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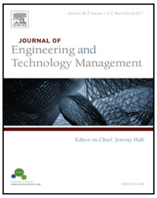

Product recovery decisions within the context of Extended Producer Responsibility

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ABSTRACT

Environmental and economic evidence is increasingly supporting the need for better analytical tools for evaluating the recovery of consumer products. In response, we present a novel mathematical model for determining what we call the Optimal Recovery Plan (ORP) for any given product. The ORP is based on an evaluation and optimization of the economics of remanufacturing consumer products versus demanufacturing in the context of Extended Producer Responsibility (EPR) legislation, a driving force behind the adoption remanufacturing initiatives by firms. We provide an illustrative application of the model and then discuss its implications for scholars and practitioners concerned with sustainable business development.

Introduction

Sustainable business development (SBD) refers to how businesses create products, services, and processes that are economically sound, socially responsible, and environmentally conscious (Rainey, 2006). A number of related factors are driving firms to adopt SBD practices. These include: higher levels of consumption, shortening of product life spans, and industry strategies that increasingly focus

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on rapid innovation and obsolescence (McCarthy et al., 2010); increases in environmental regulations (Sanchez and McKinley, 1998) and the risks and costs of waste management (Gunasekaran and Spalanzani, 2011). Furthermore, this need to pursue SBD is compounded by developing nations that are increasingly refusing to be dumping grounds for electronic waste (e-waste) generated internally or imported illegally from developed nations (Nnorom and Osibanjo, 2010).

In terms of the regulations that are driving SBD adoption, there is a growing body of environmental regulations called Extended Producer Responsibility (EPR). EPR focuses on the end-of-use treatment of consumer products and has the primary aim to increase the amount and degree of product recovery and to minimize the environmental impact of waste materials. For this purpose, EPR policies place financial responsibility on to the producers of consumer products and requires firms to effectively and efficiently choose from among end-of-life (EOL) or recovery options for products that exhausted their physical and/or functional lifespan (Lee et al., 2010).

To help comply with EPR, firms can practice two related product recovery strategies. One strategy is “product remanufacturing”, where a used product is returned (or collected through take-back schemes such as leasing or deposits), followed by a process of product disassembly, cleaning and rebuilding the product to specifications of the original manufactured product (Guide, 2000; Majumder and Groenevelt, 2001). Remanufacturing reduces environmental impacts by retaining the geometrical form of the product, thus allowing a “rebirth” of material usage that preserves both economic and environmental values (Lee et al., 2010). A key decision in practicing remanufacturing is to determine to what extent a new product can be built from remanufactured parts versus new parts.

The second product recovery strategy, “product demanufacturing”, has grown over the past 20 years, largely in response to growing environmental problems of landfilling EOL products. Demanufacturing focuses on evaluating the economic and environmental implications of material recycling, part reuse, shredding and landfill options. In contrast to remanufacturing, demanufacturing attempts to salvage any remaining economic value in the EOL product through disassembly and promotes material recycling over disposal. Thus, a central question of demanufacturing is the amount of disassembly efforts that should be invested in order to derive “value” from the retired product (Johnson and Wang, 1998; Karakayali et al., 2010).

As remanufacturing and demanufacturing are viewed as different ends of the same product recovery continuum, operations management literature has called for research to better understand the extent to which products can be sustainably remanufactured or demanufactured (Atasu and Wassenhove, 2012; Kumar and Putnam, 2008; Gunasekaran and Spalanzani, 2011; Jayant et al., 2012). This issue is the aim of our paper, in which we present a model for determining what we call the Optimal Recovery Plan (ORP), i.e., an evaluation of the tradeoff between remanufacturing and demanufacturing within the context of an EPR environment. As will be discussed in this paper, the optimization model provides a test-bed for evaluating product recovery decisions that impact sustainable business development issues.

The development of our model in this paper is organized around four major sections. First, we provide a review that introduces the importance of Extended Producer Responsibility (EPR) legislation and explains its relevance to sustainable business development. In this section we also examine the research on the economic and environmental tradeoffs of remanufacturing versus demanufacturing and highlight the need for research to better understand these tradeoffs at the level of whole product recovery. In the third section, we present an optimization model for addressing this problem, and in the fourth section of our paper we demonstrate an application of the model using product data from the telecommunications industry. In the final section of our paper, we discuss implications and new directions for research on remanufacturing versus demanufacturing as motivated by our model.

Literature review

In this section, we first review literature on EPR regulations that impact product recovery decisions so as to highlight the issues that drive and govern the need to understand the product recovery tradeoffs associated with remanufacturing and demanufacturing. We then review prior research on remanufacturing and demanufacturing to help develop our model and show how our model adds to and advances research on these product recovery approaches.

Extended Producer Responsibility

Both remanufacturing and demanufacturing, along with the required closed-loop supply chains (Gunasekaran and Ngai, 2012; Hall, 2001), environmental management systems (Aravind, 2012), and product design processes (Petala et al., 2010), are deemed appropriate for achieving sustainable operations. One factor that has been driving firms to consider and adopt remanufacturing and demanufacturing practices is the growing body of legislation and policies associated with Extended Producer Responsibility (EPR).

The OECD (2011) defines EPR as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle. In the past two decades, policies on EPR have been implemented for a wide range of products, especially in industrialized economies. For example, many national governments (e.g., Japan, South Korea, Taiwan and Canada), the European Union (EU) members, and 23 states in the US have adopted EPR principle based legislation for end-of-use treatment of products (Özdemir et al., 2012). The EU directive on Waste Electronics and Electrical Equipment (WEEE) has explicitly made recoverability improvements as an objective for the national regulations of member states by setting specific recovery rate targets for different product categories (EU, 2002). Furthermore, an increasing number of Asian economies have introduced or are drafting legislations on e-waste, based on EPR, including China, India, Thailand, Malaysia, Vietnam and Indonesia (Kojima, 2011).

In response to EPR legislation firms are assessing and adopting two related product recovery opportunities. One of the options is whole product remanufacturing which has been adopted by original equipment manufacturers (OEMs) such as Caterpillar, Kodak, Xerox and Delphi to deliver competitive gains, while improving their environmental performance (Martin et al., 2010; Subramoniama et al., 2011). The second option is demanufacturing which has primarily focused on material recycling of EOL products. Firms such as Nokia and Motorola have increasingly engaged in take-back programs and demanufacturing activities (Neto and Van Wassenhove, 2013). Similarly, industries as a whole are implementing demanufacturing. For example, much of the telecommunications industry is striving for a "greener" supply chain for manufacturing and recycling of e-waste (Goldey et al., 2010), and the civil infrastructure industry (commercial and residential buildings) is championing a range of green design, build and deconstruction initiatives (Mukherjee and Muga, 2010).

Recently there has been a surge of research on EPR regulation that specifically addresses the implementation of the WEEE legislation and its challenges from an operations management perspective. A number of analytical models investigate the economic efficiency of the WEEE directive and variations in legislative designs (see: Hammond and Beullens, 2007; Atasu et al., 2009; Toyasaki et al., 2011), the tradeoff between collective, multi-echelon, third-party and individual manufacturer responsibility (see: Spicer and Johnson, 2004; Atasu and Subramanian, 2012; Jacobs and Subramanian, 2011), and the impact of product design implications and the introduction of new products (see: Plambeck and Wang, 2009; Atasu and Subramanian, 2012).

