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Estimating the Amount of Electronic Waste Generated in Indonesia: Population Balance Model

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Abstract. Waste of electrical and electronic equipment, better known as electronic waste (e-waste) shows an increasing trend from time to time. By 2016, the total amount of e-waste generated globally has reached 44.7 million metric tons (Mt), i.e. 24.4% of growth over the past five years. It should not be a problem if all of this waste is being collected and recycled properly. Statistics show that only around 20% of the e-waste generated in the world was recycled properly. The situation is even worse in the developing countries where the population has not yet covered by e-waste legislation, such as Indonesia. The lack of reliable e-waste data is the main reason as no statistics are available to show that e-waste in Indonesia is growing rapidly and will cause problems in the future. This study attempts to quantitatively estimate the e-waste in Indonesia by using the population balance model (PBM). PBM enhances the estimation results by involving all three data points, i.e. sales, stocks and lifespans in the calculation step. The e-waste estimated is for four most common e-products found in the e-waste stream in Indonesia. These four products are categorized into two groups based on their market’s characteristics. Washing machines, refrigerators, and television represent part of saturated market products, while mobile phones lie in the unsaturated market category. The results show that the average growth rate of e-waste in Indonesia is 14.91% annually. The total amount of electronic waste generated in Indonesia is estimated to reach ±49,627,917 units (±487,416 ton) by 2028.

1. Introduction

Electronic waste (e-waste) is all types of electrical and electronic equipment and its parts that have reached their end of life or have been discarded by its owner as waste without the intention of reuse [1]. E-waste is not only the fastest growing waste stream in terms of quantity but also in toxicity [2]. This means that the higher the quantity of e-waste the higher the risks of toxic exposure in humans and environment. The blatant issues of e-waste rising worldwide do not followed by the development of proper treatment in the regions. According to the e-waste monitor report published by the United Nations University (UNU), only 20% of the e-waste generated in the world was collected and recycled through formal channels in 2016 [2].

E-waste needs to be collected and recycled appropriately as their contents are both harmful and valuable. Lead, mercury and other harmful substances in the e-waste stream have a big environmental and health risks when being treated improperly. E-waste also contains valuable raw material, i.e. silver, gold and palladium that have a high financial value. It is estimated that around 55 billion euros worth of raw materials were presented in the e-waste stream in 2016 [2]. The low formal recycling rate is...
mainly caused by the lack of e-waste legislation and e-waste formal take-back system development, especially in the developing countries.

Asia, as the biggest producer of e-waste, i.e. around 40.7% of the e-waste generated worldwide has not yet entirely covered by the e-waste legislation. Only several countries in Asia have covered its population by e-waste legislation, including China, India, Japan, Hong Kong, South Korea, Viet Nam, Myanmar, Cyprus, and Turkey [2] while others still pay very little attention to this issue. Indonesia is one of the countries in Asia which e-waste legislation is still nonexistence. The lack of reliable e-waste data is the main reason as no statistics are available to show that e-waste in Indonesia is growing rapidly and will cause problems in the future. The nonexistence of e-waste formal legislation resulted in a big dominance of informal sector in Indonesia.

Electronic waste is a growing issue in the developed and developing countries. In the developing countries, issue of e-waste has started gaining more attention, especially in the academic community. A lot of studies regarding electronic waste were being conducted over the past decade. Study of e-waste estimation is by far one of the most active research areas in e-waste because improvement is always needed to enhance the estimation results. Better e-waste estimation will leads to better information about e-waste and resulted in determining the best e-waste policies for each country. The best practices regarding e-waste formal take-back system are different in every country, which depend highly on their e-waste statistics thus need to be analyzed individually. Studies regarding e-waste estimation in the developing countries have been conducted in several countries, including India [3], Hong Kong [4], Brazil [5], South Korea [6], China [7, 8], Iran [9], Vietnam [10] and Indonesia [11, 12].

The methods to estimates e-waste generated are divided into four main groups, that is disposal related analysis, time series analysis, factor models and Input-Output analysis [13]. Extensive literature review shows that Input and Output Analysis (IOA) method is most widely used in e-waste estimation study. The IOA method not only estimates the outputs but also evaluates the interconnection of the data quantitatively [13]. The IOA method is classified into five groups based on the types of data needed, i.e. time step model, market supply model, stocks-based model, population balance model and sales-stock-lifespan model [10]. The population balance model and sales-stock-lifespan model are further classified as the advanced IOA method. Advanced IOA method attempted to enhance the estimation results by involving all three data points, i.e. sales, stocks and lifespans in the calculation step. Advanced IOA method is rarely used in the e-waste estimation study conducted in developing countries commonly because of data limitation. Both population balance model (PBM) and sales-stock-lifespan involved all three variables. The difference between these two methods is the type of stocks data needed. In the sales-stock-lifespan model, the disposal age profile data and the stock age profile data are required to construct the active stocks data, while in the PBM, only total number of stocks data are used [10]. Considering this factor, the PBM method is more appropriate to be adopted in the study in Indonesia as only total number of stocks data is available.

