Modeling and Optimization of Electronic Waste Collection System

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Abstract:

Accelerated and advanced development of the electronics industry in the 21st century is creating the rapid obsolescence of electrical and electronic equipment, which causes one of the largest and unstoppable waste streams called electronic waste (e-waste). There have been lots of obstacles in e-waste recycling, including the lack of government regulation, the existence of the informal sector, and the insufficiency of consumer awareness. The ideal e-waste recycling system would be able to overcome these obstacles. To establish an effective e-waste recycling system, the first important step is to implement a powerful e-waste collection system. Many research studies have only focused on solving one aspect of the e-waste collection problem, such as estimating/predicting the e-waste amount generated, identifying the e-waste drop-off points allocation, determining the e-waste processing facilities' locations, or calculating the shortest route for the collection vehicles. This paper will propose the multi-stage model, which can solve the household e-waste collection problem completely with three stages. These three stages consist of the prediction of the amount of electronic waste that would be collected, the e-waste drop-off points/containers allocation, the e-waste processing facilities' locations, and the collection vehicles routing. For this purpose, the existing studies on the e-waste collection system are reviewed. Additionally, the methods that were used in these studies are adjusted and improved. Specifically, the existing formulations for estimating the amount of e-waste that would be collected, allocating e-waste processing facilities and drop-off points/containers, and determining the collection vehicles' shortest routes are modified and improved to fit correctly into the proposed e-waste collection model. Moreover, these formulations and methods are combined to create the complete framework for the household e-waste collection system.

1. Introduction:

Electronic waste, commonly known as e-waste, waste electrical and electronic equipment, or end-of-life electronics, refers to electronic and electronic equipment, including all components, sub-assemblies, and consumables, deemed obsolete or unwanted by a user [1]. In addition to this, e-waste consists of toxic constituents that adversely affect the environment and human health. For example, there are more than 1000 toxic substances associated with e-waste including toxic metals and persistent organic pollutants [2]. In addition, the rapid growth of the electronics industry in the 21st century is creating the fast obsolescence of electrical and electronic equipment. Therefore, e-waste recycling is one of the most critical issues in the world. The optimal e-waste recycling system would be able to overcome the obstacles including the inadequacy of government control, the presence of the informal sector and the lack of consumer awareness. To create an effective e-waste recycling system, the first important step is to implement a powerful e-waste collection system. One of the important sources of e-waste is the obsolete electronics from household. This paper will propose the three-stage e-waste collection model, which can solve the household e-waste collection problem. These three stages consist of the prediction of the amount of electronic waste that would be collected, the e-waste drop-off points/containers allocation, the e-waste processing facilities' locations, and the collection vehicles routing. In the first stage, the amount of electronic waste that would be collected in household is predicted. In the second stage, the number of e-waste processing facilities and their locations as well as the allocation of drop-off containers that are assigned to each facility are determined. In the last stage, the minimum number of collection vehicles needed at each facility and the vehicles' shortest routes are calculated. Moreover, the existing studies on the e-waste collection was reviewed and analyzed. Also, the methods that were used in the existing studies are adjusted. Specifically, the existing formulations for estimating the amount of e-waste that would be collected, for allocating e-waste processing facilities and drop-off points/containers, and for determining the collection vehicles' shortest routes are modified and improved to adapt properly into the proposed model.

2. Literature Review:

Many studies only solved one aspect of the e-waste collection problem, such as estimating/predicting the e-waste amount generated, identifying the e-waste drop-off points allocation, determining the e-waste processing facilities' locations, or calculating the shortest route for the collection vehicles.

