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Ecological foraging models as inspiration for optimized recycling systems in the circular economy

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ABSTRACT

Converting the consumer electronic product system from a linear system to a circular one has a number of key challenges. A mismatch is observed between the rapidly changing devices entering the market and the slowly evolving voluntary design policies, regulations, and e-waste processing business strategies. Conventional electronic waste (e-waste) management systems were historically optimized to extract high-value components from large products that were relatively easy to disassemble, but the products now entering the waste stream are more often light-weight mobile devices that are typically not covered by regulations or do not contain as high a concentration of valuable metals. This article proposes that transformations in the e-waste processing system aimed at closing the material loop should look to the circular processes found in natural ecosystems, which have evolved to optimize closed loop nutrient cycling. Like species in nature, e-waste processors make decisions about where and what to "eat," balancing a food's quality and abundance with the energy expended in obtaining it. Adapting the concept of optimal foraging theory, we demonstrate here a conceptual framework that draws parallels between foraging behavior in the ecological and industrial world, evaluates four potential mathematical models that case be applied to the e-waste case, and demonstrate how optimal foraging decisions can guide business, design, and end of life management toward circular economy goals in the consumer electronic system.

1. Introduction

The consumer electronic product system (smart phones, televisions, computers, etc.) has permeated modern society across individual, household, industry, and national scales. Over the last 25 years, the average U.S. household went from owning fewer than eight to more than 20 different electronic devices, with rapid replacements spurred by shortened product lifespans, technological advances, lower costs, changing consumer preferences, and decreased emotional or personal attachment to the devices themselves (Ryen et al., 2014; Ryen et al., 2015; Chapman, 2015; Lauridsen and Jørgensen, 2010). Compounding the rapid growth in consumption and adoption patterns, significant resources are invested in product manufacturing (Williams et al., 2002; Williams 2004; Kasulaitis et al., 2015), but never fully recovered after the product's useful life. Consumer electronic products typically have short lifespans, are difficult to upgrade or recycle, and as a result, only a fraction of materials embedded in electronics are recycled back into new technology products (Lauridsen and Jørgensen, 2010). The linear management of consumer electronics also results in an unprecedented expansion of the global electronic waste stream (Widmer et al., 2005; Huisman et al., 2008; Zoeteman et al., 2010; Herat and Agamuthu, 2012; Taghipour et al., 2011).

Converting this linear system to a circular one is a widely held goal, but faces a number of key challenges that must be addressed. For example, electronic products contain both valuable and potentially hazardous materials and components, which on one hand can be recycled as substitutes for more expensive or scarce primary materials, but on the other have the potential to create negative impacts to human health and the environment if managed improperly (Widmer et al., 2005; Williams, 2011; Williams et al., 2008; Pérez-Belis et al., 2015; Kiddee et al., 2013). Conflicting circumstances that currently pose challenges to recycling efforts can be attributed to material content including: 1) toxic substances (e.g., mercury, lead), 2) abundant, low value materials (e.g. plastic from computer casings), 3) low volume, high value materials (e.g. precious metals found in printed circuit boards), and 4) low volumes of scarce and critical materials (e.g. dysprosium in hard drives) (Kang et al., 2012; Williams et al., 2008; Widmer et al., 2005; Robinson, 2009; Park and Fray, 2009; Wang and Gaustad, 2012; Chancerel et al., 2013).

In addition, the complex and quickly evolving nature of the

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electronic product system sharply contrasts with the slow pace at which conventional waste management approaches are being developed to safely recover and return components and materials back into the value chain. These conventional approaches include voluntary design and purchasing standards, regulations based on the concept of extended producer responsibility, and formal collection and processing of electronic devices. For example, voluntary standards such as the Electronic Product Environmental Assessment Tool (EPEAT) attempt to encourage product repair and more efficient recovery of high value materials through design features such as easy access to internal components, material labeling, radio frequency identification (RFID) tags, and bill of material databases (GEC, 2009). While these design standards were first created to improve the environmental performance of large, legacy products like desktop computers and monitors, standards aimed at smaller products, like mobile phones (EPEAT, 2017), have only recently emerged. Moreover, a trend towards using automatic shredding processes in electronics recycling (GEC, 2009) suggests that disassembly may not be the most effective strategy to process the smaller, mobile electronic devices anticipated in future waste streams.

Regulations have also been developed to formally manage devices in a circular system. Extended producer responsibility (EPR) laws like the European Union (EU) Waste Electric and Electronic Equipment (WEEE) Directive 2012/19/EU were originally designed to encourage the recovery of products and materials for a range of electronic devices entering the waste stream (Pérez-Belis et al., 2015), and drive innovation to enable product disassembly, repair, and recyclability (Lauridsen and Jørgensen, 2010). However, the WEEE Directive has lost some of this original intent, as third parties involved with the collection and recovery of materials are often not collaborating with manufacturers or designers and there is limited ability to reintegrate recovered products, components, and materials back into the same industry (Singh and Ordoñez, 2016; Ghisellini et al., 2016).

