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Modeling computer recycling in Taiwan using system dynamics

Chihhao Fan[a], Shu-Kai S. Fan[b,*], Chen-Shu Wang[b], Wen-Pin Tsai[b]

[a] Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei City, 10617 Taiwan
[b] Department of Industrial Engineering and Management, National Taipei University of Technology, Taipei City, 10608 Taiwan

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ABSTRACT

Environmental pollution becomes aggravated as human beings enjoy high-tech products without being fully aware of the consequences of excessive resource consumption. In the literature, few studies focus on people's recycling behavior. How to characterize recycling behavior appropriately poses a critical challenge in the study of electronic waste recycling. This paper develops a computer recycling model using system dynamics to predict electronic waste in Taiwan. The model is constructed and validated for "real" recycling data from the Taiwan Environmental Protection Administration. The constructed model is well qualified for the computer recycling data with only 2 percent forecast error. The three decision variables of holding duration, recycling refund and innovative technology were tested through dynamic hypotheses and found significant to be included in the proposed system dynamics model. A moving average forecast method is employed to predict future recycling quantities. The research outcomes can help the Government gain an understanding of the recycling behavior of electronic waste. Therefore, practical and feasible policies can be proposed to improve electronic waste recycling.

1. Introduction

Nowadays electronics production and assembly is the world's largest and fastest growing manufacturing industry. With the worldwide development of advanced electronics devices and rapid product obsolescence, the problem of electronic waste (e-waste) generation and management has become increasingly severe and challenging. The exponential growth of e-waste became further aggravated as rapid technological advancements shorten the lifespan of electronic devices driven by the even faster time-to-market of new products (Balde et al., 2015). Generally speaking, "e-waste" refers to waste electronic appliances such as personal computers, laptops, TVs, DVD players, mobile phones, MP3 players and tablets which have been discarded by their original users (Wath et al., 2010; Baxter and Gram-Hanssen, 2016). Aside from glass, steel and plastics, e-waste contains a variety of precious metals such as silver, gold, platinum and palladium, which could be recovered and reused for their potential value. Meanwhile, e-waste also contains various hazardous substances such as lead, cadmium, beryllium, mercury and brominated flame retardants that have high potentials for polluting the environment if not managed properly (Ravi, 2012). Except in a few developed countries, a large amount of hazardous e-waste material still poses serious threats for both the ecological environment and public health (Qu et al., 2013; Song and Li, 2014; Zeng et al., 2015).

Reverse logistics for product take-back is a potential option for efficient management of e-waste through design for de-manufacturing, recycling, and proper disposal of products (Klausner and Hendrickson, 2000). Even so, understanding the consumers' recycling attitude and behavior to e-waste is still worth a study. The major problem of e-waste management is the collection of the waste in such a substantial volume, followed by proper treatment and disposal with environmental-friendliness. Recycling involves product recovery associated with techniques to create reusable materials from waste. The recycled product has a beneficial effect on the reduction of carbon dioxide emission in comparison with the raw materials used to produce finished products. At present, large amounts of e-waste, due to obsolete features or functional capabilities, are piled in offices and households and not effectively used or recycled because of a lack of environmental awareness and reclaiming channels. Even worse, improper processing and disposal (e.g., disposal with municipal solid waste, in landfill, incineration, or by illegal peddlers) of e-waste lead to irreparable damage to the environment. Factors affecting the recycling infrastructure include the amount of waste in the waste pipeline, the recycling technology available, government policy, and the economics of end-of-life (EOL) products (Kang and Schoenung, 2005).

Based on previous studies, reluctance to engage in pro-environmental behaviors and informal/inappropriate recycling are

* Corresponding author.
E-mail address: morrisfan@ntut.edu.tw (S.-K.S. Fan).

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the most puzzling environmental issues associated with e-waste recycling (Williams et al., 2008; Saphores et al., 2012; Zhang et al., 2016). In Sidique et al. (2010), the influence of socioeconomic, demographic and behavioral factors on drop-off site visits was analyzed. The behavioral factors include environmental affiliation, perception and attitudes concerning drop-off recycling. Recycling behavior has been largely ignored by academics. In practice, drop-off recycling is much easier to implement than take-back or other recycling programs involving manufacturers. Also, the required facilities are typically less expensive to operate than curb-side collection programs.

Taking into account the foregoing concerns, a proper understanding of recycling behavior will help in designing and improving the effectiveness of recycling policies and programs. However, there have been surprisingly few studies in relation to modeling computer recycling behavior in the literature. In the context of recycling behavior, this study aims to characterize the impacts of various computer recycling sources on the potential recycling quantity. The "system dynamics" approach was employed to model and predict the recycling behaviors of various user groups, namely government, community, private sector and academic, using the e-waste recycling in Taiwan as an exemplary illustration. Systems thinking, the main part of all system dynamics simulations, is at the core of describing the forces and inter-relationships of activities that constitute the major behavior of the system under investigation. This discipline may be helpful to decision-makers in improving the recycling system more effectively. In the next section, e-waste management, computer recycling and system dynamics are briefly reviewed.