Estimation and prediction of the amount of e-waste generated are important in planning the e-waste recycling system. Ikhlayel introduced five approaches including the consumption and use (C&U) method, time step method, simple delay method, mass balance method and approximate 2 method, to estimate the generation of e-waste from the household sector [3]. This study compared the five methods by applying them into the case study of Jordan. Ikhlayel mentioned that the C&U method had been better than other methods because the variables required for the C&U method were easy to obtain [3]. Moreover, the study pointed out the disadvantages of the C&U method, which was the underestimation of e-waste amount [3]. The modified C&U method was also proposed to solve the old method's drawback by estimating the e-waste amount both first hand and secondhand product based on the penetration rate per person rather than per household [3]. In addition, the study conducted by X. Liu et al. applied three methods: The C&U method, market supply method, and Swiss environmental agency method to estimate and predict the yearly generation amount of household electronic waste [6]. The study indicated that the e-waste amount would rapidly grow untill 2020 because of the increasing consumption and urbanization [6]. B. Li et al., in their research on the retired mobile phones generation in China, showed the comparative study between three estimation methods: The market supply A method, the consumption and use method, and the sale and new method [4]. This research remarked that sale and new method is in the highest preference in estimation of the obsolete cell phones [4]. K. Breivik estimated the generation of e-waste over the world using the mass balance method by tracking the import and export data [7]. The mass balance method used in this research had a disadvantage. The research lacked data in the illicit flow of electronic waste, so the amount of electronic waste was underestimated [7]. J. Yu et al. employed the logistic model and material flow analysis to forecast the global generation of out-of-date personal computers [5]. The result pointed out that the amount of out-of-date personal computers in developing countries would surpass that of developed countries in the future [5].

After the amount of e-waste is determined, it is necessary to figure out the number the e-waste processing facilities' locations and to calculate the shortest route for the collection vehicles associated with each facility. Facility location problems mainly locates the facilities based on their capacities to meet the demand from the customer. In the e-waste industry, the location of the e-waste processing facility would be chosen so that their capacities meet the amount of e-waste that would be collected. The optimization of the cost correlates with the transportation cost and the opening cost as well as the operating cost. R. L. Rardin presented the facility location allocation problems in his book "Optimization in operations research" [10]. Moreover, C. Ortiz-Astorquiza et al. pointed out the fundamental features of multi-level facility location problems [11]. The shortest route of the collection vehicles was calculated based on the travelling salesman problem (TSP) algorithm. In his book, R. L. Rardin introduced the collection vehicles routing algorithm that could find the minimum number of collection trucks needed at each facility and their shortest route based on the distance between drop-off points and their assigned facility, the amount of electronic waste at each drop-off point, and the capacity of each collection truck [10]. Nowakowski proposed a method to solve the collection container loading problems. Basically, this method focused on maximizing the number of the electronic items packed in the container [8]. Additionally, Nowakowski's study attempted to minimize the travelled route length of the collection vehicles in order to reduce the transportation cost [8]. To reduce the route length, the study applied the capacitated vehicle routing problems [8]. In another research, Nowakowski et al. adopted artificial intelligence algorithms to solve the vehicle routing problem in the on-demand collection [9]. The method from this study presented the system that allowed users to request on-demand electronic waste collection and then calculated the shortest route for the collection vehicles [9]. The research not only used four algorithms, including simulated annealing, tabu search, greedy, and bee colony optimization to solve the routing problem, but also showed the comparison among them [9].

3. Proposed E-waste Collection System Model:

The proposed model of e-waste collection system includes three phases which are e-waste amount prediction, facility location allocation, and collection truck routing. The first phase will predict the amount of the e-waste that would be collected and the number as well as locations of drop-off containers. The second phase will determine the number and locations of e-waste processing facilities and the allocation of drop-off containers assigned to each facility. The third phase will calculate the minimum number of trucks needed at each facility and their shortest route.

3.1. First Phase: Remodified C&U method - Estimate the amount of e-waste that would be collected at time t.

The modified C&U method mentioned in Ikhlayel's research is represented by equation (1):

$$WEEE(t) = \frac{P(t)Np(t)W}{L} \quad (1)$$

Where P(t) is the population, Np(t) is the number of electronic product (e-product) owned by a person, which comprises a value lesser or greater than one, W is the average weight of each type of e-product, and L is the average lifespan of each type of the e-product [3]. This method can be applied in both dynamic and saturated market, and it does not require the sale data as other estimation methods such as the market supply method.