Despite the good intentions of EPR legislation to incorporate sustainable business practices on product recovery, literature has also identified numerous shortcomings of these policies. For example, research has criticized EPR legislation for being unsuccessful in promoting product recovery strategies through design enhancements that improve disassembly and increase the retained value in recovery operations (Atasu et al., 2009; Walls, 2006; Zuidwijk and Krikke, 2008). More related to our study, research highlights that there is some confusion regarding the impact of EPR legislation on a firm's decision to remanufacture or demanufacture EOL products. For example, Atasu and Wassenhove (2012, page 8) state: "mandated take-back and for profit take-back and reuse (e.g., remanufacturing) are likely to be confused, although most take-back legislation focuses solely on material recycling or energy recovery." One reason for this confusion is that EPR legislation has largely favored the demanufacturing activities of materials recycling over remanufacturing in the past, despite the fact that literature sides with product reuse as the preferred environmental alternative over end-of-pipe material recycling. The WEEE regulation for example, has explicitly excluded whole product reuse[1] or remanufacturing from being incorporated into the methodology of calculating recovery rates: "Until the date referred in paragraph 4, such appliances shall not be taken into account for the calculation of targets set out in paragraph 2" (EU Directive 2002, page 6 – Article 7, Part 1). At the same time, the WEEE legislation recognizes the importance of reuse (remanufacturing) over demanufacturing activities in its Article 7, Paragraph 1: "*Member states shall give priority to the reuse of whole appliances*". As a result, this policy detail has effectively discouraged whole product remanufacturing from the viewpoint of EPR legislation over the past decade. Only recently has the 2012 revision of WEEE addressed this issue and set a date of August 15, 2015 by which whole product reuse (i.e., remanufacturing) will be given its due credit and counted toward recycling targets. Similar changes are taking place in other parts of the world as well. In Canada, the Ontario Electronic Stewardship (OES) is considering adjustments in its material recovery calculations and targets to include product reuse (Karakayali et al., 2012).

This highlights that EPR legislation has clearly signaled that product reuse requirements as part of the mandated recovery rates will become increasingly important in the future (i.e., see the recast WEEE, 2012 revision). Given these future changes, it is suggested that a new era of product recovery is likely whereby manufacturers will take a closer look at the possibility of product recovery that includes whole product remanufacturing and reuse opportunities relative to current EPR practices that focuses primarily on recycling. Our paper aims to address the following gap: How can an organization evaluate the economic tradeoffs between remanufacturing versus demanufacturing alternatives in the context of stringent EPR requirements that demand an increasing percentage of product recovery as well as possible future "reuse" requirements?

Product recovery as a remanufacturing–demanufacturing continuum

A key decision in EPR is choosing the right recovery strategy (Krikke, 2010). In this paper, the term "product recovery" is defined as a continuum that ranges from demanufacturing activities to whole product remanufacturing. At a lower end of the continuum sits demanufacturing activities such as material recycling and disposal (See Fig. 1). At the higher end, sits recovery options such as whole product remanufacturing that is focused on parts reuse and parts remanufacturing whereby a large proportion of the original product is "reused" in the forward supply chain thereby reducing the need for virgin material extraction and processing. In this context, product recovery activities that lead to the "reuse" of EOL products into the forward supply chain promote multiple product life-cycles that are considered environmentally superior alternatives over single product life-cycle activities such as materials recycling. Krikke (2010) refers to the degree to which a product can be reused in the forward supply chain as the "substitution effect" as it replaces (i.e., substitutes) the need for the extraction of virgin resources (material, energy, water) accruing substantial environmental benefits compared to recycling activities. Fig. 1 depicts the difference between demanufacturing activities which have focused on single product life-cycles (primarily material recycling) compared to multiple product life-cycles such as whole product remanufacturing.[2] It also depicts the importance of "parts reuse" and "parts remanufacturing" as being an important transition point between demanufacturing and remanufacturing activities. As previously stated, EPR legislation to-date is has done poorly to encourage this transitional element and has primarily encouraged material recycling activities.

In this section, we review prior research on remanufacturing and demanufacturing with a focus on models that analyze the tradeoff of different recovery options at the product level. By doing so we highlight the need for a model capable of evaluating the economic tradeoff between demanufacturing activities (representing single product life-cycle recovery options) and whole product remanufacturing (representing multiple product life-cycle recovery) in the context of an EPR environment.

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[1] In this paper, the term "reuse" implies product recovery activities that promote multiple product life-cycles such as product reuse or remanufacturing whereby the original EOL product or its components are utilized in the forward supply chain of a new product. Please see Fig. 1 for details.

[2] For the purpose of this paper, future references of the word "remanufacturing" will mean "whole product remanufacturing", that is, the rebuilding of a consumer product to specifications of the original product using a mix of used, remanufactured and new parts.

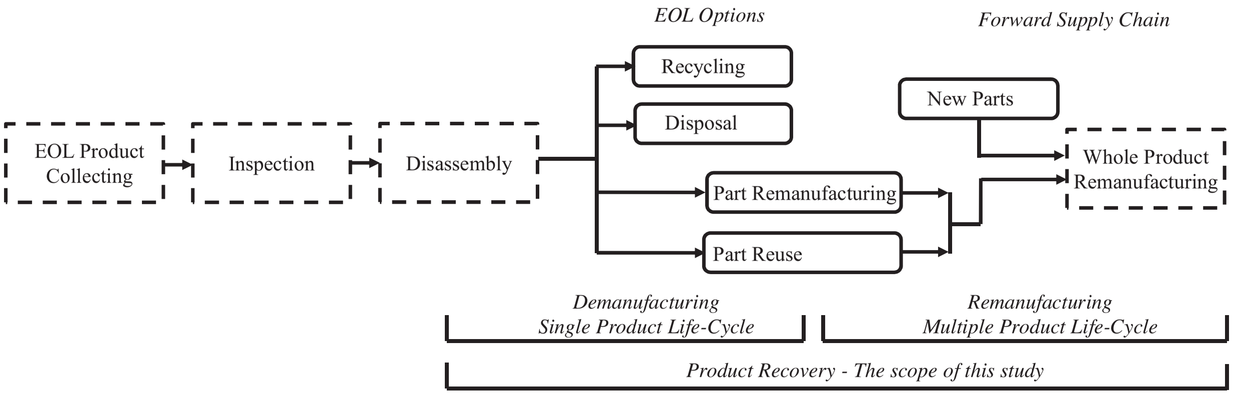

Fig. 1. Product recovery and the scope of this study. Adapted from Jun et al. (2012).

