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Economic sustainability of closed loop supply chains: A holistic model for decision and policy analysis

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ABSTRACT

We develop an end-to-end model of a closed-loop supply chain (CLSC), and identify the systemic decision making required for economic viability of participants in this chain. Economic viability is a key ingredient for environmentally sustainable behavior and policies, and our decision making framework includes producers, refurbishers and recyclers. We model the lifecycle of a consumer electronics product to examine the complex interactions among different participants and their decisions. Using data from recyclers and marketing and supply chain literature, we find that i) sustainable CLSC policies require a well-calibrated return rate among types of products (new and refurbished) and consumers (innovators and imitators); ii) a sustainable return policy increases sales significantly for both types of customers; and iii) product design that improves refurbishability, and marketing efforts that create perceived differentiation between products and at the same time social awareness and acceptability for refurbished products, is critical for economic sustainability of refurbishers and recyclers. Our model can be used at a company or industry level to conduct cost–benefit scenarios for all participants of the CLSC, and make decisions based on systemic value. It can also be used to create public policies and incentives to reward companies that meet these benchmarks, for sustained economic and environmental benefits.

1. Introduction

Today, the life cycle of many consumer electronic products (e.g., cell phones, computers) is becoming shorter [26]. Cutting-edge products can quickly become obsolete or outdated with the introduction of new ones. Therefore, millions of products in good working condition are replaced every year and in many cases laid to waste. These can create new business opportunities for refurbished products on secondary markets; on the other hand, create a global environmental concern due to the growing amount of electronic waste (e-waste) generated. Gartner [22] estimated that more than 120 million PCs will be refurbished, remarketed and reused over the next five years (2012–2016) in the global secondary market. The Environmental Protection Agency estimates that "…recycling 1 million cell phones can recover about 24 kg (50 lb) of gold, 250 kg (550 lb) silver, 9 kg (20 lb) palladium, and more than 9000 kg (20,000 lb) copper" [17]. At 2013 metal prices, that is over 1.45 million USD. In 2010 the U.S. got rid of 2.4 million tons of e-waste, of which, only 17.7% was recycled [16]. The rest was trashed in landfills or incinerators. Electronics is a growing component of waste; however the recycling rate is about 15% only [44].

Under such scenarios of increasing waste, businesses need to include decision strategies for environmental sustainability. This includes higher rates of recycling and refurbishing of older products. Legislation in the United States as well as in Europe and Japan has refocused attention on recycling for management of wastes and, specifically, e-wastes (see e.g. [1]). Consequently, it is imperative for businesses to take a holistic view of their supply chain that covers the entire product life-cycle from design to end of life. Products that cannot be refurbished need to be responsibly recycled; business must also consider the second-hand market value of their products as they design the products. Consumers' perceived value of refurbished products impacts their decisions to buy such products, which can affect the sales and end of life management of the new product [40]. Product design can affect the cost of refurbishing and recycling [44]. Taken together, legislative decisions and consumer perceptions can lead to increased costs for higher environmental sustainability.

Here we develop a methodology to study the economic impact of environmentally sustainable operations, and identify economically beneficial policies and decision making. Only those technologies, processes and products that are economically viable will be long term winners. Although extensive study exists in supply chain management research, there is a lack of a holistic approach that focuses on decisions made on the entire supply chain from an economic and environmental sustainability perspective. Such research would combine the forward and reverse logistics of the supply chain [2]. Importantly, a holistic decision making approach needs to take into consideration the economic

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incentives of all participants in the closed-loop supply chain (new product sellers, refurbishers and recyclers, in addition to consumers) to implement sustainable policies. The viability and business decisions of one determine the profitability and sustainability of other participants, creating a critical and complex chain of impact [21,67,68,70]. Hence, it is important to model these decision parameters in an integrative manner, with a focus on all supply chain participants. In other words, recycling and refurbishing rates may need to improve for environmental sustainability; however for economic sustainability, which is the true driver of decision making for firms, all participants in the supply chain need to be profitable for the "closed-loop" to function. Our research provides a path towards evaluating environmentally beneficial economic scenarios. Research and current events also suggest that company actions to improve social responsibility and resultant consumer awareness can improve goodwill and firm value [48,59,60]. This can be coupled with the benefits from increasing market size and related economies where a product seller may be profitable.