The only disadvantage of this method is that it can only estimate the amount of e-waste "generated" but it can't estimate the amount of e-waste that "would be collected". "Would be collected" amount means the e-waste that will be brought to drop-off points/containers for collecting. "Generated" amount means bigger scope. It can be e-waste that would be collected, e-waste that would be left in the storage, or e-waste that would be thrown away as normal waste. The estimation of the e-waste amount that would be collected will assist the recyclers to accurately determine the number of facilities, drop-off points/containers, and number of collection vehicles needed to operate the effective e-waste collection system.

Therefore, this paper adjusts the modified C&U method to address its drawback. This paper replaces the variable L, the average life span of the e-products with Lr(t), average duration from the time when the electronic product was bought until it would be collected. The new method is called as the remodified C&U method. The remodified C&U method was represented by equation (2):

$$WEEE(t) = \frac{P(t)Np(t)W}{Lr(t)} \quad (2)$$

3.1.2.Predict the amount of e-waste that would be collected:

The consumer behavior and awareness towards e-waste recycling change over time that leads to the change of the amount of e-waste that would be collected. Therefore, it is important to predict this amount based on the consumer behavior and awareness toward e-waste recycling. The prediction of the population P(t) can be obtained from the Community Research Institute statistics, and the average weight W of each type of electronic product are recorded every year in the United Nations e-waste statistic [12]. The number of e-product owned by a person, Np(t), and average duration from the time when the electronic product was bought until it would be collected, Lr(t), can be predicted by applying the correlation analysis and regression analysis between the dependent variables, which are Np(t) and Lr(t), and the independent variables. The independent variables include: Age Range (X1), Income (X2), Education level (X3), Vehicle availability (X4), Type of e-waste (X5), Residential Condition (X6), Awareness about Effect on Environment (X7), Awareness about Effect on Human Health (X8), Awareness about Law & Regulation (X9), Recycling Habit (X10), Convenience of Recycling Service (X11), and Economic Benefits (X12). Figure 1 presents the procedure of the analysis. The correlation analysis will be performed on the data obtained from the survey to find out which independent variables strongly affect the consumers' willingness to participate in e-waste collection. The correlation analysis is concerned with measuring the strength of the relationship between variables [13]. In the correlation analysis, the sample correlation coefficient, more specifically the Pearson Product Moment correlation coefficient, is estimated/calculated. The sample correlation coefficient has values between -1 and +1 and indicates the direction and strength of the linear relationship between two variables. The correlation between two variables can be positive (for example, higher levels of one variable are associated with higher levels of the other) or negative (for example, higher levels of one variable are associated with lower levels of the other). The sign of the correlation coefficient shows the direction of the relationship. The magnitude of the correlation coefficient presents the strength of the relationship. For instance, a correlation of r = 0.95 indicates a strong and positive relationship between two variables, whereas a correlation of r = -0.1 indicates a weak, negative relationship. A correlation close to zero suggests no linear relationship between two variables [14].