Demanufacturing research has developed a number of mathematical models to analyze the tradeoffs between EOL options such as material recycling, part reuse, part remanufacturing or disposal. In essence, demanufacturing is a salving operation that strives to economically recover materials and components from EOL products, focusing on the extent of disassembly required to recover value from retired goods. Thus, prior research on demanufacturing has focused on three major decisions: (i) determining optimal levels of product disassembly (see: Johnson and Wang, 1995; Penev and de Ron, 1996; Willems et al., 2006; Achillas et al., 2013): (ii) optimal disassembly sequences (see: Johnson and Wang, 1998; Lambert, 2007; Hui et al., 2008) and (iii) the optimal selection of EOL options (see: Krikke et al., 1998; Jun, 2007; Jun et al., 2012). Recently, Ma et al. (2011) developed a methodology for dealing with all of these three issues simultaneously, so as to examine both EOL treatment processes and product design issues. Furthermore, Tsai and Hung (2009) optimize the demanufacturing processes of treatment and recycling using a two-stage multi-objective decision framework and consider various factors such as the probability of component reuse, regulations on recovery rates and environmental impacts of parts and subassemblies. Zuidwijk and Krikke (2008) investigate the gains of product recovery in e-waste demanufacturing by comparing changes to product design and recovery technologies.

Remanufacturing (i.e., whole product remanufacturing) deals with an entirely different approach to product recovery. It is the rebuilding of a product to specifications of the original manufactured product using a combination of reused, remanufactured and new parts. It is for this reason why previous research on product recovery decisions have largely focused on demanufacturing and whole product remanufacturing practices as independent research initiatives. As discussed, demanufacturing has largely focused on improving the efficiency of the disassembly planning process to reclaim materials inherent in EOL products. Although remanufacturing and reuse are often defined as recovery options of demanufacturing, literature most often refers to remanufacturing and reuse on a part or subassembly level, not as “whole product” remanufacturing. One reason for this is because demanufacturing is inherently focused on EOL products that do not have either the technical or commercial (secondary markets) characteristics to sustain a secondary product life. The product may however, have parts or subassemblies that can be reused or remanufactured.

For the purpose of this paper, our review of prior research on remanufacturing and our model focus on remanufacturing related to EOL decision making at the product level (with regard to tradeoffs between economic and environmental issues and the context of EPR legislation). As we will now discuss, despite much attention to this topic, there is a dearth of research focusing on decision making of EOL products within an EPR system. In particular, product level EOL selection decisions associated with demanufacturing versus remanufacturing in the context of EPR legislation.

A number of papers have addressed the significance of evaluating the EOL selection decisions associated with product remanufacturing. For example, Tang et al. (2004) developed a disassembly-strategy decision model based on an EOL product’s economic value for remanufacturing. To take into account the time value of money, they evaluated the economic value of disassembly strategies using the net present value (NPV) method. Xanthopoulos and Iakovou (2009) propose a mixed integer linear programming model to determine subassemblies and components to be disassembled for remanufacturing. Although these papers make valuable contributions for evaluating the potential remanufacturability of consumer products, they focus on parts or subassemblies that are economically remanufacturable as opposed to addressing the potential of whole product remanufacturing versus demanufacturing.

A number of notable research studies partially address tradeoff considerations of remanufacturing versus demanufacturing. Pochampally and Gupta, 2012 use fuzzy logic and Bayesian updating to evaluate repairing an end-of-use product versus remanufacturing the same. However unlike our model, theirs is not completed within the context of mandated EPR legislation. Another study by Lee et al. (2010) presents a hierarchical decision model for maximizing the economic value of remanufacturing options within the context of EPR. Their analysis is geared to current product remanufacturers, while in contrast our model can be used for the startup of remanufacturing versus demanufacturing activities. Furthermore, the Lee et al. (2010) model takes a step-wise approach to remanufacturing decision-making within the environmental constraints, whereas our model analyzes both remanufacturing and demanufacturing decisions from an economic perspective of product rebuilding using an integrative optimization model with respect to EPR constraints. Two other studies papers have gone a step further to analyze and promote remanufacturing over demanufacturing activities. Krikke (2010) advocates the need for whole product remanufacturing (with multiple lifecycle loops) over demanufacturing activities that are viewed as short-term profit maximizing (or opportunistic) decision making; and Krikke (2011) discusses the importance of maximizing the "substitution effect" in the forward supply chain especially when compared to cascade recovery options (i.e., material recycling) that fail to demonstrate any substitution effect as they serve alternative or lower segments in the market. Our paper seeks to complement this research by developing a diagnostic tool that can be used to maximize the extent of substitution at the product level by evaluating the economical tradeoff of remanufacturing versus demanufacturing options within EPR legislative requirements. We propose a model for optimal product recovery (ORP) based on "substitution" at the product level so as to determine the extent of remanufacturing that is economically preferable over demanufacturing activities.

A model for optimal product recovery in the context of Extended Producer Responsibility

In this section we first present decision rules for evaluating the economics of remanufacturing versus demanufacturing at the product level. We then develop a model for optimal product recovery that incorporates these rules with consideration for teardown and re-assembly of the new product. The model presented uses integer programming to evaluate the proportion of any given product that can be economically remanufactured versus demanufactured within an EPR setting.

Decision models and product recovery rules

Logic would dictate that for an OEM to invest into remanufacturing, the costs of remanufacturing any given part (to a level of quality as the original part specifications) should be compared to the cost of an equivalent new part. This can be expressed as follows:

$$CRM_i \leq CNP_i \tag{I}$$

where CRM_i is the cost of remanufacturing the ith component and CNP_i is the new part replacement cost of the ith component. From an OEM perspective, it would not be economical to invest in a remanufacturing cost that would exceed the cost of an equivalent new part. However, within an EPR environment, the potential incurred cost of demanufacturing must be considered and is shown by:

$$CRM_i \leq CNP_i + Cdeman_i \tag{II}$$

where $Cdeman_i$, the cost of retiring a component at its end-of-life, becomes a new factor within the remanufacturing question. Noticeably, Eq. (II) provides insight into a number of considerations that may impact the economics of remanufacturing. First, if demanufacturing leads to a cost situation (i.e., landfill, recycling, etc.) the economic balance may shift to justify an investment into remanufacturing. For example, consider a scenario whereby the total cost of remanufacturing is estimated to be $125 and the total costs of new parts for original manufacture of the product is $100. Under Eq. (II), it would not be economical to remanufacture a product where new parts could be purchased (or manufactured) for less (with a probable higher retail value and profit margins). If however, there is a cost of demanufacturing, say $50, remanufacturing suddenly becomes a viable consideration to the expense of demanufacturing in an EPR environment.

A second insight from Eq. (II) is that demanufacturing can compete with remanufacturing from an economical perspective. This happens if the value of $Cdeman_i$ generates revenue as defined by Eq. (II). When the demanufacturing of a product creates enough revenue to break-even in an EPR setting, remanufacturing traditionally is not considered. As discussed in the literature review, demanufacturing research is largely devoted to determining the value of retired products in a highly constrained environment of the costs involved in salvaging products with little or no value. When value can be achieved with demanufacturing, the added effort and potential liabilities of remanufacturing (investment of a new business line and its costs, etc.) are less readily recognized.

