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A COMPUTATIONAL MODEL FOR ELECTRONIC-WASTE DYNAMICS

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ABSTRACT

This paper presents an overview of a research project focused on the development of computational models for studying the dynamics of Electronic waste. E-waste is becoming an issue of concern in developing countries in general and Nigeria in particular. The e-waste problem is increasing in dimension due to two main reasons: (i) lower prices of electronics and computer hardware and peripherals and (ii) the progressive reduction in the usage lifespan of electronic equipment. These result in the accessibility of electronic equipments to a greater number of people as well as in the increase in the rate at which the equipments become obsolete. This research is motivated by the need to developing a computational system for studying and predicting the pattern of e-waste accumulation. The methodology to achieve this aim includes data collection, e-waste process characterization and the design of a computational model based on the Markovian Birth-death process. Data from the Obafemi Awolowo University e-waste environment is used to develop the model. Our model will be useful in supporting decisions about the technical and economic problems emerging as a result of rising demand, user population growth, short usage life span and a decline of suitable disposal mechanism for e-waste.

Key words: e-waste, green computing, tragedy of the commons.

1. INTRODUCTION

Electronic waste (e-waste) is any appliance made from electronic devices that has reached the end of its useful life (OECD, 2001). It includes used computers, mobile handsets and other electronic devices which are destined for reuse, resale, salvage, recycling or disposal. The term e-waste is relative and context dependent. For example, what is considered an e-waste among a richer user population may still be able to provide several months of useful service to a poorer user population, though at a reduced efficiency. The generation and management of e-waste is a major policy and development issue "as inventory projections show its significant growth starting from the year 2012 upwards" (Ministry of Environment, 2009). E-waste from mobile phones, TVs, PCs, refrigerators, IPD, IPODS, PDAs, and so on is growing at a fast rate. The danger posed by e-waste to the health of humans and the environment is considerable and extensive. The ability to **reduce, reuse or recycle (3Rs)** this waste is a major concern for policy planners, implementers and stakeholders worldwide.

E-waste is growing in volume and dimension for two important reasons:

i. Reducing prices of electronic devices. This makes the devices accessible to more people hence increasing the effective user population;
ii. Reduced usage life of electronic devices. This leads to increase in the rate at which the devices become obsolete and the end of their useful life.

A term closely related to e-waste is **Green computing.** This can be defined as "the study and practice of defining, manufacturing, using and disposing of computers, servers and associated subsystems – efficiently and effectively with minimal or no impact on the environment" (Murugesan, 2008). It relates to an environmental footprint which deals with the level of damage to the environment as a result of all activities relating to the use and disposal of a technology product.

The problems posed by e-waste are becoming an important issue of concern in developing countries particularly African countries. This is in the background that the user population is poorer and most of the equipment being used are near to the end of their useful life-span before purchase. In addition, there is no well design mechanism for the management of the obsolete electronic equipment. A graphic picture of the evolution of e-waste can be gleaned from university campuses where there is a high concentration of electronic equipment's user population. In the Obafemi Awolowo University campus for example, a lot of e-waste are dumped indiscriminately on the campus.

The junk of IBM 360 machine (see Plate 1) used on the campus more than fifteen years ago is dumped at the back of the Computer Buildings. Plate 2 shows the junk of the popular IBM AS 400 minicomputer that was used in the Department of Computer Science and Engineering for student practical classes, student projects and exam processing abandoned at the Utility Block area of the campus. Plate 3 depicts old monitors littered on the staircase of the Computer Building along with other paper waste while Plate 4 shows junks of computer system units left abandoned in one of the stores in the Computer Building. The e-waste story is not different for other departments/units in the university campus.

PLATE 1: Junk of IBM 360 Mainframe

PLATE 2: Junk of IBM AS 400 Minicomputer

PLATE 3: Junk of Computer monitors

PLATE 4: Junk of computer system units

The characteristics and dynamics of e-waste is complex. An abstraction that adequately and effectively describes the e-waste behavior while at the same time simple enough for comprehending the problem of e-waste is desirable. This research addresses this problem by developing a computational model and simulation software for studying the e-waste problem dynamics.

In section 2, some of the models found in literature are given that tackle the e-waste problem along with valuable and hazardous e-waste materials. In Section 3, the theoretical foundation of this work is described. In section 4, the solution paradigm is given with the aim and objectives of the study listed. In section 5, the methodology for achieving the objectives is narrated while section 6 concludes the paper.

