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Identifying ways of closing the metal flow loop in the global mobile phone product system: A system dynamics modeling approach

Rajib Sinha*, Rafael Laurenti, Jagdeep Singh, Maria E. Malmström, Björn Frostell

Industrial Ecology, Department of Sustainable Development, Environmental Science and Engineering (SEED), KTH Royal Institute of Technology, Stockholm, Sweden

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ABSTRACT

In the past few decades, e-waste has emerged as one of the fastest growing and increasingly complex waste flows world-wide. Within e-waste, the life cycle of the mobile phone product system is particularly important because of: (1) the increasing quantities of mobile phones in this waste flow; and (2) the sustainability challenges associated with the emerging economies of reuse, refurbishment, and export of used mobile phones. This study examined the possibilities of closing the material flow loop in the global mobile phone product system (GMPPS) while addressing the broad sustainability challenges linked to recovery of materials. This was done using an adapted system dynamics modeling approach to investigate the dominant paths and drivers for closing the metal flow loop through the concept of eco-cycle. Two indicators were chosen to define the closed loop system: loop leakage and loop efficiency. Sensitivity analysis of selected parameters was used to identify potential drivers for closing the metal flow loop. The modeling work indicated leverage for management strategies aimed at closing the loop in: (i) collection systems for used phones, (ii) mobile phone use time, and (ii) informal recycling in developing countries. By analyzing the dominant parameters, an eco-cycle scenario that could promote a closed loop system by decreasing pressures on virgin materials was formulated. Improved policy support and product service systems could synchronize growth between upstream producers and end-of-life organizations and help achieve circular production and consumption in the GMPPS.

1. Introduction

Waste electrical and electronic equipment (WEEE, also well known as e-waste) is one of the fastest growing waste flows world-wide (Kuehr, 2012). On a global scale, e-waste increased from 20 million tons in 1998 to 41 million tons in 2010 and was estimated to reach 50 million tons by 2014/2015 (Kuehr, 2012). The European Commission has estimated that the average European citizen generates 17–20 kg e-waste per year, and that mobile phones are a potential candidate for generating e-waste (Basel-Convention, 2008). Indeed, mobile phone subscribers have increased exponentially during the past 20 years (Basel-Convention, 2008; ITU, 2013), resulting in more e-waste at the end-of-life (EoL) (Panambunan-Ferse and Breiter, 2013). In industrialized countries (IC), less than 20% of used phones are properly managed at EoL (Panambunan-Ferse and Breiter, 2013; Umair et al., 2013).

With rapid technological improvements and innovations, users frequently replace their phones, decreasing the life span (Basel-Convention, 2008; Kuehr, 2012; Tischner, 2012; Herat and Agamuthu, 2012). Because of the potentially remaining active life in used phones and the possibility to upgrade mobile phones at a lower price, interest in using second-hand (or/and refurbished) phones has emerged in both IC and developing countries (DC). In addition, due to increasing interest in e-wastes for reuse and informal recycling in DC, IC export e-wastes to DC (Umair et al., 2013). In DC, these wastes mostly end up in landfills after informal recycling consisting of manual dismantling with bare hands and open burning (Panambunan-Ferse and Breiter, 2013; Umair et al., 2013). Due to a very low overall recovery rate in this informal recycling (Bollinger et al., 2012; Herat and Agamuthu, 2012; Umair et al., 2013), the global mobile phone product system (GMPPS) loses a substantial amount of valuable resources that could be recovered (Basel-Convention, 2008; Geyer and Blass, 2010; Tischner, 2012; Wang et al., 2013).

In a life cycle perspective, the EoL management of mobile phones is a global, rather than a local or regional, problem and

* Corresponding author at: Division of Industrial Ecology, Department of Sustainable Development, Environmental Science and Engineering (SEED), KTH Royal Institute of Technology, Teknikringen 34, 10044 Stockholm, Sweden.
Tel.: +46 8 790 67 44.
E-mail address: rajib.sinha@abe.kth.se (R. Sinha).
URL: http://www.kth.se (R. Sinha).

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involves a multitude of actors such as consumers, manufacturers, retailers, collectors, refurbishers, recyclers. In addition, emerging socio-technical/economic activities among these actors (e.g., reuse, export of e-waste, informal recycling) make the EoL complex. For example, export of used phones to DC increases their life span, but valuable metals (used in phones) are lost through informal recycling in DC, whereas IC have better and more efficient technologies for recycling. Apart from reuse or export, consumers either hibernate phones by storing them unused in drawers, or throw away/dump their phones, due to lack of proper collection systems. This study investigated the factors and activities that are the drivers for closing the material flow loop in the GMPPS. To investigate the drivers in such a complex global system and to produce insights into closing the material flow loops efficiently, a broader systems approach with dynamic analysis is warranted to understand the system (Sterman, 2000).

