PRODUCT RESYNTHESIS: AN OPTIMAL END-OF-LIFE STRATEGY FOR CLOSED-LOOP SUPPLY CHAINS

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ABSTRACT

Electronic waste (e-waste) is one of the largest waste streams in the world because it is environmentally hazardous, chemically complex and economically expensive to treat. There is a general lack of governmental legislation or enforcement surrounding e-waste since it is difficult to hold a single entity accountable. A contributing factor in e-waste generation can be attributed to the shorter lifespans of products today and the lack of sustainable/economically viable End of Life (EOL) strategies. The average lifespan of computers in developed countries has dropped from six years in 1997 to just two in 2005, while mobile phones have a lifecycle of less than 2 years. Environmental protection legislation, consumer interest in “green” products and a trend toward corporate responsibility has resulted in increased interest in product take-back. However, this also means that companies engaging in product take-back are doing so, with the objective of brand enhancement and are not primarily driven by profit. The trend of increasing waste and comparatively low growth of waste treatment methodologies has created the need for better utilization of the products we deem unfit for use. While traditional forward logistics focuses on the flow of products from factory to consumer, reverse logistics refers to the processes associated with returning products, components, and materials from the final consumer. A closed-loop supply chain is a combination of forward and reverse logistics. Within a closed-loop supply chain network, the options currently available for utilizing these returned EOL products are restricted to reusing, recycling, remanufacturing and permanent disposal. Through recycling, original equipment manufacturers (OEMs) are establishing closed-loop supply chains from which they can obtain raw material for production, delivering payback through environmental benefits and reduced supply chain carbon footprint. At the same time, a refurbished product strategy helps retailers introduce refurbished variants of products to the market which can provide additional economic benefits and extenuate environmental impact challenges. However, refurbishing is
limited to an existing product market, possibly a subset of the existing market, and thus fails to commercialize/target new markets. Refurbishing also does not involve OEMs since the returned products are refurbished by third party firms and sold/distributed by retailers. Also, recycling has proven to be an economically and environmentally inferior strategy compared to the other EOL options. The current closed-loop supply chain networks, thus, do not give OEMs the opportunity to improve their profit margins and gain economic benefits through reverse logistics. In this thesis, a new EOL option called “resynthesis” is introduced that utilizes existing waste from EOL products in a novel way through the synthesis of products/components across multiple domains (i.e. consumer electronics, health care, automotive, etc.). A product resynthesis driven closed-loop supply chain methodology is proposed that leads to higher economic benefits and allows OEMs to participate directly in closed-loop supply chains and thus enhance their profit margins. A case study involving the resynthesis of two products; a computer mouse, belonging to the domain of computer accessories, and a white-board eraser, belonging to the domain of office supplies, is presented. These two products are resynthesized to create an ergonomically shaped eraser that would be incorporated into a closed-loop supply chain.
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Chapter 1

Introduction

In 2009, over 2 million tons of electronic devices such as computers, computer accessories, televisions and cell phones were discarded. According to the Environmental Protection Agency (EPA), approximately only 25% of these unwanted electronics were recycled, of which 38% were computers, 17% were television sets and 8% were mobile devices. Only about 15-20% of electronic component-based waste was treated with End-of-Life decision-making, with the remainder of these electronics going directly to landfills and incinerators [1]. Considering the environmental hazards that these landfills pose, there is an urgent need to mitigate this problem by ensuring full utilization of these discarded products [2].

While many organizations engage in product take-back that can prevent these hazards, they have ignored the various economic benefits that can be derived through product take-back. The focus of many organizations is driven by corporate social responsibility and brand/image enhancement, rather than profit increment [3]. This is due to the fact that the existing economic benefits derived through product take-back and subsequent EOL decision making, are not significant enough [4]. Companies facilitate product take-back through reverse logistics that helps result in a closed-loop supply chain [5]. Reverse logistics are an important component of closed-loop supply chain management, defined as “the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time” [5]. In recent years, factors such as evolving financial and competitive pressures, increasingly demanding customers, and complex environmental regulations have elevated the attention paid to sustainable supply chains and reverse logistics activities. Presently, the sustainability practices that industries employ are
limited to reusing/repurposing, recycling, remanufacturing or simply disposing, with their large scale applicability possibly being one of the reasons.

Reusing can be defined as the act of using an item for more than one lifecycle by subjecting it to minor repair (if needed) for the same function [6]. Repurposing is simply another form of reusing that involves modifying a single product for a different purpose without significantly reforming it. Repurposing can apply to multiple product domains; although its main usage is in pharmaceuticals and fabrics [7]. Throughout this thesis, repurposing is treated as a subset of reusing and hence will not be considered separately. Recycling is the breaking down of an EOL product into raw materials which are then used to make new products [6]. *Upcycling* and *downcycling* are both subsets of recycling depending upon the quality (higher or lower than the original product respectively) of the product that is fabricated from the raw material obtained through the recycling process. In both upcycling and downcycling, modifications are made at the material level [6]. Remanufacturing involves repair or replacement of worn out or obsolete components and modules [8]. Remanufacturing and reusing can be collectively referred to as refurbishing [8]. Disposal of products comprises of collecting and depositing EOL products in landfill, and sometimes incineration of organic substances and waste, but these disposal methods do have negative environmental effects [9] [10]. Estimates of the EPA suggest that the annual revenues generated by the recycling industry far exceed the reuse and remanufacturing industries, meaning, recycling is a more preferred EOL option for organizations [11]. One of the reasons for this is the fact that manufacturers tend to use Design for Assembly and Manufacturing (DFAM), making remanufacturing/reuse of parts, difficult [12]. Recycling, on the other hand, has economic and environmental drawbacks, due to the energy that is required to decompose the products to raw materials [13]. Furthermore, certain products/components have hazardous chemicals, materials, making them extremely difficult to recycle [14] [15]. The cost to recycle can also be a
prohibitive factor in product recycling efforts due to the complexities of the material extraction process [16].

In the context of closed-loop supply chains, refurbishing, recycling and disposing are the only EOL options that organizations currently utilize for end-of-life product treatment. As mentioned, recycling is economically and environmentally inferior to other EOL options like refurbishing. While refurbishing can prove to be a better alternative than recycling, OEMs are unable to take advantage of the economic benefits obtained through refurbishing since they are not directly involved in it. Figure 1 indicates the direction in which capital would theoretically flow in the presence (right) and absence of resynthesis (left). The network setups in both cases are generalized (and simplified), and are independent of the domain of the product(s) the OEM manufactures.

![Diagram](image)

**Figure 1: Flow of capital in a closed-loop supply chain**

As per the network models obtained through current literature (Without Resynthesis - left), the OEMs make revenue selling their product(s) at a wholesale price, through forward logistics, to a retailer, which in turn makes profit selling that product(s) to the customer. When customers return
their end-of-life products to retailers, 3rd party firms make revenue sorting and refurbishing these products and selling it to the retailer. The retailers make money by selling these refurbished products back to the consumer market. The remaining products are sent to recycling firms which eventually sell the extracted raw material back to the OEMs, thus completing the loop. However, OEMs do not buy back all the raw material and the remaining EOL products have to be disposed in landfills, resulting in e-waste. It can be observed, however, that capital does not flow back to the OEMs after products are returned by customers. The resynthesis EOL option proposed in this work aims to be both environmentally and economically more viable than the aforementioned EOL options, by utilizing existing waste from EOL products in a novel way through the synthesis of existing products/components spanning multiple domains. The network on the right in Figure 1 indicates how capital would flow, in a closed-loop network, in the presence of resynthesis (the additional capital is indicated by red arrows). In this setup, OEMs can have an economic advantage through closed-loop supply chains by incorporating resynthesis into their dynamics. OEMs can contract with 3rd party firms, who can design resynthesized product candidates and provide raw materials directly to the OEMs. The OEMs can introduce these resynthesized products into forward logistics and thus make additional profit, otherwise not realized. Resynthesis can prove to be an integral facet of their business strategy not only in order to uphold their enterprise value but also to grow and prosper. In other words, an organization can enhance its revenue and market share by employing a strong closed-loop supply chain strategy which can aid their engagement with key stakeholders (such as employees and communities) to protect their license to operate, reduce costs, manage risks and increase operational efficiencies [17]. Most members (corresponding OEMs based on domain, as well as retailers and third party firms) of a closed-loop supply chain network will be better off in the presence of resynthesis as an EOL alternative. Existing research methodologies focused on product sustainability have overlooked the potential advantages of resynthesizing EOL products since they only consider the above EOL
options. Product resynthesis thus aims to not only mitigate the environmental impact that the current EOL options have, but also increase the economic benefits that can be derived through EOL treatment of returned products.