Previous study regarding e-waste estimation in Indonesia shows several limitations, i.e. average lifespan was used for both saturated and non-saturated products, the growth of electronic products was assumed to be constant each year for both category products, and stocks variable were not considered in the estimation [11]. Average lifespan is applicable to saturated market products but less accurate for non-saturated market products, which growth and innovation are still very dynamic over time. This study attempted to improve the estimation of electronic waste in Indonesia by using the advanced IOA method and using distribution lifespan in the calculation.

Estimation of e-waste generated in Indonesia in this study is based on the four most common types of product found in Indonesia e-waste stream, which is refrigerator, washing machine, television, and mobile phone. Initial literature review shows that there is a characteristic that classified the electronic product in Indonesia, i.e. saturation level. Considering this factor, the extended logistic function is adopted in this study instead of the conventional simple logistic function. The extended logistic function is selected because it can capture either saturated market or non-saturated market well and give better performance than the latter [14]. This study will be the first to incorporate the extended
logistic function into the population balance model to estimate e-waste quantity for both saturated and non-saturated market in Indonesia. The study for the non-saturated market category has been conducted earlier in 2018 [12]. This study is the extended version of the previous study and will combine both markets in estimating the total e-waste generated in Indonesia.

The purpose of this study is to provide quantitative insight and basis in decision making for the formal sector in Indonesia to develop formal e-waste take-back policies and systems in Indonesia. Better e-waste statistics is expected to provide a quantitative basis in helping the policy makers in Indonesia to identify the best practices regarding e-waste formal management system in Indonesia, i.e. developing e-waste take-back policies that suits Indonesia condition at best, identifying the right capacity for recycling infrastructure based on the e-waste generated. A well-developed formal management system can minimize and prevents informal recycling because the formal sector will have a better track of e-waste statistics over time. High accuracy of estimation results is expected to develop an applicable e-waste system and infrastructure in Indonesia.

2. Materials and method

Data is the most important factor in e-waste estimation study [13]. Types of data available and quality of the data determine the most appropriate method to be adopted in the study. After an extensive literature review, PBM is found the most suitable method to be used to estimate e-waste generated in Indonesia based on current condition.

2.1. Data

Secondary data obtained from literature review and expert interview were used as the inputs in this research. Table 1 presents the type of data used and the source of these data. The data were divided into three types based on the type of data needed in estimation using IOA method. Table 1 also shows that each type of data from each type of product does not have the same data source and timeframe. Data of mobile phone subscriptions were used to construct the sales data of mobile phone products. It is assumed that one subscription of mobile phone denotes one unit of mobile phone sold in the market.

Table 1. Types of Data and Data Source.

| Types of Data | Types of Product | Data available (timeframe) | Source |
|--------------|-----------------|----------------------------|--------|
| Sales        | Mobile phone    | Subscriptions Data (2000-2016) | [15]   |
|              | Television      | Import data (2012-2016)     | [16]   |
|              | Refrigerator    | Sales data (2007-2013)      | [17]   |
|              | Washing machine |                             |        |
| Stocks       | Mobile phone    | Product/inhabitant (1985-2017) | [2]    |
|              | % Mobile phone penetration rate (2005-2015) | [17] |
|              | Television      | Product/inhabitant (1980-2017) | [2]    |
|              | % Television penetration rate (2013-2016) | [17] |
|              | Refrigerator    | % Refrigerator penetration rate (2008-2013) | [16, 17] |
|              | Washing machine | % Washing machine penetration rate (2008-2013) | |
| Lifespan     | Mobile phone    | Weibull Parameter: initial value (2015) | [18]   |
|              | Television      |                             |        |
|              | Refrigerator    |                             |        |
|              | Washing machine |                             |        |

The lifespan of products will follow a statistic distribution to illustrate a more representative of electronic products used in Indonesia. Distribution lifespan represents a larger population compared to the average lifespan. Weibull distribution is adopted to represent the product lifespan in Indonesia. Data of initial Weibull parameter values are needed to model the lifespan of each electronic product. The initial values of Weibull parameter used in this study are obtained from the e-waste statistics.
2.2. Method: population balance model

Estimating e-waste using Population Balance Model consists of three main steps, i.e. modeling the product lifespan, constructing the time series of product active-stock, calculating total product sales and calculating total e-waste generated.