2. Literature review

2.1. E-waste management and recycling in Taiwan

Over the past two decades, environmental awareness of the proper treatment and disposal of e-waste, also referred to as Waste Electric and Electronic Equipment (WEEE), has risen remarkably. Reported by the "Solving the E-Waste Problem (StEP) Initiative", nearly 49 million tons of e-waste were generated globally in 2012, an average of 7 kg for each of the world's 7 billion people. This flood of e-waste keeps growing. Based on current trends, as predicted by StEP, by 2017 the annual global quantity will arrive at 65.4 million tons (Balde et al., 2015). To promote e-waste recycling, two possible policies are often considered: Extended Producer Responsibility (EPR) and Advanced Recycling Fee (ARF). The European Union (EU) chose the former policy through the WEEE Directive (Directive 2002/96/EC, 2003), where the burden of recycling is transferred to manufacturers by requiring them to take back and recycle WEEEs. EPR, first proposed by Lindhqvist (1992), holds manufacturers responsible for the collection and disposal of products in environmentally friendly ways at the end of their lives. In the developed world, e-waste take-back legislation has been implemented through directives under the guiding principle of the EPR concept. In the longer term, EPR initiatives may drive manufacturers to produce product designs that are more environmentally friendly and easier to recycle/reuse, such as improving product recyclability and reusability, reducing material usage, and downsizing products (Dwivedy et al., 2015).

There are several reasons to require the proper recycling of e-waste. The principal one is resource scarcity, which has become one of the top concerns in the world economy. The electronics industry always consumes a significant portion of precious and specific metals. Therefore, e-waste recycling generates profits by retrieving these valuables from WEEEs, prevents the release of toxic materials in the environment, and reduces the emissions of greenhouse gases if conducted appropriately (Saphores et al., 2012). Taiwan is one of the environmental leaders in the Asia Pacific region. In the past 15 years, e-waste recycling and management has received considerable attention in Taiwan (Kuo 2010, 2013). The Taiwan Environmental Protection Administration (TEPA) is responsible for all e-waste recycling, including its collection and processing, but manufacturers have to pay a fixed fee to the government for recycling when electric and electronic products are sold to customers (i.e., the ARF policy). In addition, the TEPA authorized the non-profit, non-governmental organization, the Foundation of Taiwan Industry Service (FTIS), to promote recycling and renewable resources where e-waste is anticipated to be reduced through an environmental audit and accreditation system of the recycling and disposal of e-waste. Along with the regulations and policies established in Taiwan, the recycling quantity of e-wastes has noticeably and steadily increased in recent years.

The TEPA categorizes general end-users into four groups, i.e., government, community, private sector and academic. Government comprises central and local (city and township) governmental organizations, and science and technology parks. Community includes non-governmental organizations, charitable institutes, private individuals, scavengers, office buildings, and suburban settlements. This specific group also includes people who recycle their e-waste themselves or civilians who take e-waste in recycling vehicles. Private sector means private enterprises and manufacturing factories. Academic includes all levels of learning and research institutes. In this study, these recycling groups serve as the four building blocks of the computer recycling model.

2.2. Personal computer recycling

The factors influencing effective e-waste management include: (1) the laws/regulations that encourage the awareness of e-waste recycling, (2) the accurate estimation of the quantity of e-waste that will be generated in both the short and long term, (3) environmentally sound treatment of qualified facilities, and (4) the success of the after-market materials recovered in recycling and recovery operations (Kang and Schoenung, 2006). Personal computers are becoming an important part of social development, and human dependency on those has been increasing in a massive variety of activities, from business to entertainment, education, shopping and communication.

Access to a personal computer has evolved from a privilege to a requirement in daily life (Kahhat and Williams, 2010). Overall personal computer ownership has increased dramatically in the past few decades. In the United States, more than 100 million personal computers became obsolete from 1995 to 2000, and only a small fraction of them were recycled. Millions of pieces of computer equipment were disposed of in landfill or incinerators each year. The International Association of Electronics Recyclers (IAER) reported that about hundred million computers became obsolete in 2003 (IAER, 2003). Until 2007, the estimated recycling rate was merely 18% for computer products in the United States (Saphores et al., 2012). Based on the above findings, there clearly is a huge gap between the quantities of used computer equipment being recycled and obsolete, suggesting that a large quantity is stored in-house, creating a greater risk of ending up with improper recycling/treatment/disposal.

In general, a personal computer comprises 23% plastic, 32% metallic material and 18% non-metallic material. Furthermore, 12% precious and specific metals are scattered throughout its printed circuit boards (PCB). Those precious metals have significant economic values if refined properly. Environmental impact is certainly a key concern resulting in the necessity of computer recycling. Advances in information technology can quickly render current systems obsolete. The chemicals used in computer manufacturing

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