Given the present discussion of the economics of remanufacturing versus demanufacturing, two equations are presented to evaluate the economics of the two end-of-life strategies. The cost margin

(CM) of remanufacturing the ith component is represented by:

$$CMreman_i = [CRM_i + CA_i + CD_i] \tag{III}$$

where CRM_i represents the cost of remanufacturing including sorting, cleaning, refurbishing and inspection; and CA_i and CD_i represent the respective assembly and disassembly costs to remove and reattach the ith component in the remanufacturing process. The cost margin (CM) of demanufacturing the ith component or subassembly is represented by:

$$CMdeman_i = [CNP_i + CA_i + CD_i] \tag{IV}$$

which represents the costs of purchasing a new replacement part, assembly and disassembly costs. As will be shown shortly, Eqs. (III) and (IV) are incorporated into an optimization model that is used to evaluate the economic trade-off and inevitably optimize the economics of remanufacturing versus demanufacturing any given part. In order to evaluate this trade-off, the cost (or revenue) of demanufacturing the component (i.e., represented by $MaxMRO_i$) and the potential cost of landfill (i.e., CLF_i) will need to be added to Eq. (IV). The following remanufacturing rules are presented to depict this situation.

Assuming suitable market conditions for a remanufactured product, the following rules demonstrate how optimization may be used in the decision process of remanufacturing versus demanufacturing within a product stewardship system:

Component rule

As demonstrated in literature, remanufacturing is more profitable when a large proportion of the original product (and its inherent value) is recaptured in the remanufacturing process (Lund, 1984). In this context, we compare the costs of remanufacturing to the cost of new parts within an EPR environment whereby financial responsibility of a retired product is extended to the original producer of the product along with any possible demanufacturing and disposal costs. Remanufacture any given component when the following is true:

$$CRM_i + CA_i + CD_i \le CNP_i + CA_i + CD_i + MaxMRO_i + CLF_i$$

where the costs of assembly and disassembly will vary both in remanufacturing (as some parts need not be removed in the remanufacturing process) and demanufacturing. This rule states that one would chose to remanufacture when the costs of remanufacturing are lower than the costs of the purchase of new parts and the corresponding costs of demanufacturing the retired component.

Subassembly rule

Remanufacture the entire subassembly when the following is true:

$$\sum_i (CRM_i + CA_i + CD_i) \le \sum_i (CNP_i + CA_i + CD_i) + \sum_i (MaxMRO^* + CLF_i)$$

Again, the costs of assembly and disassembly will vary both in remanufacturing (as some parts need not be removed in the remanufacturing process) and demanufacturing. This equation states that if the costs of remanufacturing are lower than the costs of new parts of the subassembly (and optimal benefit acquired from demanufacturing the retired subassembly – represented by $MaxMRO^*$), then remanufacturing is more economical than demanufacturing. When the costs of remanufacturing are greater than the costs of new parts and the potential benefits gained through demanufacturing, remanufacturing would not be economical. Note that the optimal benefit of demanufacturing a subassembly may range from complete disassembly to no disassembly of the retired subassembly. The above decision rules for remanufacturing versus demanufacturing are used within the model formulation in the next section for optimizing the economics of product recovery.

Model for Optimal Recovery Plan

The purpose of the optimization model is to evaluate the extent to which an entire product can be economically remanufactured versus demanufactured; and to provide a test bed for sensitivity

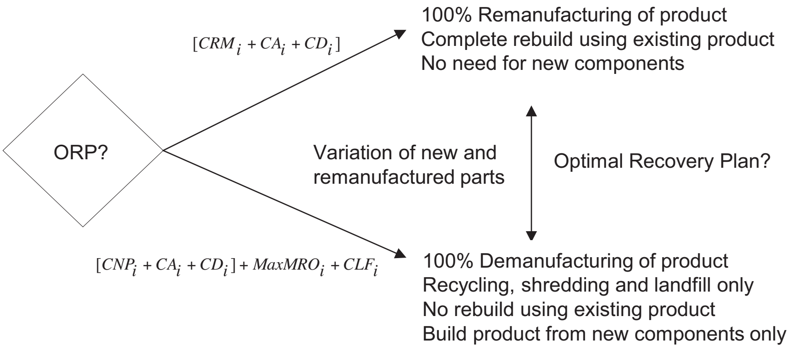

Fig. 2. Decision making in product recovery.

analysis to gain further understanding of the economic drivers of remanufacturing versus demanufacturing. The output of this evaluation we call the Optimal Recovery Plan (ORP). It is based on the reassembly of the product to its original (or specified) warranty condition, using the most economical mix of remanufactured and new parts. For example, if analyzing an automobile seat, how should components and subassemblies be dealt with from an economic perspective in order to maximize profits (or minimize costs if in a cost situation) in considering the rebuilding of the complete seat to a specified level of reliability? That is, what proportion of the seat's assemblies and parts can be economically remanufactured and what proportion of the seat would be uneconomical to remanufacture (i.e., it would make better sense to use new parts in the rebuilt product and demanufacture the old parts using recycling and disposal) within the context of EPR legislation?

Fig. 2 encompasses the decision problem and the extremes associated with product recovery. It is based on the decision to build a new product, but while assessing the economics of remanufacturing existing components versus the cost of new parts and the economics of demanufacturing the retired parts. At one extreme, 100% of the components are economical for remanufacturing (0% demanufactured). At the other extreme, 100% of the product is demanufactured and only new parts are used to rebuild the product (0% remanufacturing). When remanufacturing is more economical over demanufacturing, a large proportion of the parts within the product will be refurbished or reused in the rebuilding process. When remanufacturing is not economical over demanufacturing, a large proportion of the product is demanufactured and the rebuilt product consists predominantly of new parts.

The optimization model provides feedback on numerous issues when evaluating remanufacturing from the perspective of EOL product management within the context of EPR. First, it provides the optimal proportion of the product that is economically remanufactured versus demanufactured (i.e., the decision of remanufacturing versus demanufacturing on both component and subassembly levels). The optimization model also determines the level of disassembly required for parts in demanufacturing (and evaluates recycling versus disposal options) when remanufacturing is relatively uneconomical. Lastly the model generates the above optimal decisions associated the end-of-life management of parts and subassemblies within the context of an EPR setting; that is, achieving mandated recovery rates of EPR legislation at the lowest possible cost.

We define an ORP as a plan that maximizes the profits concerning (i) which parts and subassemblies to remanufacture, and (ii) which parts and subassemblies to demanufacture (reuse, recycling, shredding and disposal). An ORP is based on the reassembly of the product to its original (or specified) warranty condition, using the most economical mix of remanufactured and new parts. It is based on the subassemblies to be removed for both remanufacturing and demanufacturing, and the components to be removed for remanufacturing and demanufacturing. An ORP identifies the components and subassemblies in these categories in order to maximize the profitability of recovery decisions at the product level.

Data requirements

The data requirements for evaluating product recovery in our model are based on three major groups: (i) market information, (ii) physical product characteristics, and (iii) economic data.