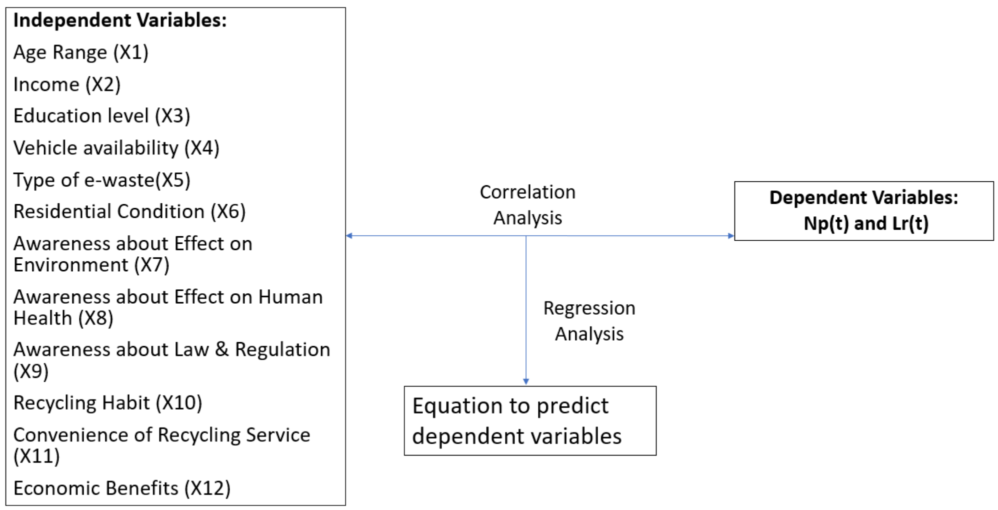

Figure 1: Correlation and Regression Analysis procedure.

The regression analysis is helpful in assessing specific forms of the relationship between variables, and the ultimate objective of this analysis is to predict the value of one variable corresponding to a given value of another variable [13]. In regression analysis, the interest is the population regression equation that describes the true relationship between the dependent variable y and the independent variable x. The correlation analysis is adopted to identify which variables of twelve independent variables significantly affect the two dependent variables which are Np(t) and Lr(t). From there, the regression analysis will be applied to generate the equation that can predict Np(t) and Lr(t) based on the independent variables that have the significant correlation. The prediction equation is shown in equation (3):

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_i x_i \text{ for i = 1, 2, …, n} \qquad (3)$$

Where y is the dependent variable, b_0 to b_i are regression coefficients, n is number of independent variables and x_1 to x_i are independent variables [13]. With the predicted Np(t) and Lr(t), the amount of the electronic waste that will be collected in the future will be calculated.

After the amount of e-waste that would be collected is predicted, the drop-off containers' amount and size will be determined regarding the collected e-waste amount at each region in the research scope.

3.2. Second Phase: Facility Location Allocation

The facility location allocation phase requires five inputs which are (1) pre-defined number of the e-waste facilities and their capacities, (2) fixed cost to open and operate each facility, (3) pre-defined number of drop off points/containers, (4) transportation cost between each drop of container and each facility, and (5) amount of e-waste at each drop-off container. With these five inputs, this phase will compute the number and locations of the e-waste processing facilities needed to be opened and the allocation of the drop-off containers that are assigned to each facility. Figure 2 showed the visual illustration of the facility location allocation phase. According to the Figure 2, in step 1, the facilities' location and the drop-off containers' location are pre-defined. After that, in steps 2 and 3, the locations of needed facilities are identified along with the allocation of drop-off containers associated to each facility.

Figure 2: Facility Location Allocation visual illustration

The formulation of the facility location allocation is presented below:

$\boldsymbol{D_j}$: amount e-waste (tons) at the drop-off point j

$\boldsymbol{c_{i,j}}$: unit charge of transportation (dollar/tons) from the drop-off point j to the facility i

$\boldsymbol{f_i}$: fixed cost (dollars) to open and operate the facility i

$\boldsymbol{C_i}$: capacity (tons) of the facility i

$\boldsymbol{y_i}$: opening status of the facility i

$\boldsymbol{X_{i,j}}$: linking status between the facility i and the drop-off point j

Decision Variables: $y_i = 1\ if\ facility\ i\ is\ opened,\ = 0\ otherwise$

$X_{i,j} = 1$ if all the e-waste at drop off point j is processed at facility i

Objective Function:

$$\boldsymbol{min \sum_i \sum_j c_{i,j}\, X_{i,j} D_j + \sum_i f_i y_i}$$

for i = 1, 2, 3…, number of facilities and j = 1,2, 3…, number of drop-off points

Facility Constraint: $\sum y_i \leq p$ for i = 1, 2, 3…, number of facilities (p is pre-defined number of facility)