2. LITERATURE REVIEW

There are quite a few models in the literature used in the study of the e-waste problems. Those relevant to this study include the Process model for e-waste disposal services, the e-waste recycling model, and the Green e-waste channel model. These give a general overview on how the challenges of e-waste are being addressed in various parts of the world. Also we will examine valuable e-waste materials and hazardous materials found in e-waste which contain toxic components which constitute danger to the environment and human life.

2.1. E-waste Models

The Process model for e-waste disposal services is a model devised by the Government of Andhra Pradesh to recycle all the e-waste available in various government Departments/Head of Departments offices (Information Technology and Communication Dept., 2010). The model works as follows:

i. Departments will indicate the details of e-waste available including their locations.
ii. The department officials will certify that this e-waste equipment for recycling and disposal is no longer working and cannot be repaired having no important data/ Information relating to the department.
iii. The collection agency would collect the e-waste material showing the components, weight and date of handing over.

iv. The agency would supply a certificate stating that the e-waste material collected from the department is recycled and disposed as per the relevant norm.

The empaneled agency made payment at RS. 27/per kilogram of e-waste. 20 percent of this amount received was used towards services rendered and also management of e-waste corpus fund while the remaining 80 percent was used as per instruction of the Information Technology Communications Department, Andhra Pradesh Secretariat.

The e-waste Recycling model: This model is a linear model and is based on input-output principles to handle e-waste management in India (Sinha and Mahesh, 2007) (see Figure 1). It recommends a very important role for the manufacturers/ producers of electronic goods. Others include generators of waste, the recyclers and the policy makers and regulators who will direct the process. An organization called Producer Responsibility Organisation (PRO) will take responsibility of the end-of-life disposal of products being manufactured or assembled and they are largely responsible for environmentally sound management of e-waste.

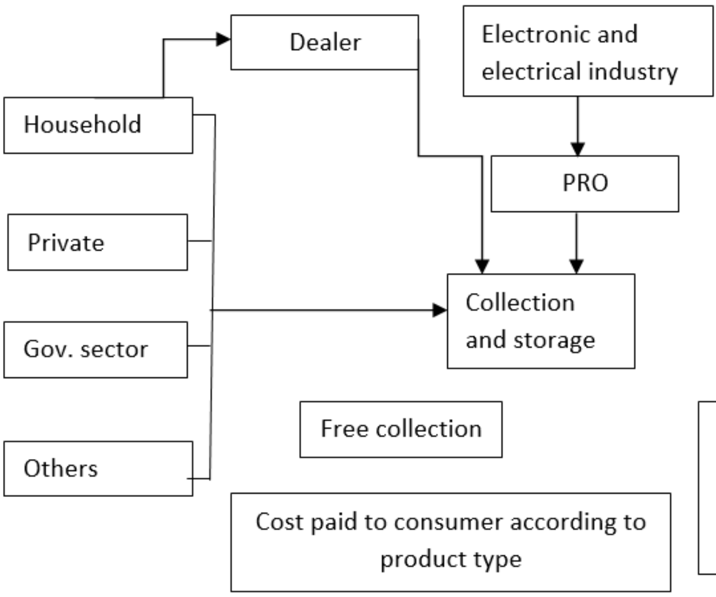

Figure 1: E-waste recycling model (Sinha and Mahesh, 2007)

The benefits of that model are efficient resource recovery, potential to create jobs, environmental benefits, occupational safety and integration of present informal sector. Additional element of the model is the need for a strict ban on import of e-waste into the country and permanent ban imposed on donation of computers by developed countries.

The Green e-waste channel is a model for a reuse and recycling system of electronic waste in South Africa. The Green e-waste channel is a concept that represents the infrastructure and the processes e-waste go through from the discarding of the end-of-life equipment from private households and corporate consumers to the clean raw material to be reprocessed or to the final disposing (Bondolfi, 2007). The model was designed to define the role of each stakeholder within a channel that the e-waste should go through, right from the collection of the discarded equipment to the very last step in the process-raw material, through several intermediate steps including the take-back, the recycling and other loops to extend the lifespan. The SWOT analysis (strengths, weaknesses, opportunities, and strengths) was used to test the viability of the model. The analysis showed that the model had many opportunities with advantages for all stakeholders such as sufficient material to be provided to processors and refurbishers, safe creation of jobs, a convenient solution provided for the customers and solutions for end-of-life equipment offered for the producers. The Green e-waste channel is suitable for South Africa because its e-waste situation is relatively clean, with limited informal recycling and more sustainable waste management.