This thesis is organized into 5 chapters. While the current chapter provides an introduction to sustainable supply chains and the motivation for the proposed methodology, Chapter II discusses the relevant literature involved in this work. Chapter III describes the proposed supply chain network methodology. A case study is presented in Chapter IV that illustrates the pertinence of the network model detailed in III. Finally, Chapter V summarizes inferences/conclusions and highlights potential future work.
Chapter 2

Literature Review

Sustainable design addresses principles of economic, social and environmental sustainability. Research confirms that embracing sustainability in product design and manufacturing not only yields environmental improvements, but offers key business benefits as well [18]. This chapter reviews the literature that is relevant to this work by discussing the various disassembly techniques (literature review section 2.1) that are employed to create feasible subassemblies of returned products. Literature relating to modularity and *bisociation* is introduced in section 2.2 that explains the interactions between products and subassemblies, and reviews mathematical models aimed at quantifying these interactions using product similarity based techniques. Literature related to the EOL decision making process for various products/subassemblies is presented in section 2.3. Literature related to the background of reverse logistics and closed-loop supply chains is discussed in Section 2.4, followed by the cases and models developed in the field of closed-loop supply chain network modeling in 2.5.

2.1 Disassembly Sequence Implementation

Boothroyd defines a design artifact as a combination of its constituent subassemblies [19]. Different subassemblies of a design artifact may possess different material properties, reliabilities and accordingly, can have different EOL value. A returned EOL product may have many of its subassemblies in working condition that can be separated and used with other subassemblies of the same (or different) product [20]. Hence, it is essential to incorporate product disassembly strategies to obtain subassemblies (components). Various EOL decisions can then be
applied such as reuse, remanufacturing (or simply refurbishing), recycling and disposal to the individual components.

Kara et al. propose a disassembly sequence for some selected products that require minimal removal of their components [21]. A disassembly sequencing process is defined by Lambert as a sequence of operations for separating a single part from a product or separating a product into two different subassemblies. A method for solving optimal disassembly sequence generation problems by linear programming is also developed [22]. Gonzalez and Adenso-Diaz propose a recurrent algorithm to determine the optimal disassembly sequence and corresponding EOL strategy using graphical CAD/CAM and product bill-of-materials [23]. Figure 2 illustrates the disassembly of a portable gaming device product into subassemblies. It can be observed that disassembly is not done all the way to the atomic level (for example, disassembling down to nuts and bolts) but only up to its subassemblies. This proves to be more economical and time-efficient [21]. Lambert presents a method to automatically derive all the feasible sub-assemblies and transitions between them from assembly drawings using a transition matrix method with an AND/OR graph used as an illustration [24]. Kang et al. propose a model that utilizes a product's architecture and derives a transition matrix using a recurrent algorithm [25].

Figure 2: Disassembly of a product into its subassemblies
Capozucca and Sarni discuss how organizations have significant opportunities to use sustainability for driving innovation and improving their business, but are not actively doing so [26]. Companies that achieve this vision have the opportunity to enhance revenue and brand value, engage effectively with key stakeholders, manage risk and potentially reduce costs [26]. Pandey and Thurston present a model that measures the randomness or variability imposed by an EOL alternative along with its environmental impact (calculated using SIMAPRO). The effective-age of EOL products is also measured using this model [27] [28].

While disassembly gives us knowledge of a product’s constituents, Roozenburg and Ekels state that a product’s design characteristics can be defined in terms of its form and function [29]. The form, in this thesis, is defined as the physical representation of a product based on its geometric features and the function of a product is obtained using its technical specifications, mentioned in user manuals [30]. Hirtz et al. show that relationships between product designs can be established based on similarity between their form and functions [31]. Incorporating the aforementioned models, will help determine feasible disassembly combinations which can then be tested for form and function similarities to ultimately obtain candidates for resynthesis.

### 2.2 Modular and Bisociative Product Design

Once the various feasible disassembly combinations are determined, the next step is to determine a relation between the various subassemblies that can provide us with candidates for sustainable product design. Thus, there is a need to investigate existing product modularity and bisociation based product design literature.

Gershenson et al. define product modularity as the decomposition of a product into subassemblies that can be combined based not only on the form/function of a product, but also on various lifecycles [32]. Schilling develops a model that intelligently designs modularity into
components and subsystems [33]. Huang and Kusiak present a formal approach to modular product design which refers to the use of common units to create product variants. [34]. Sosale et al. state that modularity provides designers the option of constructing larger systems by integrating smaller subsystems. This enables application of EOL alternatives like recycling and remanufacturing on modules rather than products to optimize their utilization [35].

Through modularity it can also be found that optimality of an EOL strategy depends significantly on the geometric form and functional similarity between modules in an assembly, in the context of product resynthesis. Quantifying the form and function similarity across EOL product domains allows enterprise decision makers to determine whether the proposed product resynthesis EOL option is a viable sustainability strategy when compared to the traditional EOL options of reuse, refurbishing and disposal.

The term bisociation was originally coined by Koestler to describe a “synthesis of elements drawn from two previously unrelated matrices of thought into a new matrix of meaning by way of a process involving comparison” [36]. Tucker and Kang propose the term Bisociative Design as a product design methodology that aims to quantify hidden, previously unknown design synergies across seemingly unrelated product domains [37]. Form and function similarities act as numerical system of measurement to evaluate compatibility between two products from same or different domains [31]. By quantifying the geometric compatibility of possible subassembly combinations of EOL products in large dimensions, the process of similarity measurement can be made non-cognitive, which is essential for extremely large databases which resynthesis aims to take into account. Thus, resynthesis can be applied to EOL products through a framework based on bisociation using form and function analysis. Tierny et al. suggest that Reeb graphs can be implemented to represent the form of a product and can then be used to compare form similarity between two products [38]. Their discussion, however, is restricted to the physical
form of products and their functional characteristics are not taken into account. Furthermore, their work also does not address quantifying product similarities for EOL decision making. Product functions in this thesis are represented as textual descriptions from user manuals and functional similarity is determined using Latent Semantic Analysis (text mining based) described by Song et al. and Banea et al. [39][40]. Thus form and function similarity values can be utilized to quantify the value obtained through combination of products/subassemblies and determine the optimal EOL strategy.

2.3 EOL Strategies & Decision-making

This section demonstrates how modular and bisociative design methods (discussed in 2.2), that provide form and function similarities between products/subassemblies, can be incorporated into the EOL decision making process. Several models have been proposed in the literature for determining the optimal EOL strategies for different components of a product. Mangun and Thurston develop a model for incorporating long-range planning for component reuse in product design. It helps determine when a product should be taken back, and which components should be reused, recycled, or disposed by optimizing product utility. Product utility is formulated as a function of cost, EOL reliability and environmental impact. [6].