2.2.1. Modeling the product lifespan. The first step in estimating e-waste is by modeling the distribution of each product lifespan. Product lifespan is the interval of the period from when a product is purchased to the time it is discarded by its owner with no intention of reuse [12]. The product lifespan used in this study is the product lifespan for one owner and does not include storage time of the product.

There are two types of lifespan used in estimating e-waste, i.e. average lifespan and distribution lifespan [19]. Average lifespan is often used in estimating e-waste in developing countries to simplify the calculation because data are usually neither available nor reliable. Distribution lifespan provides a better representative of product usage but usually difficult, time-consuming and expensive to obtain. A simplified estimation method was proposed by Oguchi et al. [20] to estimate a lifespan distribution without the requirement of detailed data such as product discarded age profile or active-stock age profile. The method of estimating is based on the surviving rate of each product age in the year t. The equation used to estimate using the survival rate function is as follows [20]:

\[ W_t(y) = \exp \left( -\frac{y}{y_{av}} \times (\Gamma(1 + 1/b))^b \right) \]  

(1)

\( W_t \) is expressed by using Weibull distribution function, \( y \) is the product age, \( y_{av} \) is the average lifespan, \( b \) is the shape parameter, and \( \Gamma \) is the gamma function.

Next, the survival rate data are used to calculate the disposal rate of product for each year. Disposal rate data of each product each year is then used to model the product lifespan based on the Weibull distribution function. The Weibull function is adopted because it was verified to produce the best fit of most electrical and electronic product lifespan [19]. The Weibull function is written as follows:

\[ L(t, t_n) = \frac{b}{a} (t_{n} - t)^{b-1} e^{- \left( \frac{(t_{n} - t)}{a} \right)^{b}} \]  

(2)

where \( t \) is the time in the historical year, \( t_n \) is the evaluation year, \( a \) is the scale parameter and \( b \) is the shape parameter. The shape and scale parameter used in this study is constant for each year.

2.2.2. Constructing the time series of electronic product active stock. Time series of product active stock is obtained by multiplying the time series of products per household with the total number of households using electronic products. The total number of households using electronic products is described and forecasted using the extended logistic function. The carrying capacity in extended logistic function is dynamic over time, which overcomes the limitation of the simple logistic function [14]. The equation of the extended logistic function is as follows [14]:

\[ S_t = \frac{k(t)}{1 + C e^{-a(t-t_0)}} = \frac{1 - D e^{-a(t-t_0)}}{1 + C e^{-b(t-t_0)}} \]  

(3)

Where \( k(t) \) is the carrying capacity that fluctuates with time, \( t \) is the evaluation year, \( t_0 \) is the initial year and \( a, b, C, D \) are the parameters determined using a nonlinear estimation method.

2.2.3. Calculating total product sales and calculating total e-waste generated. E-waste in Indonesia will be estimated based on the principle of population balance model (PBM) using lifespan distribution in this study. The equations for PBM method are given below [21, 6].

\[ f_t(i) = L_t(i) - L_{t-1}(i-1) \]  

(4)

\[ N_t = P_t + \sum_{i=1}^{n}[P_{t,i}(1-L_t(i))] \]  

(5)
\[ G_t = \sum_{i=1}^{t-i} P_{t-i} f_t(i) \]  \hspace{1cm} (6) 
\[ P_t = N_t - N_{t-1} + G_t \]  \hspace{1cm} (7)

\( f_t(i) \) is the disposal rate of the product of age \( i \) which has reached its end of life in the year \( t \). \( L_t \) is the cumulative lifespan distribution based on the Weibull distribution that obtained in the previous step. \( N_t \) is the number of active-stock products at the end of year \( t \). \( G_t \) is the amount of e-waste generated at year \( t \). \( P_t \) is the number of product sales in year \( t \). The estimation of e-waste generated for each year is calculated using (6), while the product sales for upcoming evaluation years can be calculated using (7).

3. Results and discussion

3.1. Distribution lifespan of electrical and electronic products in Indonesia

Distribution lifespan for each product is modeled by following the Weibull distribution. Distribution of the lifespan is assumed to be constant for each evaluation year. Best-fit Weibull parameter for each product is obtained after validating the model obtained using the least squares method with the help of Microsoft Excel Solver. Results show that best-fit shape parameter and scale parameter obtained for products in Indonesia are 3.1 and 3.6 for mobile phone, 2.87 and 11.69 for television, 2.73 and 16.22 for refrigerator, 2.85 and 12.82 for washing machine.