System dynamics (SD) approach, which is grounded on feedback control theory and non-linear dynamics (Sterman, 2000), can be used to explain the behavior of complex systems to better understand GMPPS. Studying various interconnections in the GMPPS using this approach could help explore the complexity of alternative EoL systems and assist in decision making and in development of effective interventions in complex systems. Apart from the SD approach, agent-based modeling (ABM) can be used to explore complexity (Sterman, 2000; Bollinger et al., 2012; Achachlouei, 2015). Bollinger et al. (2012) compared SD and ABM approaches for modeling metal flows in a mobile phone product system and concluded that the SD approach is beneficial for aggregated analysis, whereas ABM has advantages for individual action analysis. The present study deals with the global system and aggregated flows and parameters, and therefore SD modeling was selected as the analytical approach to create a deeper understanding of the GMPPS in a life cycle perspective and to explore an eco-cycle scenario (see Section 2).

In similar research, Spengler and Schröter (2003), Georgiadis and Besiou (2008, 2010) studied electrical and electronic products using SD to investigate closed-loop material flows. However, their studies mainly focused on supply chain management and the influence of consumer behavior, while effects of other factors, e.g., using a product for a longer time, on a closed-loop system received little scrutiny. Asif et al. (2015) used SD models to analyze the potential application of product multiple life cycles (Asif, 2011; Asif et al., 2012) in a closed-loop supply chain based on the dynamics of material scarcity. The present study extended the investigation on causal loop diagram (CLD) studies, often used during the initial stages of SD modeling (Sterman, 2000). Nguyen et al. (2015) used CLD to understand smartphone usage in Singapore by exploring the leverage points and resistance to change. Our research group also has previously used CLD to analyze unintended environmental consequences when designing electronic products, using an example of closing the material flow loop in the mobile phone product system (Laurenti et al., 2015a,b,c). The present study also extended the analysis in other types of dynamic modeling studies performed on e-wastes and on mobile phones. Most of the studies conducted dynamic analysis on small-scale systems (Williams et al., 2013), for example e-waste management in a city or a country level, without considering a life cycle perspective (Andarani and Goto, 2013). To our knowledge, a broader systems approach, i.e., with a life cycle perspective and dynamic analysis, has previously only been applied to the mobile phone product system by Bollinger et al. (2012).

In a broader systems approach, Bollinger et al. (2012) performed a dynamic substance flow analysis of global flows of metals in mobile phones in a cradle-to-cradle perspective. The study was based on the research question "*. . .[w]hat [modeling] conditions foster the development of a closed-loop flow network for metals in mobile phones?*". The focus was on comparing SD and ABM approaches, while testing and implementing the modeling outcomes in the real world were beyond the scope of the study. However, the model has potential applications in a real-world situation. Adopting the SD model of Bollinger et al. (2012), the aim of the present study was to investigate possibilities to close the metal flow loop in the GMPPS. Specific objectives of the study were to:

- Identify potential drivers for closing the metal flow loops efficiently by better understanding the dynamics of the GMPPS.
- Propose a future eco-cycle scenario based on the potential drivers and the eco-cycle concept, and provide suggestions for implementing this eco-cycle scenario in the real-world situation of the GMPPS.

The intention was not to predict the future, but to understand, explore, and learn about the complexity and dynamics of the GMPPS.

2. Methods

2.1. The eco-cycle concept

The eco-cycle concept (Ravetz, 2000; Eco-Cycle, 2014) represents the industrial metabolism (Fischer-Kowalski and Haberl, 1998) in a socio-technical system (Geels, 2012) where substances or resources continuously circulate within the socio-economic system with low or no leakage of the resources. The term eco-cycle is used in this study to represent nearly closed-loop material flows or very low leakage in the mobile phone product system. The conceptual eco-cycle model focuses on the technical nutrients, e.g., metals, that are circulated in the socio-technical system with little or no re-entry into the lithosphere (Graedel and Allenby, 2003; Preston, 2012).

The necessary links between actors to close the material flow loop in the GMPPS are illustrated in Fig. 1. Physically, the product system entails the extraction of necessary raw materials, production and assembly of parts by manufacturers and suppliers, a maintenance and distribution network, utilization by consumers, material collection and recycling, waste treatment, and transports. In a societal context, the system includes the behavior of markets and user practices, costs, price and demand elasticity, purposes, function and objectives, consumer preferences, awareness, economic development, and aspects of a social and a softer character.

The eco-cycle concept in mobile phone product systems thus includes both physical resource management and social aspects. In this study, the eco-cycle concept illustrated in Fig. 1 only provided the mental model to visualize the eco-cycle scenario qualitatively. The quantitative eco-cycle was formulated by experimenting with the SD model. The default SD model was parameterized based on a business as usual (BAU) scenario.

2.1.1. Eco-cycle indicators

Based on circularity indicators produced by the Ellen MacArthur Foundation (2015) and Bollinger (2010), two indicators were employed for examining the GMPPS. These were loop leakage and loop efficiency, which quantify the degree to which metals are efficiently preserved in the system. The loop leakage indicator, based on the linear flow index by Ellen MacArthur Foundation (2015), determines the resource fraction leaving the product system, i.e., it indicates to what extent the loop is closed and metals are preserved in the system. The loop efficiency indicator, based on the cradle-to-cradle indicator (C2CI) developed by Bollinger (2010), determines how efficiently the resources are utilized in the system. In this case, efficiency indicates the efficient uses of resources without hibernating resources. Eq. (1) illustrates quantification of loop leakage