Johnson et al. discuss the scheduling of disassembly operations for reclaiming post-consumer products for recycling, remanufacturing and reuse. A quantitative method of disassembly analysis is developed that aims to improve the efficiency of the disassembly planning process and to generate an optimal disassembly sequence which maximizes profit. [41]. Lee et al. describe end-of-life disassembly charts to determine optimal stage of disassembly. A multi-objective methodology for minimizing environmental impact and minimizing loss (or maximizing gains) in order to determine appropriate EOL options for manufactured products is discussed [42]. Behdad et al. describe a procedure for identifying the best sequence of
disassembly operations for maintenance and/or component upgrade using a graph-based integer linear programming problem [43]. Bufardi et al. analyze aspects that constitute a set of EOL alternatives, the selection of a list of relevant criteria to evaluate the EOL alternatives and the choice of an appropriate multi-criteria decision-aid method [44]. Remery et al. propose a model that takes environmental, economic and legislative aspects into account and provides a method for evaluating the various options for the EOL scenario of a product during the early design phase.[45]. The model described by Pandey and Thurston utilizes the features of various solution algorithms to address difficulties in implementing decision based design partial ordering of alternatives [8].

The aforementioned literature successfully proposes methodologies that are extremely efficient in EOL decision making. However, their scope is restricted to single-domain products (for example consumer electronics, automotive, etc.) rather than a more realistic scenario involving multi-domain products. The product resynthesis methodology proposed in this manuscript take into account products (and their subassemblies) belonging to multiple domains. End-of-life decision making needs to be eventually incorporated into closed-loop supply chains to ensure efficient utilization of returned products. The following sections explore reverse logistics and closed-loop supply chain networks, and how resynthesis can be placed in their dynamics.

2.4 Reverse Logistics and Closed-loop Supply Chains

EOL-Decision making, discussed in the previous section, is the basis on which closed-loop supply chain systems are based on [46]. Donald Blumberg defines reverse logistics as an integral subset of closed loop supply chain systems [47]. Guide et al. introduce closed-loop supply chains with focus on profitable value recovery. They define a closed loop supply chain as a combination of the traditional forward supply chain and the additional activities of reverse logistics [5]. Rogers and Tibben-Lembke describe reverse logistic activities as “collection of
returned goods, logistics of the products from the points of use to a point(s) of disposition, testing, sorting, and disposition to determine the products’ condition and the most economically attractive EOL option” [48]. The American Reverse Logistics Executive Council states that, “Reverse logistics can be viewed as the process of planning, implementing and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information, from the point of consumption back to the point of origin, for the purpose of recapturing their value or proper disposal” [49]. Thus, reverse logistics and closed-loop supply chains provide a platform for EOL decision making and ensures proper treatment of returned products.

Kopicki et al. carried out a comprehensive study including interviews with numerous firms and several trade associations acknowledged to be leaders in waste reduction efforts [50]. A broad range of reverse logistics network systems, multi-stage field studies including survey data from Warehousing Education and Research Council (WERC) is described by Carter and Ellram [51] and, Stock and Mulki [52]. Rogers and Tibben-Lembke have comprehensively examined economic and supply chain issues related to reverse logistics and developed working network models involving reverse logistics and closed-loop supply chains [19] [48] [49]. All of these incorporate recycling and proper disposal of returned products, and may/may not include reusing/remanufacturing in their model. Guide and Van Wassenhove [5], and Dowlatshahi [55] analyze a variety of reverse logistics problems and discuss strategic and operational factors such as costs, overall quality, customer service, environmental concerns, and legislative concerns associated with closed-loop supply chains. However, the emphasis of these methodologies focuses more on creating a green supply chain, rather than profit attainment. Also, the end product of closed-loop supply chains would be refurbished variants of an older generation of the OEM’s products, only targeting a subset of the already existing consumer base/market segment.
This thesis proposes a way to incorporate resynthesis into the dynamics of a closed-loop supply chain. By combining the advantages derived through resynthesis, profit margins can be substantially enhanced. However, a 3rd party firm that is capable of performing design analysis (to be discussed in chapter 3) is integral to the implementation of this closed-loop network. Several closed-loop networks have been modeled that describe the role that third party firms can play.

2.5 Closed-loop Supply Chain Networks

This section describes how various closed-loop supply chain networks have been formulated thus far, that focus not only on the dynamics, but also, contracting strategies that different members of the network employ. Guide et al. discuss the evolution of closed-loop supply chains from a single-loop unidirectional to more complex closed-loop. Closed-loop systems combine the forward and reverse logistics flow of products [56]. Ross and Evans demonstrate that recycle and reuse strategies for plastic-based products can yield significant environmental benefits [57]. Shi et al. discuss the production planning problem for a multi-product closed-loop supply chain where the manufacturer can supply products by, either, producing brand-new products or remanufacturing returns into as-new ones [58]. Some research papers examine recycling or green practices in specific industries, i.e. paper [59], and automobiles [60]. Nagurney and Toyasaki [61] and Hong et al. [62] develop frameworks for modeling reverse supply chains of electronic waste. Their models however only incorporate recycling for EOL treatment of e-waste. Krumwiede and Sheu review current industry practices in reverse logistics and develop a model to aid the process of examining the feasibility of implementing reverse logistics in third-party firms [63]. Siegel and Vitaliano indicate that most manufacturers tend to emphasize more on green supply chains than a profit and recovery maximization based objective [64]. This could possibly be due to the lack of economical benefits that closed-loop supply chains provide manufacturers. Dai and Wang develop a very effective
system for recovery of EOL vehicles with the objective of cost minimization (but not value maximization) [65]. Third-party firms involved in the business of recycling and/or refurbishing, transportation services, or non-profit organizations to operate recycling programs are quite common [66]. For example Hewlett Packard contracts with a waste removal and management firm to collect e-scrap [67].

As can be seen, most network models do not utilize closed-loop supply chains for maximizing value, but tend to focus more on environmental and legislative objectives through corporate social responsibility [64]. Most models restrict their EOL strategies to recycling since manufacturers gain no economic benefits from reverse logistics (as explained in Chapter 1). Resynthesis aims to redirect profit to the manufacturers which can provide them the financial motivation to actively engage in reverse logistic activities.

Another factor that is also responsible for driving organizations away from involving actively in closed-loop chain planning is product cannibalization. It is defined as a scenario that often results in a decreased demand for an existing product when a vendor releases a new/competing product [68]. Resynthesis aims to solve this issue, since the product obtained from the EOL products has characteristics distinct from existing products, thus reducing its potential to cannibalize new and refurbished products that an OEM manufactures. Moreover, organizations may actually choose to cannibalize their products in case of fierce competition as discussed by Guide and Li [69][70].
Chapter 3

Methodology

The term *synthesis*, by definition, is the systematic combination of otherwise different elements to form a coherent whole [71]. As far as product design and development is concerned, product synthesis represents the actual manufacturing/assembly process of any product since any product is a coherent assembly of otherwise distinct materials/subassemblies. A subassembly is a unit assembled separately but designed to be incorporated with other units into a larger manufactured product. Taking into account the limitations of existing EOL options (as described in Chapter 1) and acknowledging the definition of synthesis, a new dimension of product sustainability called *resynthesis* is introduced in this thesis. Resynthesis is the creation of a product that is distinct from its parent products/subassemblies or that adds functionality to an existing product through the combination of different EOL products (assembly or subassembly), or both. Resynthesis aims to overcome the various limitations that other EOL options possess by identifying viable candidate assemblies/subassemblies that when combined, enhance the functionality and overall value of EOL products.