Based on the parameter obtained in validation step, the model of lifespan distribution for each product type can be constructed. Figure 1 shows the distribution model for each product. Average lifespan can be calculated by the mean value of Weibull distribution. The average lifespan for a mobile phone in Indonesia is 3.42 years [12]. This number shows that a mobile phone in Indonesia is almost the same as the average lifespan of a mobile phone in South Korea, i.e. 3.4 years [6] but has a shorter average lifespan compared to Europe, i.e. 9.62 years [18]. Average lifespan of the saturated market products in Indonesia is 10.42 years for television, 14.43 years for refrigerator, and 11.42 years for washing machine.

![Figure 1. Lifespan model for electrical and electronic products in Indonesia.](image)

Lifespan comparison of each product observed in this study shows that products with saturated market characteristics have a longer lifespan than the non-saturated market products. One of the reason is sales in the saturated market usually happen to replace the old device that had reached its end of life while in non-saturated market, sales are basically caused by new users or new technology offered by the company [5]. Dynamic technological innovation resulting in the shortening lifespan for products in non-saturated market category [5]. This phenomenon can be seen happening in the mobile phone market.
3.2. Estimation results for electrical and electronic products stocks
Penetration rate for upcoming evaluation years is predicted using the extended logistic function. The extended logistic function can perform well in predicting market growth with limited historical data [14]. This characteristic makes the extended logistic function suitable for Indonesia market condition, which not every product has a large historical data [1]. Penetration rate for each product is predicted by finding the best-fit parameter for each product based on its historical penetration rate data. The least squares method is used in validation by minimizing the residual sum of square ($R^2$) values.

Based on the calculation step, a best-fit growth curve for each product penetration rate is obtained. Previous study for the non-saturated market product, i.e. mobile phone shows that the growth speed mobile phone carrying capacity in Indonesia is 0.2 [12]. Results obtained in this study shows that the growth rate for refrigerator and washing machine has reached the value of zero while for television the growth rate is very close to zero, i.e. 0.02. These results proved that television, refrigerator and washing machine market in Indonesia had saturated but the mobile phone market has not yet reached saturation.

3.3. Estimation of e-waste generated in Indonesia.
The population balance model (PBM) is adopted to estimate the total e-waste generated in Indonesia. The estimation is done in a time frame of 10 years, i.e. from 2018 until 2028. The estimated result of electronic waste is expected to illustrate the condition of electronic waste in Indonesia quantitatively. Figure 2 and Figure 3 presents the total of electronic waste generated in Indonesia by quantity (units) and by weight (tons) respectively. The growth rate in e-waste volume in Indonesia is predicted to increase by ±23.2% in 2028 compared to the amount discarded in 2014, i.e. from 38,112,915 units in 2014 to 49,627,917 units in 2028. The average growth rate is estimated at approximately 14.91% annually.

4. Conclusion
The amount of electronic waste coming from the saturated market product category is predicted to reach 8,845,502 units or approximately 483,337.87 ton in 2028. The total of electronic waste from the non-saturated market is predicted to reach 40,782,415 units (82.18% from the total of e-waste generated in Indonesia) or around 4,078.24 ton in 2028. In total, the number of e-waste generated in Indonesia e-waste stream is predicted to reach 49,627,917 units in 2028, i.e. approximately 487,416 ton. Mobile phones being the highest product discarded in Indonesia by quantity.

It should be noted that distribution of the lifespan was made constant for every year in this study. In reality, shortening lifespan of products, especially in non-saturated products, is ongoing. This means the growth rate might be much higher in future years and resulted in a faster growth of total e-waste generated. The time-varying shape and scale parameter of the Weibull distribution should be considered in future research to enhance the estimation result of e-waste in Indonesia. Extensive
consumer survey might be needed to accurately define the time-varying parameters. Another limitation to be considered is that the estimation results obtained in this study are based on only four most common products in Indonesia electronic waste stream. The results are considered to represent the statistics of electronic waste in Indonesia as they are the main products found in the waste stream in Indonesia but fluctuations in the estimation results are still bound to happen.

Limitation aside, the result of this study is expected to provide an insight into the rapid growth of Indonesia e-waste quantities to show the urgency of e-waste problem in Indonesia. A high dominance of informal sector in Indonesia is also a factor to be considered. Around 90% of total e-waste generated in Indonesia flows to the informal and being treated through inappropriate channel.

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