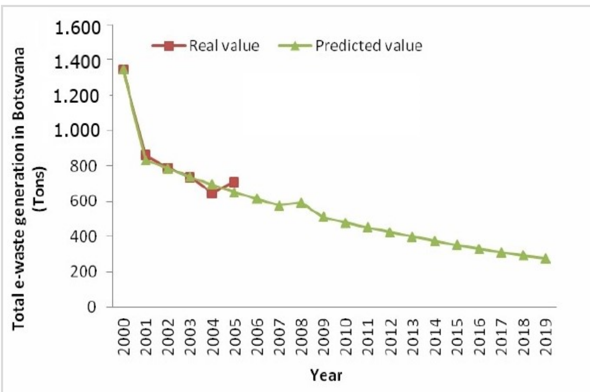

Fig. 3. Comparison and prediction of e-waste generation in Botswana, 2000-2019

3. Results and discussion

3.1. E-waste generation in Botswana

The quantities of e-waste produced from 2000 to 2005 are given in Table 1. These estimates of e-waste were made considering the aggregated quantity of e-waste produced annually (tons). As a middle-income country, Botswana's real GDP growth is relatively higher. The real GDP growth of the country from 2005 to 2011 is given in Table 2.

The GM (1,1) forecasting method was used to predict the quantities of e-waste from 2006 to 2016. Analysis was performed utilizing Microsoft Excel 2007. The findings of the model indicate that the quantities of e-waste in the country for the only five selected electronic items were, 509, 480, and 451 tons year^{-1} for 2010, 2011 and 2012, respectively.

The predicted quantities of e-waste between 2013 and 2019 varied from an estimated 424 to 293 tons annually. Based on the estimates from 2008 to 2010, the quantities of e-waste being generated was lower (Fig. 3). Two fundamental factors could be associated with this scenario: Firstly, psychological obsolescence (associated with households keeping e-products for perceived value after end-of-life, posing a series of environmental risks). Secondly, an even more puzzling point is that during this period there was a shift from CRT monitors to LCD monitors, laptops, Ipads etc. However, this shift does not result in higher e-waste levels. This might have reduced the quantity per unit of PCs. In addition, some e-products may have remained in storage and some reused, thereby extending their lifespan.

It is, however, to be noted that the e-waste generation figures do not necessarily reflect the quantities of e-waste disposed of. It can be said that the shift from CRT monitors to LCD monitors, laptops, etc., may not have reduced the quantity but has enhanced the complexity of its management. As previously explained, only five types of electronic equipment were analyzed, and the investigation team was not able to properly establish certain data on transboundary e-waste figures into the country. Therefore, figures on transboundary e-waste could not be included in the estimates of the quantities of e-waste being generated in the country. Thus, if all e-products (refrigerators, washing machines, air-conditioners etc.) and figures on transboundary e-waste were included in the dataset, the total estimated quantities of e-waste being generated annually could be considerably higher than the amount estimated by the present study. Therefore, the effects of improper disposal practices of e-waste such as open incineration, open air dumping etc., on the environment, public safety and health could be considerably higher. The extent of e-waste generation from these e-products needs to be assessed.

Besides the estimates of the quantities of e-waste studied, there is evidence of other end-of-life products such as microwave ovens, washing machines, refrigerators, and air-conditioners. The total weight of waste produced from these products in 2010 was more than 7,500 tons (NCSA/GTZ, 1996). In the informal disposal streams, it is difficult to measure the quantities of e-waste being generated, but it may be at even higher rates due to the economic value associated with these relatively high-quality electronic systems.

3.2. Current management practices in Botswana

At present, Botswana has a general waste management project (launched landfill guidelines; promulgated Waste Management Act of 1998 etc.) and strategy to address the problem of growing quantities of waste in the country that is built on the key principles of waste prevention, "polluter pay principle", and the cooperation among all the different stakeholders involved in the waste management lifecycle. The strategy also encourages waste reduction, reuse and recycling, prescribed in waste management hierarchy, where disposal of waste is the least preferred method.