The proposed product resynthesis methodology postulates the development of a novel product(s) through combination of multiple EOL products/subassemblies using *form-function* similarities between them and finding feasible candidates. The proposed methodology introduces resynthesis as part of a closed-loop supply network. Figure 3 shows the supply chain network, with resynthesis, that the methodology employs. The arrows indicate product flow, with orange arrows implying forward, while blue implying reverse flow. There are 4 sets of players considered in this supply chain network (Figure 3): the set of $n$ OEMs, a retailer, the customer, and the third party firm. It is assumed, for a given region, that the $n$ OEMs sell their products to a
single retailer for distribution. The list of \( n \) OEMs (manufacturers), contract with a retailer to sell their products at a wholesale price as part of forward logistics. The retailer subcontracts with a third-party firm to engage in refurbishing, while OEMs contract with the 3rd party firm for resynthesis of returned products (reverse logistics) as part of a closed loop supply chain model. The task of collecting returned EOL products is handled by the retailer. In addition to these, the network contains a secondary manufacturing firm that purchases specific EOL components from the 3rd party firm for resynthesis, a recycling firm where returned products can be recycled, and a landfill where they can be disposed.

![Diagram of closed-loop supply chain network methodology](image)

**Figure 3**: Closed-loop supply chain network methodology
**Original Equipment Manufacturers:** An original equipment manufacturer (OEM) manufactures products that are purchased by another company (retailer) and retailed under that OEM’s brand name. A set of $n$ OEMs is considered constitute the forward logistics. i.e., an OEM manufactures and sells a product to a retailer at wholesale prices. The retailer then sells products to the end consumer (Steps 1 and 2 in Figure 3).

**Retailer:** The retailer handles the task of distributing new products to consumers as well as collecting returned products from consumers. Retailers buy new products from OEMs at a wholesale price of $w$, and sell them to consumers at a selling price of $p$. Retailers make profit by setting $p$ to be numerically greater than $w$. The retailer provides customers who choose to return their EOL products with discounts/store credits or can choose to purchase them directly.

**Customer:** Customers, in this model, buy product(s) from retailers. They may choose to return them back to the retailer (Step 3, Figure 3). As mentioned, the retailer would, in return, provide them with economic benefits, such as discounts, credit, etc.

**3rd Party Firm:** A 3rd party firm, is traditionally responsible only for handling the logistics involved in product take-back (Step 4, Figure 3). However, in this manuscript, the 3rd party firm, in consideration, is also capable of performing EOL decision making. It cooperates with the retailer in handling the end-of-life products and providing it with refurbished products (Step 5, Figure 3). Refurbishing in this model is considered a combination of reuse and remanufacture. For recycling, the 3rd party firm contracts with recycling firms which handle recycling of products (Step 9, Figure 3). In addition to the existing EOL options available to the 3rd party (refurbishing, recycling and disposing), a fourth EOL alternative of resynthesis is proposed (Step 6, Figure 3). The 3rd party firm should be capable of successful implementation of resynthesis, and can optionally choose to act as provider to a secondary/tertiary manufacturer.
which performs resynthesis (Step 8, Figure 3). If the returned products are not worth refurbishing, resynthesizing or recycling, then the third party firm can choose to dispose it in a landfill (Step 7, Figure 3).

The demand function for products (forward logistics) in most cases has a negative correlation with the retail price. Let \( D(p_i) \) be the original demand for product \( i \) as a function of retail price. Once purchased, the customers may return their product to the Retailer, indicated by Step 3 in Figure 3. The retailer, thus, does the job of collecting the returned products. Since, not all customers who buy would choose to return their products, let \( \lambda_i \) be fraction of product \( i \) that would be returned. The 3\textsuperscript{rd} party firm collects these returned (EOL) products from the retailer through reverse logistics and sorting them in Step 4. Since the 3\textsuperscript{rd} party firm is subcontracted with the retailer, the demand for refurbished products is preset as per the contract. The 3\textsuperscript{rd} party firm first fulfills the demand for refurbished product \( i \) as a fraction (say \( \mu_i \)) of total demand \( D(p_i) \) as per its contract (Step 5, Figure 3). Refurbishing involves minor repairs and refining through machining, milling, etc... With the remaining products, the 3\textsuperscript{rd} party firm uses the resynthesis procedure (discussed in subsequent sections) and chooses an optimal EOL strategy with recycling and disposal being the other alternatives. Depending upon the product domain of the resynthesized product, it is sold to the corresponding OEM by the 3\textsuperscript{rd} party as a product concept (possibly as a blue print, prototype, etc.) along with the appropriate (and available) raw materials that it possesses (Step 6, Figure 3).

Thus, the 3\textsuperscript{rd} party firm, after fulfilling the demand for refurbished products, utilizes resynthesis as an EOL alternative in addition to recycling and disposing. The procedure for resynthesis is discussed in detail in Section 3.1.

3.1 Resynthesis: End-of-Life Strategy
This section presents a detailed description of resynthesis as an EOL method. Since the remaining EOL alternatives (namely, refurbishing, recycling and disposal) are well known, and discussed in the Chapters 1 and 2, this section focuses only on resynthesis. According to this model, the 3rd party firm carries out this procedure (Step 6, Figure 3). The procedure begins by forming a large-scale database of feasible subassembly combinations. The database would comprise of form and function data that is explained in section 3.1.1. This is followed by introducing the form and function similarity models which quantify the relationship between different assemblies/subassemblies. The values of the resynthesized combinations are used to determine the optimal EOL decisions for the remaining subassemblies.

3.1.1 Creating a Product Database

The first step that the third party firm carries out (after Step 4, Figure 3) is to access a large database of products. The form data is obtained from digital 3D CAD models (shown in Figure 4) of all assembled components and their subassembly combinations existing in a company’s product design database, or by using 3D scanners to create CAD images of these products. Figure 4 also describes how form and function data will be stored. While the 3rd column contains CAD data, column 4 contains function or characteristic of the product/subassembly in text form. Function data is obtained from technical user manuals patent data [72].

<table>
<thead>
<tr>
<th>Object</th>
<th>Image</th>
<th>3D Cad Image (Form data)</th>
<th>Function data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surfboard</td>
<td>![Image]</td>
<td>![Image]</td>
<td>Float, plan shape or outline, tail design, rails, rocker and fins.</td>
</tr>
<tr>
<td>Calculator</td>
<td>![Image]</td>
<td>![Image]</td>
<td>Mathematical computation, add, subtract, multiply, divide, numbers</td>
</tr>
</tbody>
</table>

Figure 4: Form-function representation
Selective disassembly proves to be more efficient and profitable than considering all possible assembly configurations (irrespective of the disassembly sequence) through complete disassembly of products [73]. The next subsection describes the disassembly planning technique involved in resynthesis.

3.1.2 Disassembly Planning: Feasible options

Lambert defines the disassembly process as a sequence of single operations for separating a component from a product or separating into two different subassemblies. [22]. Introducing the concept of transition matrix, Lambert explains that this matrix represents the transitions caused by the possible disassembly operations. The cells of the matrix represented by $T_{ik}$, where $i$ refers to the different subassemblies (rows) and index $k$ refers to the disassembly actions (columns), are generated for each assembly and subassembly possibility. Here, a value of $T_{ik} = -1$ indicates that action $k$ disassembles subassembly $i$, and $T_{ik} = 1$ means that action $k$ creates subassembly $i$. When no action takes place, the other elements of the matrix are 0.

