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A proposal to improve e-waste collection efficiency in urban mining: Container loading and vehicle routing problems – A case study of Poland

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ABSTRACT

Waste electrical and electronic equipment (WEEE), also known as e-waste, is one of the most important waste streams with high recycling potential. Materials used in these products are valuable, but some of them are hazardous. The urban mining approach attempts to recycle as many materials as possible, so efficiency in collection is vital. There are two main methods used to collect WEEE: stationary and mobile, each with different variants. The responsibility of WEEE organizations and waste collection companies is to assure all resources required for these activities - bins, containers, collection vehicles and staff - are available, taking into account cost minimization. Therefore, it is necessary to correctly determine the capacity of containers and number of collection vehicles for an area where WEEE need to be collected. There are two main problems encountered in collection, storage and transportation of WEEE: container loading problems and vehicle routing problems. In this study, an adaptation of these two models for packing and collecting WEEE is proposed, along with a practical implementation plan designed to be useful for collection companies' guidelines for container loading and route optimization. The solutions are presented in the case studies of real-world conditions for WEEE collection companies in Poland.

1. Introduction

Large cities and agglomerations generate a large amount of waste. It is estimated in 2012 world cities generated 1.3 billion tonnes of waste (Hoornweg and Bhada-Tata, 2012). An example of forecast for waste generations in cities was presented by Beigl (Beigl et al., 2004).

The new approach towards recycling can be defined as urban mining (Brunner, 2011). Urban mining processes help to recover secondary materials. Transportation of wastes and recyclables must be efficient, otherwise environmental benefits can be diminished or the waste management companies will experience losses.

One of the groups of waste generated by human activity is e-waste, defined in the European Directive (European Union, 2003) as WEEE (waste electrical and electronic equipment). It is characterized by its significant amount of valuable materials (Oguchi et al., 2012). Therefore, urban mining activities for this type of waste can be profitable. After collection, the WEEE has to be transported to disassembling plants where materials separation and sorting processes are conducted. This process includes removal of hazardous substances (Morselli et al., 2009).

The general scheme of collection of WEEE has been proposed in the WEEE Directive. There are a variety of collection possibilities for WEEE. In order to take back the waste equipment, collection companies have to prepare vehicles, containers and employees. This is the main influence on storage, transportation and service costs (Huisman and Magalini, 2007). The size of the city, the policy of municipal administration and WEEE collecting companies can determine the most suitable methods of WEEE collection. The efficiency of e-waste collection depends on the total cost of the equipment collection from households. Taking into consideration the revenues, WEEE is characterized by high recycling potential. This includes sale of the materials acquired after disassembling, shredding and sorting of the equipment (Williams, 2006). The efficiency of these processes varies, depending on the type of equipment and the disassembling technology used (manual/mechanical) (Bohr, 2008).

Therefore the main factors that influence the efficiency of urban mining of WEEE are: transportation and storage costs, disassembling and processing costs, and revenues from sale of the raw materials to recycling plants (Gamberini et al., 2008, 2010). Transportation cost depends on type and fleet of vehicles, route length and number of employees. Another cost arises once the vehicles are packed with the waste equipment and a portion of their capacity is used. A similar problem occurs when we consider the containers set up in waste collection centres or large superstores for electrical and electronic equipment (EEE) where the customers of the new equipment can dispose of old or unwanted items.

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In this study we focus on describing a model of collection that addresses both of these issues and proposes a possible improvement for collection companies. The capacitated vehicle routing problem (CVRP) will be used in formulating a solution for minimizing route length for collection vehicles, and the container loading problem (CLP) will be used in creating a solution to maximize used volume of a container capacity. It can be also applied to the cargo compartment of a lorry or van used in mobile collection schemes. These two solutions are presented in real-world case studies of two WEEE collection companies in Poland.

This paper describes a novel approach to handling and transporting WEEE. Although the models are known and used in solving problems in supply chain management, they have not yet been used in WEEE management studies. Numerous studies have been conducted concerning different issues in WEEE collection, but studies about loading and transportation optimization are rarely published. Improvements in the reduction of the number of shipments or distances travelled are important and increase efficiency. The models applied in this research are suitable to solve the problems occurring with WEEE; however, additional software support is necessary for more difficult cases (large cities or long distances between collection points).

2. Model and methods

2.1. Schemes of WEEE collections

Stationary collection of WEEE is provided mostly in municipal collection centres or EEE stores and superstores. Another variant of stationary collection is special events or collection days. WEEE can be also collected directly from households or companies as a mobile system.