McDonough and Braudnart (2002) proposed a full cradle to cradle life cycle analysis which depicted the entire environmental impact of all the energy and materials that flow into and out of a notebook computer. Such an analysis looked at the impact from raw material extraction to final recycling (DesAutels and Berthon, 2011, p.114). Yet none of the existing research provide a full cradle to grave analysis on notebooks in particular or e-waste in general. All the models discussed above do not include any computational model to study and evaluate e-waste dynamics. This study proffers such a model as the Markovian birth-death process to be used for the analysis of e-waste dynamics.

2.2. E-waste materials: Valuable and Hazardous Materials

When electronic equipment reaches its end-of-life, some its components may still be useful. The equipment may be reduced, recycled or reused (3Rs) but one may still be able to extract valuable scrap materials. Some valuable materials found in e-waste include copper, tin, lead, aluminum, nickel, iron, zinc and plastic. If some of these are abandoned for too long, they may become hazardous to the environment and humans. For example, lead can leak into the pipes for drinking water. When such water is consumed, it can result in nervous damage (see Table 1). Table 1 shows computer e-waste and their environmental/ health impacts. In the next section, the theoretical context of the e-waste problem is examined.

3. THEORETICAL CONTEXT OF E-WASTE

The problem of e-waste accumulation can be explained using the theory of the *Tragedy of the commons*. This is a theory describing a mechanism by which utility maximizing individuals sharing a collective resource (the commons) will, without intervention, take actions that depletes and eventually destroy the very resource they are taking benefit from (Lloyd, 1833). The theoretical context of the tragedy of the commons as applied to e-waste model is illustrated in Figure 2.

The *commons* in this model is the natural resource from which electronic systems are made. These resources are limited and finite in quantity. They also form part of the components of a delicate ecosystem. An imbalance in the ecosystem will produce a catastrophic consequence. The user group forms the utility-maximizing individuals sharing the collective resource (the commons). These individuals are increasing in numbers, becoming more assertive and their demand for the electronic devices, i.e. the commons, is increasing rapidly.

Table 1: Computer e-waste and their environmental/health impacts

Material	% of total (by weight)	Main Applications in Computer production	Environmental/Health Impacts
Plastics including polyvinyl chloride (PVC)	23.00%	Cabling, computer casing	Various cancers, endocrine system disruptions
Lead	06.00%`	Soldering of printed circuit boards; glass panel in CRT	Damage to nervous system, blood system and kidneys; serious effect on child brain development
Barium	0.03%	Vacuum tubes in CRT monitors	Brain swelling, muscle weakness, damage to the heart, liver and spleen.
Beryllium	0.02%	Used for thermal conductivity	Causes lung cancer and skin diseases.
Cadmium	0.01%	SMD chip resistors, infrared detectors, semiconductors.	When landfilled, can leach into ground water. Can be absorbed either through respiration or ingested through food.
Hexavalent chromium	0.006%	Hardener for steel casing	Causes strong allergic reactions – may cause DNA damage.
Selenium	0.002%	Used in rectifiers and printed circuit boards	Causes selenosis – hair loss, nail brittleness and neurological abnormalities.