The market information category is used to assess both market demand for the remanufactured product and the availability of returned products (or "cores"). To apply any product to the current methodology, it is assumed that there exists a potential market demand, a defined mechanism of replenishing core supply and a retail market opportunity to sell the remanufactured product. In essence, this data category is central to a firm's market information processing (Veldhuizen et al., 2006), that help identify and overcome any market conditions that might be working against a product remanufacturing effort.

The physical product characteristics category is used to define the components within a product including material type (ferrous or non-ferrous metal, plastic, elastomer, organic or inorganic materials), mass of individual parts and subassemblies, identification of subassemblies, parts within subassemblies, and independent parts. It will also contain disassembly and re-assembly times, estimated remanufacturing process times for each component including inspection and testing, cleaning, sorting, and refurbishment process times.

The economic data category comprises all economic parameters for remanufacturing and demanufacturing. This includes data for demanufacturing economics such as part resale opportunities, landfill costs, recycling prices for all identified material types, and shredding prices; and data for remanufacturing economics such as estimated new part replacement costs, calculation of remanufacturing costs based on estimated remanufacturing process times and materials, estimated overhead costs and estimated resale price of the remanufactured product.

A prior assessment is required for determining all economic, physical product and marketing parameters. It is assumed that any part can either be remanufactured or demanufactured. Likewise, any part that is demanufactured, cannot be remanufactured (i.e., a new part is needed). Lastly, the cost of remanufacturing parts (CRM_i) is assumed to reflect a cost of remanufacturing the part to a level of quality defined by the original manufactured part.

Notation

Decision variables

X_{i1}	X_{i1} is a decision variable to identify specific parts that are to remain within the product during the demanufacturing of a complete subassembly. This occurs when it is more economical to demanufacture a complete subassembly as a whole entity (i.e., no further disassembly) and purchase new parts, as opposed to breaking the subassembly down and remanufacturing existing components
X_{i2}	X_{i2} is a decision variable to identify specific parts that should be remanufactured
X_{i3}	X_{i3} is a decision variable to identify specific parts or subassemblies that should be removed for demanufacturing
X_{i4}	X_{i4} is a decision variable for identifying subassemblies that should be disassembled for further remanufacturing (i.e., the majority of the subassembly is remanufactured over demanufacturing activities)

Parameters (exogenous variables)

RRM_{PV}	Resale Price of remanufactured product
CO_p	A factor of the overhead cost associated with remanufacturing the product
$CMreman_i$	The cost margin (*CM*) of remanufacturing the *i*th component
$CMdeman_i$	The cost margin (*CM*) of demanufacturing the *i*th component
$MaxMRO_i$[3]	Maximum recovery opportunity for demanufacturing the *i*th component or subassembly. The following identifiers are used to define a parts optimal MRO: RU_i represents reuse or resale, RC_i represents recycle, or SV_i represents shred

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[3] Demanufacturing strategies (i.e., resale, shredding, and recycling values) are defined within this paper as Material Recovery Opportunities (MRO) from Johnson and Wang (1998). On a component level, selecting the maximum MRO can be expressed in equation form as: $MaxMRO_i = \max(RRU_i, RRC_i, RSV_i)$.

RRU_i	Resale value for reusing the *i*th group of component(s)
RRC_i	Recycling value for recycling the *i*th group of component(s)
RSV_i	Shredder value for shredding the *i*th group of component(s)
CLF_i	Landfill cost for landfilling the *i*th group of component(s)
LF_i	Landfill identified for the *i*th group of component(s)
CRM_i	The cost of remanufacturing the *i*th group of component(s)
CD_i	The cost for disassembly of the *i*th component(s)
CNP_i	The cost of replacing the *i*th component with a new component(s)
CA_i	The cost of re-assembly of the *i*th component(s)
R_{LF}	Landfill mass rate that ranges from 0 to 1 and defines the percentage of a total product mass that may landfilled (WEEE Directive)
M_i	The mass of the *i*th component
M_{SUBi}	The mass of the *i*th subassembly
M_{TOT}	The total mass of the product
SV_{LFi}	A decision variable to identify the mass of the *i*th component or subassembly that cannot be shredded for metallic content (i.e., the item is landfilled)

Integer Programming Model

Objective function:

$$\begin{aligned}&MAX\,Z\ =\\&\text{line 1}: +RRM_{PV} - CO_p\\&\text{line 2}: +\sum_i(-CMremani)Xi2\\&\text{line 3}: +\sum_i(-CMdemani + MaxMROi - CLFi \times LFi)Xi3\\&\text{line 4}: +\sum_i(-CAi - CDi)Xi4\end{aligned} \tag{1}$$

Subject to:

$$\sum_i(Xi1 + Xi2 + Xi3) = 1 \tag{2}$$

$$\sum_i(Xi1 + Xi3 + Xi4) = 1 \tag{3}$$

$$\sum_i(Xi3 - MaxMROi - LFi) = 0 \tag{4}$$

$$\sum_i(Xi3 - Xn1) \leq 0 \tag{5}$$

$$\sum_i(Xi1 + Xn1) \leq 1 \tag{6}$$

$$\sum_i(Xi4 + Xn1) \leq 1 \tag{7}$$

$$\sum_i(Xi3) = 1 \tag{8}$$

$$\begin{aligned}&\sum_i(LF_iM_i + LF_iM_{SUBi})+\\&\sum_i(SV_{LFi}M_i + SV_{LFi}M_{SUBi}) \leq R_{LF}(M_{TOT})\end{aligned} \tag{9}$$

$$\sum_{i} SV_{LFi} - SV_i \leq 0 \tag{10}$$

$$X_{i1}, X_{i2}, X_{i3}, X_{i4} = 1 \text{ or } 0. \tag{11}$$

The objective function defines the profits associated with removing parts for remanufacturing and demanufacturing, and rebuilding the entire product under the defined assumptions. The first line of the objective function defines the revenues generated from the estimated retail value, less the cost of overhead on a per unit basis. The second line of the objective function defines the costs of remanufacturing components (including the costs of disassembly and assembly) and the third line defines the costs of demanufacturing individual parts or a complete subassembly and replacing demanufactured parts with new parts. Lastly, the fourth line defines the costs of disassembly and re-assembly of specific subassemblies that are disassembled and rebuilt in the ORP.

The constraints are defined as follows. Eq. (2) states that the *i*th component within a subassembly will undergo only one of the following alternatives: a part remains within its parent subassembly for demanufacturing, or a part is remanufactured, or a part is demanufactured. Eq. (3) states that the *i*th subassembly will undergo only one of the following alternatives: the subassembly remains within the product for remanufacturing, or the subassembly is removed from the product for complete demanufacturing, or a subassembly is disassembled from the product to remanufacture or demanufacture children parts. Eq. (4) states that the *i*th component or subassembly is allowed only one EOL option when it is most economical to pursue demanufacturing (i.e., demanufacture the part according to its maximum MRO or landfill the part).