The examples of collection schemes are shown in Fig. 1a–c.

In the first case (Fig. 1a), the collection of WEEE is provided in an EEE superstore where customers purchasing new equipment can also dispose of the obsolete one and the superstore delivery department can collect waste equipment directly from households. In this case the storage area, in a superstore's backyard, is sufficiently large to store many WEEE items. Usually there is a steel container set up by a collection company to be loaded with the obsolete equipment. This container is to be taken after being filled to a WEEE disassembly plant.

In the second case (Fig. 1b), a vehicle from a collecting company has to collect all waste equipment delivered to the stores belonging to a store network. It then has to be delivered to a central warehouse or directly to a WEEE disassembly plant if the distance is short. This type of collection allows for selection of a vehicle with capacity suitable to collect all waste equipment on the route. Information regarding the number of items, their type and size can be sent by stores' staff prior to sending a vehicle.

Both cases allow for predictability for the collection company as the number of waste items can be known prior to collection.

The third case shown in Fig. 1c describes mobile collections. These can be provided as curbside collection according to designed schedules (once per month, biannually, etc.) along streets in a suburb or district. The main disadvantage of this scheme is uncertainty.

A collection company does not know how many items will be disposed. Some of them might even be taken by illegal companies prior to scheduled collection. The alternative form of mobile collection is waste on demand pickup after prior arrangements via website or telephone. In order to assign the vehicles or containers for a collection area, the total volume of WEEE arising from the households has to be calculated. Total volume of WEEE from households would depend on the number of EEE items in a household and frequency - f of replacement individual items. For example, large home appliances (LHA) like washing machines, dishwashers or refrigerators are usually replaced every 8–15 years, TV audio equipment every 6–8 years and small equipment 3–5 years (Huisman and Magalini, 2007; Jofre and Morioka, 2005; Yang et al., 2008). Volume of WEEE from a household V_H annually would be:

$$V_H = \sum_{i=1}^{m} v_i * f_i \quad [\mathrm{m}^3/\mathrm{year}] \tag{1}$$

where m-number of WEEE from a household in [m^3], v_i – volume of i – WEEE item, f_i - frequency of replacement individual items [1/year]

This also depends on type of housing, such as a flat in a bloc or a house. These data can be obtained from Statistic Offices reports. In Poland, the estimated volume of WEEE arising annually in a household is 0.143 m^3 (single family house) and 0.124 m^3 (flats) (GUS, 2012). It is based on the large scale survey conducted in 2011 in Poland. It was national census and about 80 thousand households responded to questionnaires from Central Statistical Office of Poland.

Total volume V_T to be collected for an assigned number of households nH would be:

$$V_T = \sum_{i=1}^{nH} V_{H_i} \quad [\mathrm{m}^3/\mathrm{year}] \tag{2}$$

Therefore, for the collection of the WEEE volume from 1000 households, the capacity of containers should be 143 m^3 (single-family households) and 124 m^3 (households in flats) annually. The details of WEEE generation in households in Poland are shown in Table 1.

Calculated volume should be used in preparation of collection schedules or container capacity selection.

Recycling potential V_{Hrp} of the waste equipment disposed by a household will depend on the mass content m_i [kg] of individual materials in a piece of equipment and the revenue of the materials r_i [€/kg] for l – number of WEEE items in a household:

$$V_{Hrp} = \sum_{i=1}^{l} m_i * r_i \quad [€] \tag{3}$$

Taking into consideration the mass of raw materials in a piece of equipment, this generates the main income for the disassembling company:

$$R_T = \sum_{i=1}^{d} \sum_{j=1}^{m(i)} r_{i,j} \quad [€] \tag{4}$$

where: R_T – total revenue from materials sale after processing all WEEE in a collected volume (used capacity of a container or a van), $m(i)$ – number of raw materials obtained after disassembly of i-item, $r_{i,j}$ – revenue from sale of j – raw material to recycling plant after disassembly, i – item of collected WEEE, d – number of collected WEEE items

Each type of the equipment is characterized by weight to volume ratio. Selected items from various WEEE categories are shown in Table 2. The list includes the equipment commonly used in households. Sample calculations include estimated mass of main materials used in the equipment construction. It has been based on own calculations and literature (Oguchi et al., 2011; Peeters et al., 2012; Renteria et al., 2010; Widmer et al., 2005). The revenue for individual metals: steel, copper, aluminium has been based on quotation of prices from recycling plants (Feb. 2016) in Poland. In example of refrigerators the average material content is: ferrous metals – 56%, plastics – 30%, aluminium and copper – 6%.