***Source**: Environment Victoria (2005)*

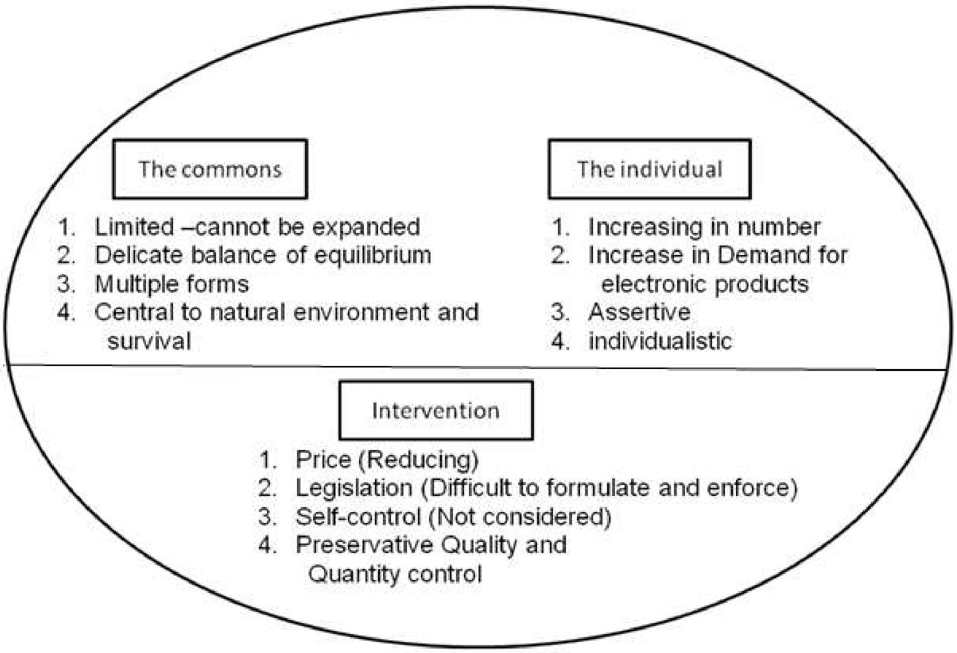

***Figure 2**: The theoretical context of the 'tragedy of the commons' as applied to e-waste model **Source**: Olufokunbi (2015)*

If there is no effective intervention, such as discriminative pricing or enforceable user control mechanism, the users group will eventual act to destroy the natural resource, through primitive and uncoordinated accumulation. In the next section we will discuss the development of a phenomenon and process that could be used to explore the characteristics and dynamics of the e-waste environment using computational models.

4. SOLUTION PARADIGM

Computational models and their simulation can allow individuals to study this problem in order to gain useful incite knowledge and better understand the situation. Verification and validation will be done using the computer e-waste situation of the Obafemi Awolowo University as our case study. This will be compared with the research done by Olufokunbi (2015) where automata theory and a Petri net model were used for e-waste process dynamics. The aim of this study is to develop a computational model that captures the e-waste dynamics in terms of its generation and accumulation. Such model will serve as a tool for observing various views of the pattern of growth and dynamics of the e-waste. This will allow us to investigate the key actors and events responsible for e-waste and the nature and scale of their contribution in the e-waste cycle. To achieve the above aim, the following objectives will be deployed. We will analyze and characterize the e-waste life-cycle in the context of a developing country environment and collect data in respect of the computer e-waste. A computational model that captures the behavior of the processes underlying e-waste generation and accumulation will be developed. The model developed will be verified and validated.

4.1. Methodology

To achieve the set objectives, first classify e-waste into categories using variables such as usage, source type, disposal challenges, and environmental impact. The source will give us information on the manufacturer, the make, the year of purchase, etc. The disposal challenges will consider data on how the e-waste will be disposed after the end of its usage life. The environmental impact relates to data on the positive or negative impact of the e-waste on the environment. Data will be collected on e-waste by designing appropriate data collection instruments and administering them in the Obafemi Awolowo University as discussed in the section below. A computational model based on the Birth-death methods for capturing the behavior of the e-waste generation and accumulation is developed. The model will be simulated and validate using comparative analysis of the data with respect to other models used for e-waste. The novelty of our approach comes in the context of the use of computational model in the study of e-waste.

4.2. Data collection

In this research, the focus is on computer e-waste at the Obafemi Awolowo University in Ile-Ife, Nigeria. This consists of computer components and peripherals such as personal computers (PCs), notebooks, laptops, printers, monitors, scanners, plotters, keyboards, disc drives, floppy discs, flash drives, mouse items, etc. Plates 1 to 4 given in Section 1 depict some of the e-waste that feature on campus. The e-waste data will be collected from the academic area of the campus, the student hostels and the staff quarters. Structured questionnaires will be administered and interviews will also take place to consider the use of computer items, years of usage, make (model), the source, the disposal challenges, etc. An archive of images of the e-waste is being collected using digital cameras. The collected images will be analysed to collect further data and augment the data collected.

4.3. Computational Model Development

A computational model is formulated based on the Markovian birth-death process. This is a process which provides a full cradle to grave view of the elements comprising the e-waste in an environment. The Markovian birth-death process formulation of the e-waste problem, models the stages from the time a computer system is produced and put in the market for sale (a birth), unto the time it has reached its end-of-life becoming obsolete (a death). A *population* is a set of objects having a common characteristic (Bronson and Naadimuthu, 1997). The population to be considered here is computer, working or obsolete. The number of members in a given population at time t is designated by $N(t)$. The *states* of a growth process are the various values $N(t)$ can assume; these are generally the nonnegative integers. The probability that $N(t)$ equals a specific nonnegative integer n is denoted by $P_n(t)$.