There are some important initiatives by Non-governmental organizations (NGOs), the public and the private sector in Botswana for waste management activities. Most of these focus on providing more convenient collection channels and recycling of other classes of wastes (e.g. scrap metals, oil containing wastes etc.). Despite these measures e-waste is still not given special attention but included in the general legislation concerning waste management. Most critically, the Department of Waste Management and Pollution Control (DWMPC) has not developed and implemented standards for e-waste reduction and management. An objective of the department going forward is to both develop and demonstrate appropriate technologies on e-waste recycling and safe disposal of non-recyclable components through research and development efforts and pilot projects.

Table 1. Potential amounts of e-waste generated in Botswana 2000-2005

Year	***Televisions (tons year^{-1})***	***Radio, video players, tape recorders (tons year^{-1})***	***Computers (tons year^{-1})***	***Total (tons year^{-1})***
Until 2000	241	474	631	1,346
2001	202	499	160	861
2002	300	270	220	790
2003	288	287	160	735
2004	304	202	140	646
2005	325	225	160	710

In the course of assessment of the current condition of e-waste management and disposal from the two cities, Gaborone and Francistown by the authors, it was found that there is no legislation dealing specifically with e-waste management or a well-established system that describes the actual practice of e-waste management and disposal.

Table 2. Real GDP growth for Botswana (Statistics Botswana, 2013)

Year	***Real GDP growth***
2001	0.3
2002	6.1
2003	4.6
2004	2.7
2005	4.6
2006	8.0
2007	8.7
2008	3.9
2009	-7.8
2010	8.6
2011	6.1
2012	4.2
2013 Quarter 1	3.3
2013 Quarter 2	7.4

The two cities do not have correct data on an allocated budget for solid waste management, and do not have separate solid waste management departments. Transfer stations do not exist in the two cities. Collection and recycling facilities were observed to be meager. It is, however, to be noted that the legislation is good on paper, but does not provide operational guidelines that describe categories of equipment covered under e-waste. An examination of the two cities has revealed that no set of guidelines for identification of e-waste has been put into effect.

The same conditions exist in all urban and rural areas in the country; e-waste is either refurbished and resold, or dismantled to extract recyclables. The following deficiencies have been observed in the two cities due to the absence of legislation dealing specifically with e-waste:

- The Ministry of Environment, Natural Resources Conservation and Tourism, and the DWMPC have limited capacity to apply pressure on manufacturers and importers of EEE to recycle product after end-of-life.
- Landfill is the final disposal method of e-waste and non-recyclable components of e-waste. However, their performance and maintenance is not satisfactory.
- Informal sector is the dominant system in e-waste recycling.
- No defined roles and responsibilities of all the different stakeholders, in particular the roles of the e-product importers, distributors and consumers etc.
- There are no separate collection channels for e-waste.
- There are no incentives for e-waste recycling.
- There is no comprehensive licensing and auditing system for e-waste.
- No financing system for maintaining and managing a sound e-waste recycling system and safe disposal of non-recyclable components e-waste.
- No defined programme for scientific e-waste management or recycling in the near future.

In practical terms, there is no definite national strategy for reduction of e-waste, development of technology to gainfully use and dispose of e-products to minimize environmental and public health impacts. It raises concern that ineffective waste management strategies may lead to increased e-waste volumes and complexities in waste management. The volume of e-waste disposed of is influenced by the handling practices of the consumers. The management of e-waste is generally done unscientifically, by consumers, local authorities' solid waste workers, by workers in repair shops or refurbishment outlets and sometimes by scavengers who illegally separate waste at landfill sites and improvised dumpsites.

The main channel for e-waste recycling and collection in Botswana is still informal (legally or illegally), under non-organized conditions, which results in a disordered market system with little government oversight, sometimes using archaic techniques to extract valuable and recyclable materials from the discarded e-products, and then discard the rest of e-waste directly into the surroundings. The remaining proportion of e-waste is collected and co-disposed of with municipal solid waste (MSW). Consumer‘s influence on disposal of e-waste is limited. Hence, it will be nearly difficult to protect public health and safety, and the local environment.