Figure 5(i) illustrates a conceptual assembly (product) schematic for a product made up of components A, B, C and D. Figures 5(ii) and 5(iii) indicate the correlation triangle between the components and the various possible subassemblies and Table 1 represents the transition matrix that can be generated for the ABCD model discussed in Figure 5(i). Here $T_{00} = 1$, implies that action 0 ($k=0$) generates the assembly ABC $i = 0$, i.e. ABC. Also, $T_{01} = -1$, thus action 1 ($k=1$), disassembles assembly ABC ($i=0$). Similarly, $T_{11} = 1$ and $T_{51} = 1$ implies that action 1 ($k=1$) generates subassemblies AB ($i=1$) and C ($i=5$), and so on. Here, selective or partial disassembly is considered in order to avoid unnecessary disassembly costs and does not restrict products to be disassembled up to their bill of materials levels. While the transition matrix provides all the feasible disassembly options, the optimal disassembly plan is determined only through an optimal objective when all the costs are taken into account.
3.1.3 Quantifying Form-Function Similarity and Resynthesis Candidates

With the literature review concerning form and function similarity discussed in Chapter 2, the procedure to carry out this similarity analysis is discussed in this section. This enables the evaluation of form as well as function compatibility and interactions. To understand the form of assemblies, 3-D representations of components in the form of mesh data is considered. This however needs to fully represent the form of a product. To achieve this, the mesh data in the form of 3-D CAD models is converted to Reeb graphs which provide a graphical representation of the form of each model (Figure 6). Bespalov et. al. explain the drawbacks of the Reeb graph method.
and because of its domain specificity [74]. A basic Reeb graph methodology, formulated by Doraiswamy et al. to explain how form data between two products/subassemblies can be compared and evaluate it, is adopted [75]. It should be noted that in addition to the procedure used by Doraiswamy et al., other shape geometry retrieval solutions as discussed by Iyer et al. can also be employed (again, specific to domains) to evaluate form data [76].

As mentioned earlier, the function similarity between subassemblies is measured based on the textual specifications provided by each individual component in the bill of materials or the user manual. These specifications include technical descriptions of products and their subassemblies.

Since words can have different meanings, based on context, an appropriate text mining algorithm must be employed. Design Structure Matrix (DSM) concepts have been employed in engineering to investigate relationships between engineering systems and subsystems, but might be unsuitable for analyzing large scale databases as would be this case with the 3rd party firm [77]. Hence, considering the time and cost benefits of automated text mining techniques, Latent Semantic Analysis (LSA) is employed to extract hidden/semantic meanings of words, given specific contexts [78]. The LSA matrix methods described in Song et al. and Banea et al. are adopted to establish a metric for comparing function similarity between the textual descriptions of two products/subassemblies [40][39].
3.1.4 Resynthesis EOL Decision-making

The *form* and *function* similarity values are obtained from section 3.1.3. These will be utilized to determine the optimal *resynthesis* strategy for a given EOL product. The assumptions made in this model presented are:

- All EOL products that are collected are assumed to be in working order.
- The reliability and effective age of the take-back products are based on manufacturer specifications.
- Only the primary *function* of each take back product is factored in this model, i.e., multi-function EOL products are not taken into account.

Sane *et al.* describe the various classifications that can be made using *form-function* similarity values obtained [79]. Figure 7 shows the *form-function* similarity graph for two subassemblies based on the *form-function* similarity metrics presented in Section 3.1.3. The following are the *resynthesis* alternatives that are quantified based on the magnitude of the similarity values.

![Form-function similarity comparison graph](image)

**Figure 7: Form-function similarity comparison graph [79]**

If the *form* similarity value (varying between 0 and 1) is greater than *Y*, then it is said to be *high* otherwise *low*. In the same way, if the *function* similarity value (also varying between 0 and 1) is
greater than $X$, then it is said to be *high*, otherwise *low* (Figure 7). The $X$ and $Y$ values are set by the manufacturer.

**Classification 1:** *Form* (high), *Function* (low)

**Classification 2:** *Form* (low), *Function* (low)

**Classification 3:** *Form* (low), *Function* (high)

**Classification 4:** *Form* (high), *Function* (high)

In order to explain the concept behind the 4 classifications above, it is assumed that two products A and B for which EOL decisions are to be made [79]. For example, A and B are products that an OEM manufactures. Let $\pi_A$ and $\pi_B$ be the profits (per unit) obtained from A and B considering that they are *refurbished, recycled* or *disposed*. Consider *resynthesis* as an EOL option, such that the *resynthesis* of the subassemblies of A and B form product C. Thus, after forming C obtaining profit $\pi_C$, A and B will have residual subassemblies left, and let $\pi_{\text{Residuals}}$ be the corresponding profit obtained. Conceptually, *resynthesis* becomes the preferred EOL decision if the following criterion is fulfilled:

$$\pi_C + \pi_{\text{Residuals}} \geq \pi_A + \pi_B \quad \text{(1)}$$

Where, $\pi_{\text{Residuals}}$ is the profit attained from the remaining subassemblies (components) of A and B that are not used in *resynthesis* post disassembly (and are remanufactured, *reused*, *recycled* or *disposed*).

Where,

$$\pi_C = (\text{Price})_C - (\text{Cost})_C \quad \text{(2)}$$

$(\text{Price})_C = \text{Price of resynthesized product C (resynthesis of A + resynthesis of B)}$

$(\text{Cost})_C = \text{Cost incurred to create resynthesized product C (resynthesis of A + resynthesis of B)}$. 
Since it is more profitable to *resynthesize* A and B to form C, than it is to *recycle* or *dispose* them, *resynthesis* in this case is justified.

When two components (subassemblies) with dissimilar functions (low *function* similarity) are combined to form a new product, the resulting product will have a higher value if both their individual functions are retained [80][81]. For example, a wrist-watch with added functions/features such as a chronograph, GPS, etc. would have a higher value since it incorporates functions of other products into itself. Also, if two products/components are physically similar, it can be said (based on Section 2.2) that they can potentially share a common module to form a new product. Because of this, it is economically easier to integrate them [70].

Consider the extreme case of two assemblies having *form* and *function* similarity matrices as seen in Table 2.

<table>
<thead>
<tr>
<th>Form</th>
<th>Assembly A</th>
<th>Assembly B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly A</td>
<td>-</td>
<td>Y</td>
</tr>
<tr>
<td>Assembly B</td>
<td>Y</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Assembly A</th>
<th>Assembly B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly A</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Assembly B</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>

Based on the original formulation of Resynthesis, the four classifications can be elaborated as follows:

**Classification 1**: If A and B have a high *form* similarity (Y=1), then \((\text{Cost})_C = \text{“low”}\) [81], and if they have a low *function* similarity (X=0), then \((\text{Price})_C = \text{‘high’}\) [70], thus the value of the final *resynthesized* assembly is ‘high’ (maximized), therefore, \(\pi_C = \text{‘high’}\). For example, the touch-screen of a tablet computer and the keypad panel of a laser printer have a high *form* similarity while their *function* similarity is low. If an EOL tablet and printer were to be *resynthesized*, the end product will be a printer with functionalities of the tablet embedded into (both hardware and software) it as seen in figure 8.
Thus, the final value (price) of the resynthesized printer would significantly increase possibly resulting in higher profit as compared with other EOL options.

**Classification 2:** If A and B have low form similarity (Y=0), then (Cost)\(_C\) = ‘high’ [70] and if they have a low function similarity (X=0), then (Price)\(_C\) = ‘high’[82]. The resultant profit obtained from product C will most likely not be ‘high’, due to extreme form dissimilarity (higher cost of integration) even though their functions are distinct (Figure 9).

**Classification 3:** Similarly, if A and B have a low form similarity (Y=0), then (Cost)\(_C\)= ‘high’ and have a high function similarity (X=1), then (Price)\(_C\) = ‘low’. Thus the cost of
integrating them would be high, while the value of the final product is low. Needless to say, the profit obtained from resynthesis ($\pi_C$) = ‘low’ (as seen in the example in figure 10).