The aim is to model and analyse the dynamics and pattern of growth of e-wastes. To this end, we identified three stages in the electronic devices life cycle: (i) birth, (ii) active and (iii) death (see Figure 3).

Figure 3: E-device life cycle

In the birth stage, S_0, new e-devices enter the life cycle. In the active/use stage, S_1, the e-device is in service and actively in use by the user. The death stage, S_2, is when the e-device becomes obsolete as a result of end of its useful life-span. The dynamics here can be modeled as a system with complex process which comprise of discrete states with exponentially distributed time. Transition between states occurs in accordance with the embedded Markov-chain. An important feature of the e-waste dynamics, which is captured by this model, is the current behavior of the process is independent of its entire history or previous states. The interrelation between S_0 and S_1 can be regarded as a pure-birth process while that between S_1 and S_2 can be modeled as a pure-death process.

Formally, let N(t) be the population of a set of objects having a common characteristic at time t. One can, then, identify 3 unique but independent populations in our model. $S_0(t)$, $S_1(t)$ and $S_2(t)$ will represent the birth, active and death population at time t. The state of a growth process will then be the various values of $N(t)$ at time t. If $P_n(t)$ is the probability that the population N(t) equals an integer value n at time t, then we can analyse the e-waste cycle model in Figure 3 as combination of a pure birth process and a pure death process.

If the probability of exactly one birth in time interval of Δt and λ_n and μ_n are the birth and death rate respectively , then as t approaches zero, the Kolmogorov equations for the state probability is given by:

$$\frac{dP_n(t)}{dt} = -(\lambda_n + \mu_n)P_n(t) + \mu_{n+1}P_{n+1}(t) + \lambda_{n-1}P_{n-1}(t) \quad for\ n = 1, 2, ... \tag{1}$$

when n = 0 (i.e. at the initial state of the process)

$$\frac{dP_0(t)}{dt} = -\lambda_0 P_0(t) + \mu_1 P_1(t) \tag{2}$$

note that $\mu_0 = 0$.

A solution to equation can be derived by using the Poisson birth-death process (PDDP). The PDDP is a Markovian pure birth-death process in which the probability of a birth in any small time interval is independent of the size of the population. This process is analysed as follows.

4.4. Modelling the Birth Process (S_0S_1).

In the Birth process, for all n, $\lambda_n = \lambda$ and $\mu_n = 0$ (i.e. birth rate is zero). If the initial population of the e-waste of interest in $N(0)$, then the solution to Equation (1) is given by:

$$P_n(t) = \begin{cases} (\lambda t)^{n-N(0)} \times e^{-\lambda t} & if\ n \geq N(0) \\ 0.0 & otherwise \end{cases} \quad (3)$$

The expected size of the population at time t is:

$$E[N(t)] = N(0) + \lambda t \quad (4)$$

4.5. Modelling the Death Process (S_1S_2)

In the death process, for all n, $\lambda_n = 0$ and $\mu_n = \mu$ (i.e. birth rate is zero). If the initial population of the e-waste of interest in $N(0)$, then the solution to Equation (1) is given by

$$P_n(t) = \begin{cases} 0.0 & if\ n > N(0) \\ (\mu t)^{N(0)-n} e^{-\mu t} & if\ 1 \leq n \leq N(0) \\ 1.0 - \sum_{n=1}^{N(0)} P_n(t) & if\ n = 0 \end{cases} \quad (5)$$

The expected size of the population at time *t* is

$$E[N(t)] = N(0) + \mu t \quad (6)$$

To synthesis the above model, we note that PDDP is that in which the probability of a birth (i.e. addition of new computer devices) and that of a death (i.e. when a computer device becomes non-usable) in any small time interval are independent of the size of the systems already in circulation whether usable or non-usable. The authors' aim is to use and collect more data to determine the parameters of equations (1), (3) and (5).

5. CONCLUSION

This ongoing work on e-waste characteristics and dynamics has been discussed. Data will be collected and compared with the result of Olufokunbi (2015). The former research was done using automata theory and a Petri net model for e-waste process dynamics. This ongoing work is to produce robust software for modeling and simulation of the behavior of e-waste using the Markovian birth-death process. The model will be validated using comparative analysis of the data. The model results will be useful in solving a pertinent problem as a result of rising demand, user population growth, short usage life span and a decline of suitable disposal mechanism for e-waste.

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