In Botswana, despite all national efforts to manage waste, it appears that no clear sustainable solution to e-waste problem is in place. A rough synopsis of e-waste flows in Botswana is presented in Fig. 4. It should be noted that most of the other localities in the country exhibit similar conditions of the two cities. Yet before this study, the quantity and quality of e-waste in the country was not predicted.

A few case studies performed by Paul and Tshetlhane in 2013, Mmereki et al. in 2012, Taye and Kanda in 2011, have investigated e-waste resulting from PCs and accessories, without any theoretical support, which leads to a series of problems (Paul and Tshetlhane, 2013; Mmereki et al., 2012; Taye and Kanda, 2011). Other studies are relatively becoming obsolete since they were done a long time ago (approximately 13 years ago) when e-waste was not a major problem and the use of technology was not as substantial as it is in recent years. Nevertheless, none of the previous studies are able to provide a methodology to estimate the quantities of e-waste disposed of in Botswana.

3.3. Potential for recycling and reuse of e-waste

Sound and effective strategies and systems for e-waste recycling can increase reuse of economic equipment and parts, and increase the recyclability of materials reclaimed from e-waste.

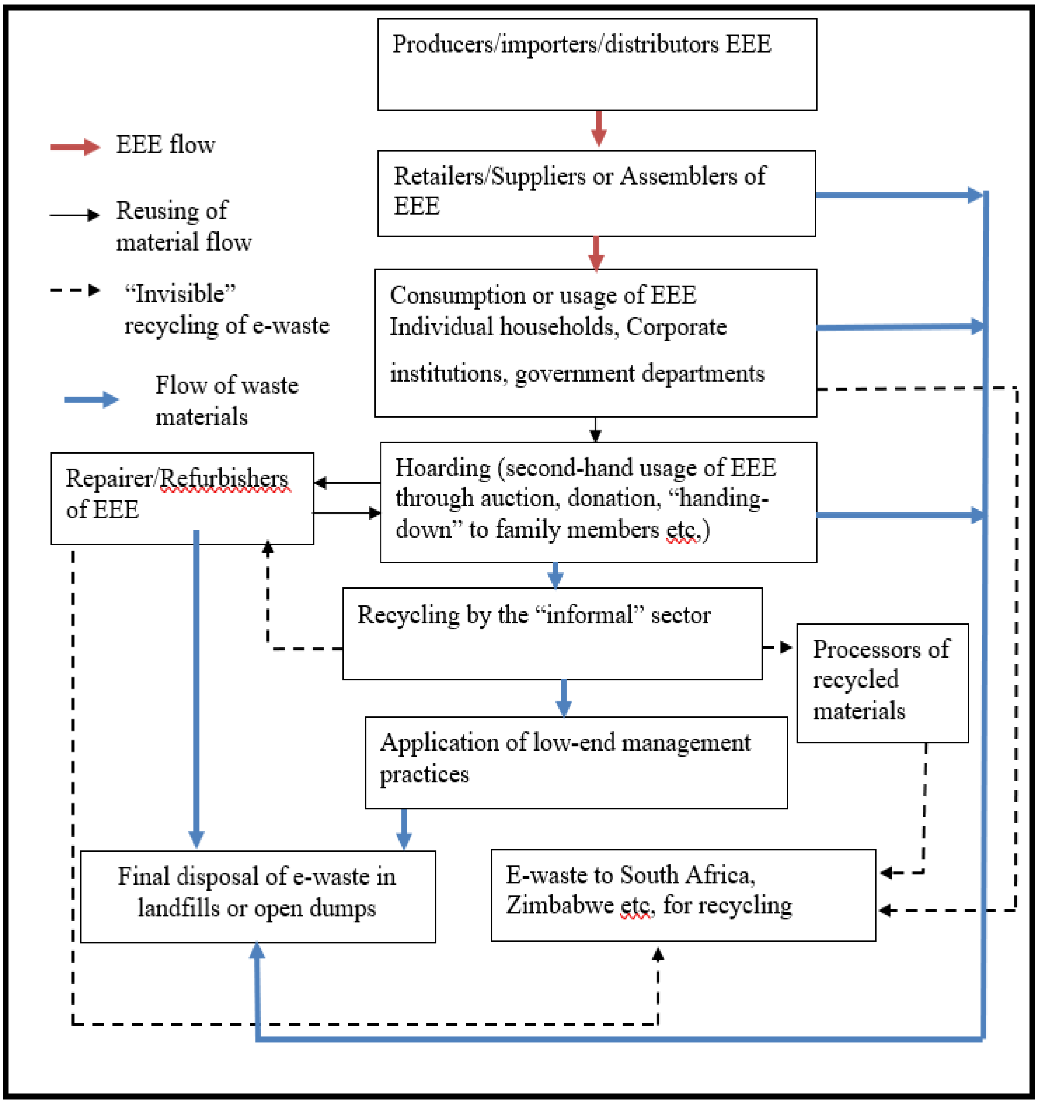

Fig. 4. General flow of e-waste in Botswana

Although recycling guidelines have been developed several years ago in Botswana, there are no signs of them being implemented for e-waste recycling and reuse and having any impact on the *status quo*. Experiences in other countries show that recycling facilities and regulations on e-waste are key factors for efficient e-waste recycling and reduction of environmental and public health impacts (Kahhat and Williams, 2012; Rotter et al., 2011; Ramzy et al., 2008). The most successful of this, is Switzerland, where collection, transportation, recycling/treatment and disposal of e-waste are vigorously implemented (Wäger