Figure 10: Example of low form, high function

**Classification 4:** If A and B, are identical (or same product), then form similarity Y = 1, function similarity $X = 1$. Thus, if we are to form a product C by combining their subassemblies, $\text{Cost}_C = \text{Cost} (\text{resynthesis}_A + \text{resynthesis}_B) = \text{“low”}$ [70]. However, in this case, product C does not provide any additional functions beyond what is already provided by either product A or B. Hence, its value is only as much as the value of A or B.

For example, if we have two similar/identical mobile phones (with comparable reliabilities), both their form and function similarity would be nearly 1 (depending upon their internal configuration). Figure 11, shows two phones with their batteries disassembled. Thus, if we are to form a new product by incorporating subassemblies from both phones, say for example, by removing the battery from one phone and placing it in the other and vice versa, the final product will not have a value higher than the sum of their individual values.

Figure 11: High form, high function similarity
Classifications (1) and (4) are the most suitable for resynthesis while classifications (2) and (3) are the least suitable candidates for resynthesis. From a purely economic perspective, classification (1) (from figure 7) is considered ideal for resynthesis, in this methodology. To summarize the above description, if the two subassemblies having different functions are combined, their synthesis could retain both functions. The final product will have an added value, since the customer would be willing to pay more for a product which has features that are auxiliary to its primary features/functions [82]. Also, if two subassemblies have a high form similarity then it is easier to physically integrate them, in turn decreasing the associated manufacturing cost [70][83], while if they have low form similarity, the design and production costs increase [70].

3.2 Recycling and Secondary-Resynthesis

This section describes Steps 7, 8 and 9 from Figure 3. Based on the concept of selective disassembly discussed in Section 2.1 and 3.2, the 3rd party firm starts with the formation of a large-scale database of compatible subassembly combinations (candidates). Then form and function similarity models are introduced that quantify the relationship between different assemblies/subassemblies, providing the OEMs with new product concepts from EOL products and opportunity to enhance their profit. The EOL strategies other than refurbishing and primary resynthesis (as discussed in 3.1) that the 3rd party firm uses are discussed.

Section 3.1 explains that feasibility of resynthesis depends on the form-function requirement similarities of the subassemblies. Thus, there would be some products remaining after Steps 6 is completed (Figure 3). The third party firm, however, can also choose to contract with a secondary/tertiary manufacturer that requires specific product/subassembly that the OEM produces for its own products. For example, Z-Corp resynthesizes EOL HP/Dell printer cartridges
to run their 3D printing business [84]. This is also a form of resynthesis. The items remaining after steps 1-6 and 8 are then sent to a recycling firm for recycling (Figure 3, Step 9). Given that recycling is environmentally and economically inferior to other EOL options (as discussed in Chapter 1), recycling is generally the last EOL alternative (other than disposal) a 3rd party firm would choose. In the event that the recycling firm is unable to accept a product/component for recycling, the 3rd party chooses to dispose it (Figure 3, Step 7: landfill). The third party firm, however, makes no revenue by disposing its remaining products in a landfill.

3.3 Methodology Equations and Variables

The optimization problem that is formulated, involves making one of three EOL decisions (namely recycle, resynthesis and disposal). Refurbishing (combination of reuse and remanufacture) is not part of the decision making process since its demand is based on a contract between the retailer and the 3rd party firm. The solution to the optimization problem provides the EOL strategy that should be followed. The objective function is based purely on the profit that each player (as described earlier) makes, along with environmental constraints added to it. This model will then be simulated to test its optimality. There are several variables involved (deterministic, probabilistic and decision) in this model and this section sequentially introduces them. Sane & Tucker discuss these variables [85] and classify according to the organization involved (OEM, retailer or third party) based on the following equations listed below:

1. **OEMs**

   \( e_{j,i} = \) manufacturing cost for product \( i \) (total of \( N \) products) for OEM \( j \) (deterministic variable)

   \( w_{j,i} = \) wholesale selling price for product \( i \) for OEM \( j \) (to retailer; decision variable)

   \( s = \) resynthesis cost (to the 3rd party firm, fraction of resynthesis profit)
2. **Retailer**

\[ w_{j,i} = \text{wholesale cost for product } i \text{ for OEM } j \text{ (paid to OEM)} \]

\[ p_{j,i} = \text{retail price for product } i \text{ for OEM } j \text{ (decision variable)} \]

\[ a_{j,i} = \text{collection and sorting cost for product } i \text{ for OEM } j \text{ (per unit)} \]

\[ z_{j,i} = \text{price of refurbished product } i \text{ from OEM } j \]

3. **3rd Party Firm**

\[ u_{j,i} = \text{repair cost for product } i \text{ for OEM } j \text{ (variable deterministic)} \]

\[ e = \text{resynthesis cost (variable deterministic)} \]

\[ v_{j,i} = \text{refurbishing wholesale price for product } i \text{ from OEM } j \text{ (paid by Retailer - contract variable)} \]

\[ s = \text{resynthesis price (paid by OEM, contract decision variable)} \]

\[ g_{j,i} = \text{recycling price for product } i \text{ for OEM } j \text{ (deterministic variable)} \]

\[ h_{j,i} = \text{resynthesis raw material price for product } i \text{ for OEM } j \text{ (paid by secondary manufacturer M2, deterministic variable)} \]

4. **Probabilistic Variables:**

\[ D(p_{j,i}) = \text{Original demand for product } i \text{ of OEM } j \text{ as a function of retail price (negatively correlated)} \]

\[ \lambda_{j,i} = \text{Fraction of current generation product } i \text{ of OEM } j \text{ that would be returned} \]

\[ \mu_{j,i} = \text{Demand for refurbished product } i \text{ of OEM } j \text{ as a fraction of total demand } D(p_{i}) \]

\[ \beta_{j,i} = \text{Fraction of remaining products that are resynthesis candidates (based on form-function similarities)} \]

\[ \alpha_{j,i} = \text{Fraction of remaining products that are sold to secondary manufacturer (deterministic)} \]

\[ \gamma_{j,i} = \text{Fraction of remaining product } i \text{ that are recycling candidates} \]
\[ D_{\text{new}}(k) = \text{Demand of resynthesized product } j \text{ estimated using forecasting strategies discussed in Li et al. [86].} \]

Let \( \pi_{M,j}, \pi_R, \text{ and } \pi_{3P} \) be the profits of the OEM \( j \) (of \( n \)), Retailer and 3\textsuperscript{rd} Party respectively. Using the variables mentioned above, the profit functions can be formulated as follows:

\[
\pi_{M,j} = \left\{ \sum_{i=1}^{N} D(p_{j,i}) \times (w_{j,i} - c_{j,i}) \right\} + \left\{ \sum_{i=1}^{N} (w_{j,i} - s - c_{j,i}) \times D(\text{new}) \right\} \quad (3) 
\]

The first part of equation (3) relates to forward logistics, where \((w_{j,i} - c_{j,i})\) gives the profit that OEM \( j \) makes on each unit of product \( i \) it sells to the retailer, and \( D(p_{j,i}) \) is the demand for \( i \).