The next three constraints (Eqs. (5)–(7)) establish an important relationship of product configuration for parts and their parent subassemblies in the remanufacturing process. They essentially ensure three important scenarios:

- if a subassembly is demanufactured as a complete subassembly (it is “complete” meaning there is no disassembly of parts from the subassembly), then children components will not be removed,
- if a subassembly may remain within the product during the remanufacturing process, then children components must be either remanufactured or demanufactured, and
- any subassembly will either be broken down and rebuilt, or it will be demanufactured as a complete subassembly (children components are not disassembled).

Eq. (8) identifies components that must be removed for demanufacturing. As discussed earlier, remanufacturing products will lead to identification of specific components that must be removed due to extreme consumer wear, mechanical failure beyond reparation, or negative asthetic appeal.

The next two constraints limits the amount of product mass that can be landfilled and can be used for product stewardship or EPR legislation scenarios.

Eq. (9) states that the sum of landfill mass from: (1) individual components or subassemblies (defined by $LF_iM_i + LF_iM_{SUBi}$), and (2) shredding any individual components or subassemblies (defined by $SV_{LFi}M_i + SV_{LFi}M_{SUBi}$), must all be less than or equal to a maximum allowable landfill mass per product. The maximum allowable landfill mass is defined by the product of the landfill mass rate (i.e., RLF) and the total mass of the product (i.e., MTOT). For example, under the proposed 2015 WEEE revised recovery targets, between 15% and 35% by mass (depending on the product category) would be allowed as landfill (the remainder must be reused or recycled).

Eq. (10) ensures that if a component or subassembly is shredded, any mass that cannot be shredded for metallic content must be accounted for in Eq. (9). Lastly, all binary decision variables are defined.

Model application: consumer telephone

To illustrate our model, remanufacturing and demanufacturing data on a consumer telephone was collected through both collaborating with industry partners and using online research tools. Industry partners, who wish to remain anonymous, include a Telcom manufacturer located in Eastern Canada and a subsidiary firm that carries out its asset recovery and remanufacturing operations. All economic data including remanufacturing process times, disassembly and assembly times, and costs (labor rates, new part replacement costs, etc.) were provided by the Telcom company. Online research tools were used to collect economic data for demanufacturing options (e.g., material recycling values and disposal fees).

A consumer telephone is applied to two different situations in an effort to develop and enhance the usefulness of the optimization model presented. Model 1 depicts a situation of product recovery for the telephone without EPR legislation. Model 2 depicts the scenario of product recovery within the context of EPR such as WEEE.

> Model 1: Data collected on the current economic conditions of product recovery the consumer telephone in North America at the end of life. The WEEE Directive recovery rate constraints of the optimization model (i.e., constraints (9) and (10)) are not implemented. Sensitivity analysis on several economic variables will be presented.
>
> Model 2: Introduces the WEEE Directive recovery rate constraint (constraints (9) and (10)) on the consumer telephone data (Model 1). This model depicts a European situation whereby EPR is enforced through legislation.

The summary table of the ORP generated from Model 1 is shown in Appendix A. The ORP states that only the handset (or receiver) subassembly (Part A) of the phone is economical for remanufacturing. The main telephone subassembly (Part D) called the “telephone base”, the handset electrical subassembly (Part B) and the telephone cords (Part C) should be demanufactured according to the optimal economic recovery plan. That is, it is more economical to purchase new parts for these components and demanufacture the old components (according to their respective maximum MRO) than it is to remanufacture these parts. The demanufactured parts are landfilled (the telephone base) and recycled (the handset electrical subassembly and the telephone cords). Output from Model 1 also provides information with respect to the material destinations and the economics of product recovery. If the Telcom company were to invest in remanufacturing this product, the proportion of demanufacturing parts to remanufactured parts according to the ORP is shown in Table 1. Table 1 demonstrates how impractical it would be to remanufacture this product. Approximately 85% of the parts required to remanufacture the product would be new parts making it largely uneconomical to acquire the old device and rebuild it. The current economic conditions demonstrate that it is more economical to simply landfill the majority of the telephone.

Table 2 provides a breakdown of the major costs involved according to the ORP from Model 1. The greatest cost is that of new parts followed by the remanufacturing costs with respect to refurbishing the receiver subassembly.

The current economic situation is such that remanufacturing is more costly than the combined cost of demanufacturing old parts and purchasing new components. This is largely due to the fact that the components used in this telephone are simple in design, functionality and cost. This demonstrates a greater economic advantage of utilizing new parts as opposed to remanufacturing existing (old) parts in a remanufactured product of this type. Before concluding that the product is uneconomical for remanufacturing, sensitivity analysis was carried out to investigate possible changes that may

Table 1
Material destinations of Model 1.

	Mass (kg)	% of total mass
I. Material destinations		
Total mass demanufactured	1.69	84.92%
Total mass of remanufactured and reused parts	0.30	15.08%
Total mass	1.99	100.00%
II. Material destinations		
Mass remanufactured and reused (kg)	0.30	15.08%
Mass recycled (kg)	0.15	7.54%
Mass landfilled (kg)	1.54	77.39%
Total mass	1.99	100.00%

Table 2
Economic output of Model 1.

Economic total	Amount
Total product recovery cost[a]	–$7.48
Total cost of new parts (sum of CNP)	–$4.83
Total remanufacturing costs (sum of CRM)	–$1.63
Total demanufacturing costs (landfill and recycling)	–$0.07
Total demanufacturing revenue (reuse and recycling)	$0.12
Total disassembly and assembly costs (sum of CA and CD)	–$1.08

[a] Total Product Recovery costs is defined by lines 2, 3, and 4 of the objective function in the optimization model representing the optimal economical product recovery options of remanufacturing versus demanufacturing (without the defined per unit revenue and overhead cost defined as line 1 of the objective function). Total Product Recovery Cost includes rebuilding of the product using the most economical mix of reused, remanufactured and new parts.

improve the profitability of remanufacturing and increase the proportion of the telephone that is remanufacturable.

Sensitivity analysis demonstrates that the costs of new parts and the costs of remanufacturing are the more sensitive economic parameters (relative to the costs of assembly, disassembly or landfill costs). As either of these economic variables decrease, the overall profitability of product recovery improves dramatically. The results of this sensitivity analysis are shown in Fig. 3.

Model 2 introduces the WEEE directive product recovery constraint (constraints number (9) and (10)) on the original collected data (i.e., Model 1). In this model, constraints (9) and (10) were implemented placing a maximum allowable landfill mass of 15% of the total product mass. The summary table of ORP generated from Model 2 is shown in Appendices section. The results shown in Table 3 are quite significant when compared to the results of Model 1 that demanufactured the complete telephone base (Part D) using the option of landfill. The ORP generated by Model 1 calls for approximately 77% of the product's total mass to be landfilled. Most noticeably is the fact that parts D1 through D7 (with the exception of part D5) are now being remanufactured in Model 2 at a higher cost than their respective demanufacturing options due to the incorporation of the new EPR recovery rate constraint. Tables 3 and 4 provide interpreted results of the optimization output. The results clearly demonstrate that the majority of the product is remanufactured with landfill at only 2.51% of the total mass.