Capacity Constraint: $\sum_j X_{i,j} D_j \leq y_i C_i$ for i = 1, 2, 3…, number of facilities and j = 1,2, 3…, number of drop-off points

Binary Constraint: $y_i = 1\ or\ 0;\ X_{i,j} = 1\ or\ 0$ for i = 1, 2, 3…, number of facilities and j = 1,2, 3…, number of drop-off points

Linking Constraint $\sum X_{i,j} = 1$ for i = 1, 2, 3…, number of facilities and j = 1, 2, 3…. number of drop-off points

3.3. Third Phase: Collection Vehicles Routing

The collection vehicles routing phase requires four inputs including (1) group of drop-off containers that are assigned to each e-waste processing facility which is the output of the second phase, (2) the distance between each drop-off container and the facility, (3) amount of e-waste at each drop-off point/container, and (4) capacity of each collection truck. With these four inputs, the third phase will calculate not only the minimum number of collection vehicles needed at each facility, but also the shortest route assigned to each vehicle. The formulation of the collection vehicles routing is presented below:

V: number of trucks

Q: capacity (tons) of each truck

$\boldsymbol{D_j}$: Amount of e-waste (tons) at the drop-off point j

$\boldsymbol{p_i}$: total number of drop-off points who have been served when the truck arrives point i

$\boldsymbol{d_{i,j}}$: distance (kilometers) travelled from i to j

N -1: number of drop-off points,

The location of facility is denoted by **N**

Decision Variable:

$\boldsymbol{Z_{i,j}} = 1$ if the truck travels from i to j, 0 otherwise

Objective Function:

$$\boldsymbol{min \sum_{j=1}^{N} \sum_{i=1}^{N} d_{i,j} Z_{i,j}}$$

for i = 1, 2, 3…, number of facilities and j = 1, 2, 3, …number of drop-off points

Constraint:

The truck either visits a drop-off point from the facility or from another drop-off point:
$\sum_{i=1,\, i\neq j}^{N-1} Z_{i,j} + Z_{N,j} = 1$ for j = 1, 2, 3, …N-1

The truck either leaves from a drop-off point to other drop off point or to the facility*:*
$\sum_{j=1,\, i\neq j}^{N-1} Z_{i,j} + Z_{i,N} = 1$ for i = 1, 2, 3, … N-1

Number of trucks that start from the facility must be equal the total number of trucks*:*
$\sum_{j=1}^{N-1} Z_{N,j} = \mathrm{V}$

Number of trucks that arrive at the facility must be equal the total number of trucks*:*
$\sum_{i=1}^{N-1} Z_{i,N} = \text{V}$

Subtour Elimination: $p_i - p_j + (N)Z_{i,j} \leq \text{N} - 1$

Capacity Constraint*:* $\sum_{j=1}^{N-1} D_j Z_{i,j} \leq Q$

4. Conclusion:

This paper introduces the three-phase e-waste collection system model that can solve the household sector's e-waste collection problem. These three phases include the prediction of the amount of electronic waste that would be collected, the e-waste drop-off containers allocation, the e-waste processing facilities' locations, and the collection vehicles routing. In the first stage, the amount of electronic waste that would be collected in household sector is predicted based on the population of the research scope, the average weight of each type of e-product, number of e-products owned by a person and the average duration from the time when the electronic product was bought until it would be collected. In the second phase, the number of e-waste processing facilities and their locations are determined. Moreover, the allocation of drop-off containers that are assigned to each facility is also found. In the final phase, the minimum number of collection vehicles needed at each facility and their shortest routes are computed.

5. Limitation and Suggest for Future Research

Among five variables that determine the candidate facilities' locations including population, e-waste generation stream, labor cost, government permission, and real estate price, it is difficult to assess the labor cost, government permission, and the real estate price. Therefore, future researchers should consider collecting the information on labor cost, government permission, and real estate price in order to identify the candidate facilities' location. Moreover, future researchers can apply the three-phase model to solving the e-waste collection problem in a specific region.

6. References:

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