\( \lambda \) and \( \mu \) indicate the quantity of products returned and the demand for refurbished variant of the product(s) represented as fractions of the total demand, as described earlier. The third term represents profit from resynthesis.

\[
\pi_R = \left\{ \sum_{i=1}^{N} D(p_{j,i}) \times (p_{j,i} - w_{j,i}) \right\} + \left\{ \sum_{i=1}^{N} \lambda_{j,i} \times \mu_{j,i} \times D(p_{j,i}) \times (v_{j,i} - u_{j,i}) \right\} \quad (4) 
\]

The first part of equation (4) refers to the profit the retailer makes from buying product \( i \) from OEM \( j \) at a wholesale price \( w_{j,i} \) and selling it to the customer at a selling price \( p_{j,i} \). The second term implies the profit it makes by buying refurbished products from the 3\textsuperscript{rd} party firm and selling it to the customer. The cost of initial collection per unit \((a_{j,i})\) is also included in the second term of equation (4).

\[
\pi_{3P} = \left\{ \sum_{i=1}^{N} \lambda_{j,i} \times \mu_{j,i} \times D(p_{j,i}) \times (v_{j,i} - u_{j,i}) \right\} + \left\{ s \times \beta \times \sum_{i=1}^{N} (1 - \mu_{j,i}) \times \lambda_{j,i} \times D(\text{new}) \right\} + \left\{ \sum_{i=1}^{N} (1 - \beta) \times (1 - \mu_{j,i}) \times \lambda_{j,i} \times \alpha_{j,i} \times h_{j,i} \times D(p_{j,i}) \right\} + \left\{ \sum_{i=1}^{N} \gamma \times (1 - \beta) \times (1 - \mu_{j,i}) \times \lambda_{j,i} \times (1 - \alpha_{j,i}) \times g_{j,i} \times D(p_{j,i}) \right\} \quad (5) 
\]
The components of equation (5) can be broken down as shown above; such that each part represents the revenue/cost the 3rd party bears. The first term indicates the profit the third party makes by refurbishing products and selling it back to the retailer. The wholesale price that it sells the refurbished products \((v_{j,i})\) is a contract decision variable. The second term refers to the profit that the 3rd party firm makes in selling the resynthesized product concept to the corresponding OEMs (along with the raw materials required). The demand for the resynthesized is determined using forecasting and is represented as \(D(new)\). The OEMs makes profit by introducing this resynthesized product back into forward logistics by selling it to retailer. The 3rd party firm contracts with the OEMs and earns a share of their resultant profit (indicated by \(s\)). After refurbishing and resynthesizing (primary), there may be returned EOL products that a secondary manufacturer may require and would purchase it from the 3rd party firm. This can be referred to as secondary resynthesis, since the resynthesis is being carried out by a secondary manufacturer other than the 3rd party firm. The fraction of such products/components is represented by \(\alpha_{j,i}\). The demand \((\alpha_{j,i} \times D(p_{j,i}))\) and price \((h_{j,i})\) for these products/components is deterministic. Finally, the fourth term of equation (5) represents the profit the 3rd party firm makes by recycling the products that remain after it finished refurbishing, and resynthesizing (primary and secondary).

By using values of deterministic variables and simulating the values of the probabilistic variables, profit functions for all three players can be computed. By varying the values of the decision variables \((w_{i,j} \text{ and } v_{i,j})\), and computing profits at each stage, optimal values of all three profit functions can be obtained. Thus, the entire network is iteratively simulated and combined with linear optimization over varying values of decision variables. The same system is then simulated with the options of resynthesis (Steps 6 and 8, Figure 3) removed, thus comprising only comprise of refurbishing and recycling. The maximum profits obtained in both cases are then compared. If the profit obtained in the first case is higher than the second, then the applicability
and optimality of resynthesis can be validated. This thesis proposes a methodology for players in a closed-loop supply chain network to be economically better off with resynthesis incorporated into their operations.
Chapter 4

Case-Study

In order to demonstrate the feasibility and effectiveness of the model described in Chapter 3, a scenario where there are 2 OEMs is presented. One OEM (Logitech) manufactures computer mice and the other manufactures white/black board erasers (Expo). Both OEMs are assumed to produce only one type of product. Logitech produces *Logitech Wireless Mouse*, and Expo produces *Dry-erase Eraser*. Thus $i=1$ for both OEMs ($j=1$ and $j=2$). The cost and prices are partly obtained from [92] [93]. Both OEMs contract with a retailer, Staples (in our case), and with a 3rd party firm, say 3P.

Both OEMs manufacture their product and sell it to Staples (Figure 12). Staples, in this case, also does the job of collecting returned EOL products from customers and through reverse logistics, sells them to 3P which inspects and sorts them. The EOL options of refurbishing, recycling, resynthesis and disposal lie with the 3rd part firm.

![Figure 12: Products (case-study)](image)

The network model similar to Figure 3 is shown in Figure 13, which describes the flow of product(s) in the closed-loop. It is assumed that all returned products (mouse and eraser) are in working condition. Hence, disposal to landfill is not considered an EOL option in this case study.
The CAD form models and textual function descriptions are obtained using the case study discussed in Sane et al. and the form and function similarity are similarly derived [79]. The disassembly matrices for the mouse and eraser are shown in Table 3.

**Table 3: Disassembly tables [79]**

<table>
<thead>
<tr>
<th>Part</th>
<th>Subassembly Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Mouse Casing (Top)</td>
</tr>
<tr>
<td>B</td>
<td>Microchip (PCB)</td>
</tr>
<tr>
<td>C</td>
<td>Mouse Base</td>
</tr>
<tr>
<td>A'</td>
<td>Eraser (Base)</td>
</tr>
<tr>
<td>B'</td>
<td>Eraser Casing</td>
</tr>
</tbody>
</table>

The resultant transition matrix obtained using Lambert’s method, is as follows:

**Table 4: Transition matrix for the two products [79]**

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>AB</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AC</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The CAD form models and textual function descriptions are obtained using the case study discussed in Sane et al. and the form and function similarity are similarly derived [79]. The disassembly matrices for the mouse and eraser are shown in Table 3.
The *form-function* similarity analysis is then carried out using Reeb graph and LSA methods as described in Chapters 2 and 3. The values of *form-function* similarities are shown in Table 5. In this case, AC and A’ have a high *form* similarity and low *function* similarity as indicated by the green highlighted cells in table 5. Thus, based on the discussion in Section 3.1, the functions of these two subassemblies can be combined to form a new product with enhanced functions. The *form* similarity being high also indicates that A’ and AC can be physically attached to form a new assembly/product A’+AC. The *form* similarities between the subassemblies are calculated based on the similarities between the generated Reeb graphs for each possible combination. This similarity is a measure of physical interchangeability or physical addition that is enabled by geometric similarity. From table 5, the subassembly combination AC and A’ can be physically added based on the geometry similarities that exist between the two. AC is given preference over BC due to a higher *form* similarity value even though BC has a lower *function* similarity with A’.

All values for $\mu$, $\gamma$, $\alpha$, and $\lambda$ in the simulation are considered to be probabilistic beta random numbers. Resynthesis costs are obtained by adding individual costs and prices by adding individual prices of candidate products as described in Saaty and Vargas [89]. It is useful to note that a product similar to the new resynthesized product is already marketed by Expo [90]. Demands for both products are gamma random numbers with means equal to 50000, and 100000 respectively [91]. In addition, the 3rd party can also sell the excess/residual mouse diode circuits to Avago technologies (Figure 13) that utilizes returned mouse LEDs [92].
With this data, the entire methodology is simulated in Palisade Decision Tools @Risk (on MS Excel interface) and run with 100,000 iterations. Table 6 shows the optimal profit values for all the players. It can be observed that in the presence of resynthesis, the profits of Expo, Staples and 3P are 35%, 34% and 84% more that in the absence of a resynthesis EOL option.