Table 4 demonstrates that there is an obvious cost associated with fulfilling the requirements of EPR within the defined recovery rates of WEEE. The advantage of the model presented here is that the total cost of remanufacturing (versus demanufacturing) can be determined within the mandated recovery constraints using the most economical mix of new and used parts.

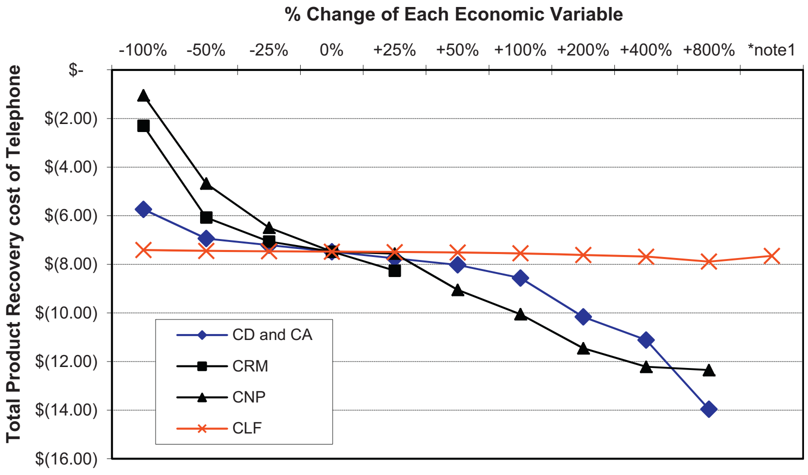

Fig. 3. Sensitivity of the total product recovery costs to incremental changes in economic variables.

Table 3
Material destinations of Model 2.

	Mass (kg)	% of Total mass
I. Material destinations		
Total mass demanufactured	0.2	10.05%
Total mass of remanufactured and reused parts	1.79	89.95%
Total mass	1.99	100.00%
II. Material destinations		
Mass remanufactured and reused (kg)	1.79	89.95%
Mass recycled (kg)	0.15	7.54%
Mass landfilled (kg)	0.05	2.51%
Total mass	1.99	100.00%

Table 4
Economic output of Model 2.

Economic total	Amount
Total product recovery cost	−$9.41
Total cost of new parts (sum of CNP)	−$1.04
Total remanufacturing costs (sum of CRM)	−$6.19
Total demanufacturing costs (landfill and recycling)	−$0.002
Total demanufacturing revenue (reuse and recycling)	$0.12
Total disassembly and assembly costs (sum of CA and CD)	−$2.29

Discussion

Product recovery is widely recognized as being important to a firm's sustainable and economic performance, yet there is limited research on how firms should undertake product recovery decisions comparing whole product remanufacturing with demanufacturing options. Our research complements studies that have examined "why" firms should undertake sustainable development via supply chain management and reverse logistics (e.g., Hall et al., 2012) and "how" individual products can be evaluated to maximize economically the substitution effects of remanufacturing versus demanufacturing in the forward supply chain.

We believe that the focus of our model (i.e., remanufacturing versus demanufacturing in the context of whole product recovery) and its application has at least four major implications for sustainable business development research and practice. First, as our application of the model shows meeting current and future recovery rates defined by WEEE will result in higher costs than selected demanufacturing activities (recycling and disposal) when manufacturers are forced through legislation to recover a higher proportion of consumer products (as shown in section "Model application: consumer telephone" when comparing the optimization results of no EPR legislation (Model 1) versus with EPR legislation (Model 2)). Surprisingly however, the optimization results of Model 2 demonstrate that remanufacturing was found to be more economical than recycling activities of demanufacturing when EPR legislation was mandatory (WEEE constraints implemented). Model 2 demonstrates that when landfill is restricted by 15% of the product's mass, remanufacturing and material recycling (i.e., demanufacturing) compete economically and physically in the sense that disposal is no longer an option. With this particular phone example, remanufacturing (the major base assembly of the phone – Part D) is more economical than the costs of acquiring new parts and incurring the recycling costs of the old product. The results demonstrate that whole product remanufacturing can be economically justified over demanufacturing alternatives for certain products within an EPR environment. This example depicts great promise for product remanufacturing as a sustainable and competitive tool for business development in the context of forced EPR legislation. It highlights an important consideration for firms facing impending EPR mandates: remanufacturing can provide a sustainable business development opportunity that may be more economical than simply meeting the minimum recovery rates set out by EPR legislation (such as WEEE) through such activities as material recycling.

Table 5
Sensitivity of remanufacturing costs (CRM).

CRM	Total product recovery cost	Mass remanufactured and reused (kg)
−100%	−2.29	100.00%
−50%	−6.07	67.34%
−25%	−7.06	67.34%
0%	−7.48	15.08%
25%	−8.26	0.00%

A second important implication is the use and application of this model to assess the viability of remanufacturing opportunities in developing countries that must deal with EPR legislation or the burden of illegal e-waste. As shown in section "Model application: consumer telephone", the economics of remanufacturing is sensitive to certain economic parameters such as remanufacturing costs, new part replacement costs and lastly assembly and disassembly costs. In developing nations, the lower labor costs associated with remanufacturing could tip the scales in strong favor of continued remanufacturing. As shown in Table 5, if the cost of remanufacturing used in Model 1 was to decrease by 100% (depicting a relative 100% decrease of current North American remanufacturing cost of this product), the EOL strategy would largely favor whole product remanufacturing whereby 100% of the product is reused and remanufactured at a fraction of the cost. This example clearly demonstrates that lower labor rates of developing nations should allow for a greater opportunity for investment in whole product remanufacturing.

These findings support the research of Nnorom and Osibanjo (2008) who advocate the application of "product life extension" for electronic waste in developing countries through remanufacturing. These authors suggest the use of "Remanufacturing Centers" where "repair", "refurbishing" and "remanufacturing" activities could be carried out by the local communities under supervision of the OEMs or their subsidiaries. This demonstrates that remanufacturing may call for a certain degree of "sustainable entrepreneurship"[4] by OEMs or third parties that could set up remanufacturing centers in developing countries for products that can be economically remanufactured and demonstrate potential for such secondary markets in developing countries.

A third implication is the application of our model to product design changes so as to evaluate the economic tradeoff of remanufacturing versus demanufacturing within the context of EPR legislation. Firms need to take into consideration factors such as facilitation of disassembly and inspection, as well as reusability and improved component durability (Robotis et al., 2012). Navin-Chandra (1994) points out that components designed for remanufacturing may be costlier to manufacture but facilitate future recovery and reuse. Clearly, product design considerations can no longer dismiss the involvement of such decisions in the early stage of product development. As stated by Nasr and Thurston (2006), some components may be designated by design for single or multiple reuse, for single or multiple remanufacturing, for recycling, or for disposal. Yet EPR legislation has primarily encouraged material recycling and disposal (i.e., demanufacturing) activities over more environmentally sustainable strategies such product remanufacturing. Furthermore, literature clearly denounces the inability of EPR legislation to facilitate design changes that lead to improvements in product recovery (Gui et al., 2013). Thus, the tool presented in this paper provides a unique modeling environment whereby designers can evaluate the economic and environmental tradeoffs of increasing the proportion of the product for remanufacturing (according to WEEE terminology, this is called products that are "prepared for reuse") and its impact to EOL product management. The use of sensitivity analysis would allow product designers a forum to assess uncertainties and variations of remanufacturing versus demanufacturing on the overall profitability of product recovery.