et al., 2011). It is based on EPR and overseen by the producer responsibility organizations (PROs): The Swiss Association for Information Communication and Organizational Technology (SWICO), the Stiftung Entsorgung Schweiz (SENS), and the newer Swiss Lighting Recycling Foundation (SLRS) (Wath et al., 2010; Wäger et al., 2011). The country has also been able to lower recycling fees and comply with high environmental standards. E-waste related targets have been met (Wath et al., 2010).

For instance, from 2004 to 2009, the amount of waste taken back in Switzerland increased from 77,800 tons in 2004 to 112,770 in 2009, registering an average annual growth rate of 9%. The resulting collection rate of approximately 11 kg per inhabitant in 2004 rose to 15 kg per inhabitant in 2009, thereby surpassing the European average figure of 3 kg per inhabitant (Eurostat, 2010). Another effective program is e-waste recycling in South Africa. To achieve this, the South African government initiated the e-Waste Association of South Africa (eWASA) program to aid the establishment of a sustainable and environmentally sound e-waste management system. This program provides an important support for the various stakeholders (e.g. manufactures, e-waste handlers, refurbishers, dismantlers, and recyclers) to treat e-waste in an environmentally friendly manner (Anderson, 2008). Lessons learned from other countries are important insights to realize the safe means treat and process e-waste in an environmentally friendly manner. The case of Botswana's e-waste generation shows that there is a great potential to ensure that such activities are environmentally sound and create jobs for the informal sector. However, challenges still exist, and Botswana needs to further improve its e-waste management and disposal system.

3.4. Challenges

As mentioned earlier, the government of Botswana has made progress in the development of the waste management policies. However, there are also a number of challenges impeding e-waste management and disposal.