### Table 6: Optimal profits of all players

<table>
<thead>
<tr>
<th>Optimal Profit</th>
<th>With Resynthesis</th>
<th>Without Resynthesis</th>
<th>Due to Refurbishing only</th>
<th>Due to Recycling only</th>
<th>% Increase in Profit due to Resynthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^*_\text{M1} (\text{Expo})$</td>
<td>$$209,000$</td>
<td>$$154,500$</td>
<td>-</td>
<td>-</td>
<td>35.28%</td>
</tr>
<tr>
<td>$\pi^*_\text{M2} (\text{Logitech})$</td>
<td>$$1,003,000$</td>
<td>$$1,003,000$</td>
<td>-</td>
<td>-</td>
<td>0.00%</td>
</tr>
<tr>
<td>$\pi^*_\text{R}$</td>
<td>$$788,000$</td>
<td>$$590,000$</td>
<td>$$322,000$</td>
<td>-</td>
<td>33.56%</td>
</tr>
<tr>
<td>$\pi^*_3\text{P}$</td>
<td>$$272,600$</td>
<td>$$148,440$</td>
<td>$$108,200$</td>
<td>$$24,300$</td>
<td>83.64%</td>
</tr>
</tbody>
</table>

Also, the optimal values of the decision variables, namely, the wholesale prices and the refurbished product prices obtained are presented in the Table 7. Since the resynthesized product, in this case, does not belong to the domain of the mouse, Logitech (i.e. OEM$_2$) does not make

<table>
<thead>
<tr>
<th>Component</th>
<th>Eraser casing - B’</th>
<th>Eraser head - A’</th>
<th>A’B’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouse top - A</td>
<td>form: 0.282</td>
<td>function: 0.480</td>
<td>form: 0.130</td>
</tr>
<tr>
<td>Microchip - B</td>
<td>function: 0.020</td>
<td>form: 0.020</td>
<td>function: 0.020</td>
</tr>
<tr>
<td>Mouse base - C</td>
<td>form: 0.159</td>
<td>function: 0.320</td>
<td>form: 0.320</td>
</tr>
<tr>
<td>AB</td>
<td>form: 0.282</td>
<td>function: 0.060</td>
<td>form: 0.060</td>
</tr>
<tr>
<td>AC</td>
<td>form: 0.301</td>
<td>function: 0.350</td>
<td>form: 0.350</td>
</tr>
<tr>
<td>BC</td>
<td>form: 0.159</td>
<td>function: 0.159</td>
<td>form: 0.159</td>
</tr>
</tbody>
</table>

Table 5: Form-function similarity values [79]
money from it, meaning its profit remains unchanged. However, constrained only by environmental restrictions, an EOL strategy containing resynthesis proves to be a lot more profitable for all the other players.

Table 7: Optimal values of decision variables (in US $)

<table>
<thead>
<tr>
<th>Decision Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V^*_{1,1}$</td>
<td>0.4</td>
</tr>
<tr>
<td>$V^*_{1,2}$</td>
<td>13</td>
</tr>
<tr>
<td>$W^*_{1,1}$</td>
<td>2.5</td>
</tr>
<tr>
<td>$W^*_{1,2}$</td>
<td>20</td>
</tr>
</tbody>
</table>

The resynthesized product is an ergonomically superior eraser (Figure 14). Since it belongs to Expo’s (OEM$_1$) domain, it is sold as a concept (CAD design, manufacturing methods, etc.) by the 3$^{rd}$ party and would gain a share of the profit ($s$ from Section 3.3) that the Expo would make selling it. The selling price is determined by the OEM based on the model described in Saaty and Vargas [89], adopting one of the strategies where the final price is computed through summation of the price of the individual refurbished component(s) whose functionalities the new product contains.

It can be observed from Table 6, that the profit of Expo (OEM$_1$) is 35% higher when resynthesis is incorporated into the closed-loop supply chain. Due to refurbishing alone, neither OEM makes any profit through reverse logistics. Thus, in order for the OEMs to make profit from reverse logistics, resynthesis proves to be a vital EOL alternative. In addition to the OEMs, as mentioned in Table 6, the retailer and the 3$^{rd}$ party firm also make significantly higher profit in the presence of resynthesis. While presenting the concept of resynthesis in this case study, several assumptions and simplifications have been made. Varying reliability and effective age amongst
returned products can be estimated more accurately with further data analysis rather than assigning probabilistic distributions as failure modes.

![Figure 14: Resynthesized final product](image)

Thus, the assumption of probabilistic reliability simplifies the model and helps in the software simulation of the setting. In a more realistic setting, the tedious task of assessing the reliability at the 3rd party and then accordingly the effective-age of the returned products will have to be modeled. Also, the OEMs used in the case study (Logitech and Expo) were assumed to manufacture a single product, whereas in a more realistic scenario, the number would be much higher and thus the form (CAD) and function databases would be much more complex.

In conclusion, it can be observed from Figure 15, that the flow of capital in the closed-loop supply chain network is significantly higher in the presence of resynthesis than in absence. The red arrows indicate the flow of capital due to resynthesis. Also, it can be noted that capital flows into Expo through reverse logistics in the presence of resynthesis which is not the case in its absence. Recycling in both cases, has comparatively lower contribution to the profit obtained, and hence proves to be an economically inferior EOL alternative.

Since it was assumed that Expo and Logitech manufacture a single product, the profit margin of 35% for Expo is significant, especially when the entire range of products that both these OEMs actually manufacture is taken into consideration.
Figure 15: Flow of capital (Expo)
Chapter 5

Conclusion

A new EOL alternative called resynthesis as part of a closed-loop supply chain is proposed in this thesis. This new EOL strategy has the potential to significantly add to the profit each player makes in the aforementioned scenario. A scenario comprising of a 3rd party that is not only capable of handling the reverse logistics but also post recovery alternatives and strategies is described. The case study illustrates how profit can be routed back to the OEM through reverse logistics. The profit can potentially increase with resynthesis (indicated by red arrows), and at the same time, a possibly new customer market can also be discovered that buys resynthesized products. The objective of a closed-loop supply chain would thus, not only be to provide OEMs with raw material post-recycling, but also profit through reverse logistics. Since, the OEMs would be manufacturing the resynthesized products, large-scale implementation of such a strategy is also possible.

The emphasis of this thesis is to lay the foundation for a novel EOL alternative called resynthesis that can operate within the dynamics of a closed-loop supply chain. Resynthesis has already started being put to practice [93] and the objective is to amplify its application and maximize the value extraction from EOL products. The EOL products returned by the customers and collected by the retailer may not have the same reliability or effective life. Testing and validating these products and sorting them accordingly would require an additional cost. This has not been incorporated in the methodology, which in reality would be an additional cost that the 3rd party firms would bear.

For future work, a uniform pricing model needs to be established that determines the selling price of the resynthesized products based on the value of the functions that its constituent subassemblies possess. Customer perception on the nature of the resynthesized products also
needs to be taken into account. This, for instance, can be done using social network data mining models. A reliable forecasting model can also be developed using these techniques. The price and demand of resynthesized products can be estimated based on their features and how they appeal to the consumer market based on customer reviews. The environmental benefits of resynthesis are theoretically more than the other EOL options; however, in reality it depends a lot on the manufacturability of the resynthesized final product. Resynthesis from a purely manufacturability perspective is also a research avenue in itself, that is worth exploring in the future. These research addendums can result in the creation of a sustainability-driven business model that manufacturing organizations can adopt to provide vantage for their economic and corporate social goals. Resynthesis would, in the long run, make sure that sustainability is no longer a fleeting trend but rather a business approach being adopted by organizations to maintain competitive positions.
### Appendix

**@Risk Simulation**

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z |
| C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 | C12 | C13 | C14 | C15 | C16 | C17 | C18 | C19 | C20 | C21 | C22 | C23 | C24 | C25 | C26 | C27 | C28 |
| 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |

[Image of @Risk Simulation output with charts and data tables.]
Bibliography