We contribute by bridging the above-mentioned existent gap in the literature and develop a holistic model of a closed-loop supply chain (CLSC). We focus on a type of product (e.g. mobile phone) that has high initial value and short lifecycle — a potent combination that creates significant e-waste with low recycling rates, short lifecycles and low values for refurbished products. These products use precious metals that have significant geo-strategic importance for companies and countries involved [7,13]. Such products also cause high cannibalization within themselves. In particular, our research focuses on the dynamics among the different participants of the closed-loop, namely the product manufacturer and its product design and marketing strategies, consumers and their product preferences, including length of product ownership, and end of life (EOL) product return options that impact refurbishing and recycling partners at the downstream of the supply chain. Typically, EOL return options and incentives are not offered or advertised by most electronic product manufacturers. This is in contrast with warranty period return mechanisms, which are quite well-established, both for new and refurbished products. Arguably, warranty returns are a small component of the CLSC, and EOL returns hold significant potential. Specifically, we provide insights to the following questions: (1) what is the impact of EOL return rates on economic sustainability?, (2) what is the impact of premature returns, which are typically before EOL occurs?, (3) what are the impacts of price and product depreciation on the sales of new and refurbished products?, and (4) what is the impact of refurbishable product design on closing the supply chain loop? We find, predictably, that higher product depreciation (perceived value) of refurbished products increases its price differential with new products, thus lowering the prospects for refurbishers. While refurbishable design improves their prospects and helps to sustain the CLSC, it creates pricing pressures for the new product manufacturer. To balance these opposing forces, we find that a diversified product market (new and refurbished) is sustainable only at EOL return rates substantially greater than zero. This strongly suggests that explicit EOL return policies and decisions need to be implemented, which are typically absent in the market for electronic products. Contrary to perception, both new product and refurbisher profits can be significantly increased by increasing planned EOL product returns. As a sustainable byproduct, recycling rates and revenues can also be improved significantly, which improve both economic and environmental metrics. A profitable operation for each business stakeholder (new product manufacturer, refurbisher, and recycler) in the chain is essential for the closed-loop to be economically – and environmentally – sustainable, and we focus on identifying the return levels, price, product depreciation and design decisions that impact and sustain such processes. Our research has a large number of applications, including tracing the lifecycle of a product and associated economics, and the manufacture, recycling and remarketing decisions of industrial products such as aircraft engines and medical devices, among others [11,58].

Table 1
Model parameters and decision variables.

Market parameter	Description
α	Adoption rate of innovators
β	Adoption rate of imitators
Decision variable	**Description**
δ	Perceived product depreciation rate relative to new and refurbished products
p_n	Price of new product
p_r	Price of refurbished product
EOL_{innov}	End of life return rate of new products by innovators
$EOL_{imitnew}$	Return rate of new products by imitators
$EOL_{imitrefurb}$	Return rate for refurbished products by imitators
RetRefurb	Return to refurbish rate
RefurbRec	Refurbish to recycle rate
$RBEOL_{innov}$	Premature return rate of new products by innovators, or return before end of life
$RBEOL_{imitnew}$	Premature return rate of new products from imitators
$RBEOL_{imitrefurb}$	Premature return rate of refurbished products from imitators

2. Literature review

Closed-loop supply chain (CLSC) has been a theme of much research. Guide and Wassenhove [34] argued that CLSC research needed to shift from individual activities in the reverse supply chain to interdisciplinary research focus. Iglin and Gupta [36] concluded that reverse logistics literature is dominated by the studies on location–allocation models, and remanufacturing systems are often analyzed by considering only one specific operations management issue. Most CLSC research focuses on different components of the loop. Substantial research exists on the capture of value remaining in products at the end of a products life through remanufacturing [20,27–30,35], and on design considerations for product recovery networks [6,12,19,21,38,68]. For example, Jayaraman et al. [38] developed a location model for remanufactureable products and grounded the model with information from a mobile telephone remanufacturer. Krikke et al. [39] considered alternatives for the design of a reverse logistics network for photocopiers. The impact of product design and its influence on the degree to which a product can be reused, remanufactured, recycled, incinerated or disposed of has also been a theme of research [25,46,47,63].

In terms of business policy, Guide et al. [28,30] and Guide and van Wassenhove [31–34] have consistently promoted the importance of business perspective to make CLSC attractive to managers and decision makers, and focused on profitable value recovery from returned products. Wells and Seitz [73] proposed business models and a typology of CLSC, where business model should be redesigned and placed at the heart closed-loop systems. Wei and Zhao [74] proposed an optimal

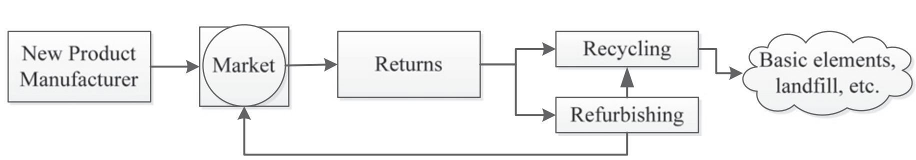

Fig. 1. Conceptual research model of shared resources.