In comparison to the EU's unified approach, a bottom-up "patchwork" of state and local e-waste policies in the U.S. has resulted in varied recycling strategies based on the concept of EPR (Nnorom and Osibanjo, 2008; Kahhat et al., 2008; Hickle, 2014). For example, New York State (NYS) laws (e.g., NYS Electronic Equipment Recycling and Reuse Act and New York State Wireless Telephone Recycling Act) focus on larger products (computers, monitors, VCRs, and gaming consoles), some newer devices (DVD, TV set top boxes) and mobile phones (NYS, 2016). Producers are required to pay for collection, transportation and recycling of these devices and their costs are allocated based on market share (Electronic Take Back Coalition, 2013). While manufacturers are required in many states to take back and recycle their electronic devices, some states provide limited reimbursement or center reimbursement on mass-base standards (a combination of allocating costs by return and market shares) (Gui et al., 2013). As a result, third party collection parties may target larger or heavier devices, which are being phased out and are of limited use for direct recovery of material or components into new, lightweight products.

These challenges are likely to be magnified by ongoing trends in the consumer technology industry, estimated to be worth $287 billion in retail revenues in 2016 (CTA, 2016). For example, rapid expansion of connected, mobile and wireless devices like wearables, audio, video, and smart home devices has led to widespread expansion of the Internet of Things. As a result, products that were never before considered to be "electronics" – like clothing, shoes, watches, toys, and household products – are embedded with sensors, circuitry, and batteries, all of which consume significant materials and energy while also creating new waste management challenges. At the same time, "traditional" consumer electronics are themselves undergoing rapid evolution in design and functionality and a diversification of sizes and material compositions.

Some of these trends may lead to net resource improvement. For example, the elimination of cathode ray tube (CRT) televisions and replacement with lightweight flat panel devices has created a net material reduction, although tradeoffs in terms of energy use, scarce material demand, and waste management are not yet quantified (Babbitt et al., 2017). To a large extent, though, trends toward lightweighting and diversification in physical attributes of electronic products has served to confound efforts aimed at converting this linear materials system into a circular, closed-loop system. For example, from 2014 to 2015, the volume of "covered" (or regulated) electronics collected in Oregon declined by 11% (Evans, 2016) because the majority of products entering the waste stream during that period were small, mobile devices not covered under existing state legislation. It is clear that new resource management strategies, like the circular economy, must take into account the dynamic nature of electronic products and their attendant material consumption and waste generation.

2. Ecological inspirations to optimize e-waste recycling systems

To create a closed-loop system for material recovery, one of the clearest design inspirations comes from biological systems themselves. Natural ecosystems have evolved over hundreds of millions of years to provide the qualities we now aim to emulate in industrial systems: circularity in closed systems, trophic level energy cascading, efficient material cycling, robust network topology, stable interdependence among species, and diverse material flows (Jorgensen, 1992/1997; Jorgensen, 1992; Korhonen, 2001; Nielson, 2007). Nutrient cycling is a primary feature of most ecological systems, where it is commonly seen that the waste from one type of organism becomes an input for others in the system (Stahel, 2016), as illustrated in Fig. 1a.

In ecosystems comprised of complex organisms, ecological nutrient and energy flows are often mediated by the evolution of behaviorally-based foraging decisions, which in turn are influenced by both interactions among the species present at any given time, as well as individual responses to exogenous factors, such as food limitations or temperature fluctuations (Pyke et al., 1977; Ricklefs and Miller, 2000). Foraging decisions influence the behaviors employed by animals to search for and handle food (e.g., physical efforts associated with capturing and debilitating prey, maintaining territory against intrusion, and/or systematically searching the landscape for opportunity).

Foraging has been widely studied by ecologists and resulted in many quantitative models because the "…stomach sways the world" (Fabre, 1913 as noted in O'Brien et al., 1990 p.152), through its influences on ecosystem level services and processes (O'Brien et al., 1990). Animals engage in foraging activities and make decisions critical to health: where to search for prey, what prey to eat, whether or not to pursue the prey, and when to leave the patch or area once the prey is found (Perry and Pianka 1997; Stephens and Krebs 1986). Invoking a combination of both instinctive and learned behaviors in animal systems, ecologists have explained and predicted foraging behaviors first with simple cost-benefit ratios and then later with more complex empirical models (Pyke et al., 1977). These foraging decisions play an important role in the ecosystem as a whole; breaking down and recovering resources and energy to be reused, minimizing waste, and competing and cooperating together to enhance the system capacity to withstand perturbations.

Like its ecological counterparts, the consumer electronics ecosystem (Fig. 1b) consists of several species or stakeholders (e.g., manufacturers, households, e-waste processing business) that interact with one another. For example, households provide a source of food or prey (i.e., obsolete devices) to e-waste processing businesses. Because in the U.S. most devices are still stored in homes or disposed landfills (US EPA, 2014), e-waste processing businesses make important foraging decisions that enable a circular flow of nutrients (materials) and embodied energy in the ecosystem while minimizing waste. Decisions include where and how to find the obsolete devices and then what type of techniques or handling strategy (e.g., testing, repair, disassembly, or shredding) to employ to break down the devices and recover technical nutrients (components and materials) for resale or resource recovery. Like a natural ecosystem, the consumer electronics ecosystem is vulnerable to external perturbations such as government regulations,