3.4.1. A lack of a well-established system that describes the actual practice of reduction and management of e-waste

The first challenge is the lack of a well-established system that describes the actual practice of reduction and management of e-waste. In fact, well-established systems that describe the practice of e-waste reduction and management have been established in many developed countries, with the US, EU member states, Japan, and Germany already achieving remarkable success in e-waste management and recycling activities (Rotter et al., 2011). In addition, informal collectors are replaced by formal collection systems. However, this is not the case in developing and transition countries, where incorporating the informal waste collectors into the under-developed formal collection systems could bring economic, environmental and social benefits (Qu et al., 2013). It is, however, to be noted, that lax enforcement of existing regulations, lack of separate collection channels and sophisticated treatment systems are the most significant obstacles to the reduction and effective e-waste management in developing and transition countries. In developed countries it has been noted that awareness of domestic users is an important aspect to successfully collect e-waste while residents need to pay for e-waste management, treatment or even collection (Taghipour et al., 2012). However, in Botswana, the local or central governments have yet to develop and implement standards for end-of-life EEE. It is not separated from municipal solid waste (MSW) because of lack of a well-established system that describes the actual practice of e-waste reduction and management. No criteria have been set to distinguish reusable e-waste from new items. Nor are they perhaps aware of the harm the batteries (i.e. contain a variety of materials such as heavy metals and other potentially toxic metals) they dispose of are causing to the environment. Currently, there is no facility in Botswana to reclaim the used batteries from e-products. Instead, they are collected with municipal waste and sent to landfill sites.

It is noted that an effective management or recycling system needs supporting infrastructure such as collection and transfer channels (Kahhat and Williams, 2012). For example, in the US, there are e-waste collection events organized time to time, including curbside collection, permanent drop-off centers or special drop-off events and point-of-purchase initiatives (Ramzy et al., 2008). In Germany, e-waste from individual residents is collected by different groups while e-waste from institutions is only collected by municipalities. In addition, Germany, Japan and the US have well-established effective and flexible collection infrastructure for e-waste collection (Kahhat and Williams, 2012; Sakai et al., 2008). However, in Botswana, there are no details and standards on e-waste management and is mainly disposal by consumers. Simultaneously, no door-to-door services for e-waste exist for residents in Botswana. These practical problems will bring many complexities to the entire e-waste management system, particularly at their end-of-life.

3.4.2. Lack of e-waste management policy

The second challenge is the lack of policy dealing specifically with e-waste management. Essentially, the cost to develop formal e-recycling programs is very high. In Botswana, as in most other developing and transition countries, the most frequently consumed e-products consists of famous multinational brands produced by well-known companies that obtain high benefits from the country. Nevertheless, the implementation of EPR programme has not taken place for these companies to take-back used electronic products at their end-of-life (EoL). The EPR is defined as…. "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle including its final disposal" (Nnorom and Osibanjo, 2008). In addition, EPR is defined as a "policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the products lifecycle, and especially to the take back, recovery, and final disposal of the product" (free of charge e.g. Germany) (Rotter et al., 2011), and also pay money for e-waste discarding (e.g. Japan), which ensures that treatment plants can get enough e-waste for economical treatment (Sakai et al., 2008). Without this kind of policy companies would not accept the responsibility for environmental protection, and formal e-waste management programs would not be initiated. Hence, it will be hard for Botswana to copy experiences from these countries, especially mandating manufacturers to take responsibility of their EoL e-products.

3.5. Simulation of the model results

A comparison between the predicted quantities of e-waste and actual e-waste generated in Botswana is shown in Fig. 3. Since the values are the same, there is no significant difference between them at the starting time point 0. This shows that the predicted e-waste generation values by the grey model are very close to the measured values of the datasets.

Following, the predictions of the quantities of e-waste using the above model, further tests are necessary to evaluate the validity of the forecast and actual values. To demonstrate the efficiency of the proposed forecasting model, this study employs two evaluation standards. Firstly, relative percentage error (*RPE*) comparing the real and predicted values to evaluate the results. *RPE* is defined in Eq. (14). We used the mean relative percentage (*MRPE*) approach to test the model (Eq. 19).

$$MRPE = \frac{1}{n}\sum_{k=1}^{n}\left[\frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)}\right] \times 100\% \quad (19)$$

where $\hat{x}^{(0)}(k)$ is the predicted value and $x^{(0)}(k)$ is the actual value.

By comparing the observed and forecast sequences (Table 3), the *MRPE* was calculated as 3.30% indicating that the GM (1,1) built in this study is an excellent representation of the e-waste generation behavior of the sample, and so, it can be used to forecast the annual e-waste generated from 2001 to 2019. Although the GM (1,1) can find the general tendency of an unknown system, it still cannot fully avoid the imprecision resulting from the insufficient database. Furthermore, when the data is old, it cannot disclose recent situations and may produce a decline in forecasting accuracy.