A final implication from our research is that the proposed model provides the unique opportunity to evaluate and maximize whole product remanufacturing (i.e., a measure of the substitution effect at

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[4] This term is defined by Schaltegger and Wagner (2011) as the characterization of an entrepreneurial activity that leads to the realization of large-scale market success that brings about societal change with environmental or societal innovations.

the product level) over simply meeting the minimum EPR recovery rates through demanufacturing activities. This particular topic is timely and relevant given that the WEEE legislation is soon to incorporate "reuse" in recovery targets by 2015 and within four years the WEEE Commission will examine the case of a mandatory 5% reuse target for all product categories[5] (Environment UK, 2013). Furthermore, the recast WEEE states that all recovery targets for all product categories will increase by 5% in August 15, 2015, further emphasizing an increased proportion of EOL products that will need to recovered in an environmentally sensitive manner. These modifications provide a signal to manufacturers that policy makers intend on making product recovery through remanufacturing an increasingly important part of EPR legislation and policies relating to sustainable business development. Although there is a substantial amount of work to be completed in evaluating the tradeoffs of remanufacturing versus demanufacturing across all product categories defined in the WEEE directive, this paper endorses the inclusion of "reuse" in recovery rate calculations in order to achieve the combined economic and environmental benefits of a higher order form (i.e., remanufacturing) of product recovery. Our findings in the application section of this paper demonstrate that whole product remanufacturing can lead to economic scenarios that are more favorable than single loop demanufacturing activities such as material recycling. We would however argue that a detailed product level analysis, as conducted in this paper, should be carried out to determine which product categories have a higher likelihood of being profitable in the context of whole product remanufacturing. It would seem probable that certain product categories are more likely to be profitable and therefore policy makers should develop specific "reuse" targets for each product category, rather than applying uniform levels of "reuse" recovery rates across all product categories.

In terms of other future research opportunities we believe our model and findings provide a platform to pursue a number of key avenues of study. First, our model could be developed to incorporate energy and material savings of remanufacturing into the decision making framework of our research. This would be important because it would serve to investigate an environmental perspective of the tradeoffs between demanufacturing versus remanufacturing activities in the context of EPR requirements. Second, our model could be adapted to investigate the impact of product reuse activities beyond the forward supply chain to investigate economic and environmental benefits over several product life-cycles of product remanufacturing followed by inevitable demanufacturing activities. For example, it would be interesting to extend this analysis to assess the economic benefits of product remanufacturing followed by material recycling activities of a third product life-cycle. Lastly, expanding this model to multiple product categories defined by WEEE to investigate the tradeoffs between remanufacturing versus demanufacturing would be a valuable area of future research. In order for practitioners to institute product recovery leading to multiple product life-cycles, research is clearly needed to identify specific product categories that are most likely to lead to positive economic returns for such recovery activities.

Conclusions

Our research contributes to the literature by presenting a novel approach to evaluate product recovery decisions of EOL products specifically addressing the tradeoff between remanufacturing and demanufacturing activities in the context of EPR legislation. We present an optimization model to allow an OEM or third party remanufacturer the ability to assess the economic viability of remanufacturing versus demanufacturing activities of EOL products within constraints imposed by EPR legislation in terms of mandated recovery rates. We then apply the model to a consumer telephone under two different scenarios (with and without EPR legislation) using remanufacturing

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[5] "Reuse" is being considered for a recovery rate requirement that is independent of "recycling" recovery rates for all product categories. This is significant as it will force manufacturers to consider options such as product remanufacturing as opposed to demanufacturing options. As of August 2015, "reuse" will be incorporated in a recovery rate that is defined by "reuse and recycling" (with a 5% increase in overall targets) allowing manufacturers the option of increasing recycling or initiating remanufacturing alternatives.

data supplied by industry. The results show that product reuse and remanufacturing can provide a sustainable business development opportunity that may be more economical than simply meeting the minimum recovery rates set out by EPR legislation through such demanufacturing activities as material recycling. Our findings support the inclusion of "product reuse" in the recovery rate calculations of EPR legislation however we argue this should only be applied to specific product categories that demonstrate economically sustainable environments for whole product remanufacturing.

Appendix A. Optimization output of Model 1

Subassembly systems	Part #	Decision variables					Interpretation of output
		*X*1	*X*2	*X*3	*X*4	MaxMRO[a]	
Handset (A)	A	0	0	0	1	0	Handset subassembly remanufactured
	A1	0	0	0	1	0	Reuse bolts
	A2	0	1	0	0	0	Remanufacture
	A3	0	1	0	0	0	Remanufacture
	A4	0	0	1	0	RC	Demanufacture via recycling
	A5	0	1	0	0	0	Remanufacture
Handset electrical (B)	B	0	0	1	0	RC	Demanufacture via recycling
Cords (C)	C	0	0	1	0	RC	Demanufacture via recycling
Base (D)	D	0	0	1	0	LF	Entire telephone base demanufactured via landfill
	D1	1	0	0	0	0	Part remains within telephone base
	D2	1	0	0	0	0	Part remains within telephone base
	D3	1	0	0	0	0	Part remains within telephone base
	D4	1	0	0	0	0	Part remains within telephone base
	D5	1	0	0	0	0	Part remains within telephone base
	D6	1	0	0	0	0	Part remains within telephone base
	D7	1	0	0	0	0	Part remains within telephone base

[a] Whereby RU_i represents reuse or resale, RC_i represents recycle, or SV_i represents shred.

Appendix B. Optimization output of Model 2

Subassembly systems	Part #	Decision variables					Interpretation of output
		*X*1	*X*2	*X*3	*X*4	MaxMRO[a]	
Handset (A)	A	0	0	0	1	0	Receiver subassembly remanufactured
	A1	0	0	0	1	0	Reuse bolts
	A2	0	1	0	0	0	Remanufacture
	A3	0	1	0	0	0	Remanufacture
	A4	0	0	1	0	RC	Demanufacture via recycling
	A5	0	1	0	0	0	Remanufacture
Handset electrical (B)	B	0	0	1	0	RC	Demanufacture via recycling
Cords (C)	C	0	0	1	0	RC	Demanufacture via recycling
Base (D)	D	0	0	0	1	0	Telephone base remanufactured
	D1	0	1	0	0	0	Remanufacture
	D2	0	1	0	0	0	Remanufacture
	D3	0	1	0	0	0	Remanufacture
	D4	0	1	0	0	0	Remanufacture
	D5	0	0	1	0	LF	Demanufacture via landfill
	D6	0	1	0	0	0	Remanufacture
	D7	0	1	0	0	0	Remanufacture

[a] Whereby RU_i represents reuse or resale, RC_i represents recycle, or SV_i represents shred.

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