Table 3. Summary of the MRPE and e-waste generation prediction by GM (1,1) model

Year	*Real value*	*Predicted value*	*Absolute value*	*Relative error (%)*	*MRPE (%)*
2000	1.346	1.346	0	0.00%	3.30
2001	861	834.05	27	3.14%	
2002	790	784.3	6	0.76%	
2003	735	737.52	-3	-0.31%	
2004	646	693.52	-48	-7.43%	
2005	710	652.16	58	8.17%	

4. Conclusions

Experience indicates that it is always challenging to collect complete and reliable data for environmental issues in developing and transition countries like Botswana. Therefore, sometimes a short-term prediction is needed for strategic planning and policy design or reform of a particular issue. To demonstrate the potential application of such an approach, only data on five selected types of e-products were analyzed.

Hence, Grey model helps to do it with higher accuracy and also fills up the data gap. However, the GM(1,1) model shows its limitation when conducting long-term forecasting and also when handling large datasets compared with conventional forecasting models.

Acknowledgements

The authors gratefully acknowledge the helpful input of Emily for proof reading the article.

References

Alake T.J., Ighalo G.I., (2012), End of life strategies for effective electronic waste management in Nigeria, *International Journal of Scientific and Technology Research*, **1**, 73-76.

Amato A., Rocchetti L., Beolchini F., (2017), Evaluation of different strategies for end-of-life liquid crystal displays (LCD) management, *Environmental Engineering and Management Journal*, **16**, 1651-1658.

Anderson K., (2008), *The Good, the Bad and the Ugly of South African E-Waste Scenario*, Proc. of the 19th Waste Management Conference of the IWMSA (WasteCon2008), Durban, South Africa, 1-11.

ATE, (2012), Identification of the magnitude of the electrical and electronic (e-waste) situation in South Africa: a Strategic Approach to International Chemicals Management (SAICM) e-waste as an emerging policy issue, Report for the Africa Institute for Environmentally Sound Management of Hazardous and Other Wastes, and the Department of Environmental Affairs, Republic of South Africa, 1-119, On line at: http://africainstitute.info/wp-content/uploads/2013/02/E-WASTE-South-Africa-2012.pdf.

Awasthi A.K., Li J., (2017), Management of electrical and electronic waste: A comparative evaluation of China and India. *Renewable and Sustainable Energy Review*, **76**, 434-447.

Bartolacci F.B., Del Gobbo R., Paolini A., Soverchia M., (2017), Waste management companies towards circular economy: what impacts on production costs?, *Environmental Engineering and Management Journal*, **16**, 1789-1796.

Ceballos D., Beaucham C., Page E., (2017). Metal exposure at three U.S. electronic scrap recycling facilities, *Journal of Occupation and Environmental Hygiene*, **14**, 401-408.

CIA World Factbook, (2011), *A Country-By-Country Guide to the World-the Product of Sixty-Eight Years of CIA Intelligence*, Skyhorse Publishing, 1-864.

Clean Up Australia Ltd, (2009), E-waste Fact Sheet, 1-2, On line at: http://www.cleanup.org.au/PDF/au/clean-up-australia---e-waste-factsheet-final.pdf.

Del-Moral-Avila M.J., Huete-Morales M.D., Navarrete-Alvarez E., Quesada-Rubio J.M., Rosales-Moreno M.J., (2018), Study of an annual waste recycling index in Spain,

Deng J.J., (1989), Introduction to grey system theory, *Journal of Grey System*, **1**, 1-24.

DPA System, (2011), WEEE and BAT statistics Denmark 2010,2-45, On line at: https://www.dpa-system.dk/media/media/5e45ccdc-d151-4b0c-9e48-73b04b382998/UK_DPA-System/.

Eurostat, (2010), WEEE collection rate, kg per capita, On line at http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastestreams/weee.

Farzana S., Liu M., Baldwin A., Hossain M.U., (2014), Multi-model prediction and simulation of residential building energy in urban areas of Chongqing, South West China, *Energy and Buildings*, **81**, 161-169.

Gramatyka P., Nowosielski R., Sakiewicz P., (2007), Recycling of wastes electrical and electronic equipment, *Journal of Achievements in Materials and Manufacturing Engineering*, **20**, 535-538.

Gurauskiene I., Stasiskiene Z., (2018), Model for regional management of electrical and electronic waste (WEEE) flows, *Environmental Engineering and Management Journal*, **17**, 135-145

Hsu L.-C., Wang C.-H., (2007), Forecasting the output of integrated circuit industry using a grey model improved by the Bayesian analysis, *Technological Forecasting and Social Change*, **74**, 843-853.

Kahhat R., Williams E., (2012), Materials flow analysis of e-waste: domestic flows and exports of used computers from the United States, *Resources, Conservation and Recycling*, **67**, 67-74.

Kang H.-Y., Schoenung J.M., (2005), Electronic waste recycling: a review of US infrastructure and technology options, *Resources, Conservation and Recycling*, **45**, 368-400.

Khetriwal D.S., Kraeuchi P., Widmer R., (2007), Producer responsibility for e-waste management: Key issues for consideration-Learning from the Swiss experience, *Journal of Environmental Management*, **90**, 153-165.

Khupe S.J.N., (1996), Water, supply, sewage and waste management for Gaborone, Botswana, *Ambio*, **25**, 134-145.

Lee C.-H., Chang S.-L., Wang K.-M., Wen L.-C., (2000), Management of scrap computer recycling in Taiwan, *Journal of Hazardous Materials*, **73**, 209-220.

Legler J., Brouwer A., (2003), Are brominated flame retardants endocrine disruptors?, *Environmental International*, **29**, 879-885.

Liu X., Tanaka M., Matsui Y., (2005), Electrical and electronic waste management in China: progress and the barriers to overcome, *Waste Management and Resources*, **24**, 92-101.

Mao M., Chirwa E., (2006), Application of grey model GM (1,1) to vehicle fatality risk estimation, *Technological Forecasting and Social Change*, **73**, 588-605.

Mmereki D., (2018), Current status of waste management in Botswana: a mini-review, *Waste Management and Research*, **36**, 555-576.

Mmereki D., Baldwin A., Li B., Liu M., (2017), Healthcare waste management in Botswana: storage, collection, treatment and disposal system, *Journal of Material Cycles and Waste Management*, **19**, 351-365.

Mmereki D., Li B., Wang L., (2012), Estimation of waste electronic and electrical equipment arising in Botswana-a case study of Gaborone City, *International Journal of Environmental Sciences*, **3**, 441-452.

Mosha A.C., (1996), The City of Gaborone, Botswana: planning and management, *Ambio*, **25**, 118-125.

NCSA/GTZ, (1996), Study on the recycling of metal wastes. Report No. NCS/GTZ 6/96, Republic of Botswana, Gaborone, 1-52, On line at: https://wedc-knowledge.lboro.ac.uk/details.html?id=19162.

Nnorom I.C., Osibanjo O., (2007), The challenge of electronic waste (e-waste) management in developing countries, *Waste Management and Research*, **25**, 489-501.

Nnorom I.C., Osibanjo O., (2008), Sound management of bromated flame retardants (BFRs) plastics from electronic waste: State of the art and options in Nigeria, *Resources, Conservation and Recycling*, **52**, 1362-137.

Ongondo F.O., Williams I.D., Cherrett T.J., (2011), How are WEEE doing? A global review of the management of electrical and electronic wastes, *Waste Management*, **31**, 714-730.

Paul T.M., Tshetlhane T., (2013), Investigation of consumer behavior on discarding of their electrical/electronic waste: A case of Gaborone city, *E3 Journal of Business Management and Economics*, **4**, 200-205.

Qu Y., Zhu Q., Sarkis J., Geng Y., Zhong Y., (2013), A review of developing an e-wastes collection system in Dalian, China, *Journal of Cleaner Production*, **52**, 176-184.

Ramzy K., Junbeum K., Xu M., Allenby B., Williams E., Zhang P., (2008), Exploring e-waste management systems in the United States, *Resources, Conservation and Recycling*, **52**, 955-964.

Rotter V.S., Chancerel P., Schill W.P., (2011), Practicalities of individual producer responsibility under the WEEE directive: experiences in Germany, *Waste Management and Research*, **29**, 931-944.

Sakai S., Ikematsu T., Hirai Y., Yoshida H., (2008), Unit-charging programs for municipal solid waste in Japan, *Waste Management*, **28**, 2815-2825.

Savage M., Ogilvie S., Slezak J., Artim E., Lindblo J., Delgado L., (2006), Implementation of the Waste Electric and Electronic Equipment Directive in the EU 25, Technical Report Series, Ref: EUR 22231 EN, 1-89, On line at: http://www.jrc.es/publications/pub.cfm?id=1408.

So K., (2011), *Electronic waste management in Hong Kong: electronic waste management in Hong Kong*, MSc Thesis, The University of Hong Kong, Pokfulam, Hong Kong, 1-95.

Stanislav A., Branko K., (2018), Eco-efficient decision support model of solid waste recycling, *Environmental Engineering and Management Journal*, **17**, 1149-1159.

Statistics Botswana, (2010), Imports of electronic and electrical equipment in Botswana 2003-2011, Gaborone, Republic of Botswana, 1-10, On line at: https://www.tandfonline.com/doi/full/10.1080/10962247.2014.892544.

Statistics Botswana, (2011), Botswana Population and Housing Census Alphabetical Index of Districts, 1-50, On line at: http://www.cso.gov.bw/media/2011%20Census%20_Alphabetical%20Index%20of%20Districts.pdf.

Statistics Botswana, (2013), Gross Domestic Product. No:2013/14 second quarter, 1-10, On line at: http://www.cso.gov.bw/templates/cso/file/File/GDP%20Q2%20Sept%202013.final.pdf.

Taghipour H., Nowrouz P., Jafarabadi M.A., Nazari J., Hashemi A.A., Mosaferi M., Dehghanzadeh R., (2012), E-waste management challenges in Iran: presenting some strategies for improvement of current conditions, *Waste Management and Research*, **30**, 1138-1144.

Talebnejad A., Nadaf A., (2011), The use of grey system theory in predicting the road traffic accident in Fars Province in Iran, *Australian Journal of Business and Management Research*, **1**, 18-23.

Taye M., Kanda W., (2011), *E-waste management in Botswana*, MSc Thesis, Division of Environmental Technology and Management, Linköping University, Sweden, 1-46.

United Nations Population Division, (2012), Botswana: country implementation profile, International Conference on Population and Development Beyond 2014, July 2012, 1-4, Department of Economic and Social Affairs, Geneva, Switzerland, On line at: http://icpdbeyond2014.org/documents/download.php?file=FINAL_Botswana.pdf.

USEPA, (2012), Waste Transfer Stations: A Manual for Decision-Making, 1-54, Online at: http://www.epa.gov/osw/nonhaz/municipal/pubs/r02002.pdf.

Wäger P.A., Hischier R., Eugster M., (2011), Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment

(WEEE): A follow-up. *Science of the Total Environment*, **409**, 1746-1756.

Wang F., Huisman J., Meskers C.E., Schluep M., Stevels A., Hagelüken C., (2012), The Best-of-2-Worlds philosophy: developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies, *Waste Management*, **32**, 2134-2146.

Wath S.B., Vaidya A.N., Dutt P.S., Chakrabarti T., (2010), A roadmap for development of sustainable e-waste management system in India, *Science of the Total Environment*, **409**, 19-32.

WRAP, (2013), Waste and Resources Action Programme, Facts and figures, Online at: http://www.wrap.org.uk/content/facts-and-figures.