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Strategic End-of-Life Management of Electronic Assembly Product Recovery in Sustainable Supply Chain Systems

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Abstract

In the past decade, technological advances in electronic data management and communications have spurred economic growth. Constant innovation and changing market forces have transformed the electronics industry into one of the most competitive business in the world. The electronics industry is a material constrained industry in which new products are constantly being introduced and older products are redesigned or recycled to use components with enhanced functionality. In the context of electronic product recovery supply chains, some of the common options include reuse, refurbishment, component recycling or material recycling that involves some of the generic tasks associated with demanufacturing and remanufacturing. In this paper we provide a comprehensive model that addresses several key disposition decisions in the context of product recovery centers. We discuss a case study based on a product recovery problem faced by an electronics company. Electronic assembly product recovery centers face complex materials separation decisions while there is an urgent need to balance between holding and processing costs and fluctuating commodity markets for recovered materials. In this paper, we provide an effective heuristic procedure to tackle a problem faced by the electronics industry. It is clear that reverse product flow offer unique opportunities for firms to create additional shareholder wealth and it is important to recognize the significant value remaining in product returns and the sensitivity to time that exists in such reverse logistics sustainable supply chains.

Key words: End-of-Life Management, Product Recovery, Sustainable supply chains, Heuristics.
1. INTRODUCTION

In the past decade, technological advances in electronic data management and communications have spurred economic growth. However, our growing dependence on electronic products has given rise to a new environmental challenge of dealing with electronic waste. Constant innovation and changing market forces have transformed the electronics industry into one of the most competitive business in the world. The electronic industry is challenged by a combination of rapidly shrinking product life cycles, supply and demand misalignment, mass customization and increasing expectations of both consumers and retailers. With the goal of creating shareholder value and to strengthen market share, electronics companies are now looking at innovative procedures to not only recycle end-of-life electronic products but also to minimize electronics waste. Over 20 million personal computers became obsolete in 1998 out of which only around 13 percent were either reused or recycled (EPA, 2001). Electronic waste makes up approximately 1 percent of the municipal solid waste stream and is a rapidly growing portion of the waste stream (EPA, 1997).

Many municipalities are facing the dilemma of what to do with growing amounts of retired electronics. Rapid changes in computer technology and the emergence of new electronic gadgets only exacerbate the problem. The impetus has come from the recognition of the deleterious effects on the environment of dumping electronic wastes
as well as the decreasing capacity of landfills. Chemicals such as lead and mercury are useful components in many products, but after their short-term societal use, these potentially hazardous materials usually end up being deposited in landfills where they remain immobilized in the exposed layers of the earth. In fact, some experts predict that approximately one billion pounds of lead from computers and other electronics will enter the ecological waste stream within the next decade in the United States (Salkever, 1999). More alarmingly, a study conducted by the National Safety Council (1999) found that three-quarters of all computers ever purchased in the United States are gathering dust in storerooms, attics, garages, and basement.

Computers and related electronic equipment contain materials that are hazardous if disposed of improperly. Certain components such as plastic, glass, steel, aluminum, copper, gold, silver and other metals represent "good" materials that are suitable for reclamation and re-use in new and refurbished products. Therefore, an open inquiry exists as to how much potentially hazardous wastes can be prevented from being introduced into the environment through waste management programs designed to recognize the benefits of reuse and recycling. This is a policy issue for federal, state, and local governments as they try to establish a way to protect society while simultaneously reducing the cost of such protection. While a number of studies on the collection and disposal of household recyclables have been reported in the literature (Jahre, 1995; Beullens et al., 1999; Bullock and Bark, 1989), reports on the collection of electronics end-of-life materials are limited.
The collection of end-of-life electronic products and waste differs from household recycling in two significant ways. First, household recyclables are usually composed of single material packaging, whereas electronic waste is a composite of many materials. Second, household recyclables are usually made of low value materials, thus limiting the amount of additional processing that can be done to separate materials in an economical fashion (Sodhi and Reimer, 2001). On the other hand, electronic waste have small quantities of valuable materials and precious metals, as well as re-usable components, which makes it feasible to collect and process these items from widely distributed sources. In the next section of this paper, we provide the background and relevant literature that focuses on reverse production systems in general and models that focus specifically on strategic end-of-life management of an electronic assembly product recovery supply chain system.

2. BACKGROUND AND LITERATURE

The Electronics supply chain has evolved from the traditional, vertically integrated structure to a complex network of participants linked to multiple end-markets. The electronics industry has faced a variety of challenges. This includes: (a) shrinking product life cycles which complicates the prediction of consumer demand since these new products may have functionality that are as yet untested; (b) Managing inventory that is subject to a rapid depreciation and (c) Misalignment between supply and demand. The electronics industry is a material constrained industry in which new products are constantly being introduced and older products are redesigned or recycled.
to use components with enhanced functionality. At the same time that product customization and supply chain complexities are challenging material recovery from discarded electronic products, legislation and environmental initiatives for product recycling are increasing in various regions (Reimer, 1999). Design for recycling calls for reduction in the types of materials as well as more easily separable materials in new electronic products (Chen et al., 1994). In this situation, electronic product recovery facilities are faced with challenging materials separation decisions.

The electronics supply chain illustrates the multiple links and various interactions between participants across the electronic supply chain.

The current process of recycling involves a number of activities with its associated costs and benefits. In a traditional supply chain environment, manufacturers did not have the need to be concerned with issues such as product recovery, disassembly and disposal costs. However, in a closed-loop supply chain, product recovery is driven by both economic (Lund 1983, Porter and Van der Linde 1995, Jayaraman and Luo, 2007) and political forces (EU 2000, President’s Council on Sustainable Development 1996).

Research on recycling and resource recovery for materials such as paper, sand, carpet and plastics include Pohlen and Farris (1992), Wang et al. (1995), Huutunen (1996), Barros et al. (1998), Fleischmann et al. (2000) and Realff et al. (2004). There are several examples in the literature that document product recovery and reuse including copy machines (Thiery et al., 1995, Krikke, 1998), reusable container management (Kroon and

Electronic assembly product recovery centers face complex materials separation decisions. They must balance between holding and processing costs and fluctuating commodity markets for recovered materials from electronic products. Lu et al. (2000) discuss several options for material separation of electronics and appliances in electronic product recovery centers. This includes manual disassembly and bulk recycling. There has been a lot of work in the literature that focuses on manual disassembly (Kroll et al., 1996; Krikke et al., 1998; Meacham et al., 1999). This involves recovery of reusable components and specific materials from products. The optimal disassembly decision balances the disassembly cost against the value of components removed (Penev and de Ron, 1996; Sodhi and Knight, 1998). On the other hand, for bulk recycling, key decisions for the electronic product recovery center include issues such as size reduction (a certain portion of hazardous parts are removed) and materials separation to perform on-site (Lauder, 1998; Sodhi and Knight, 1998). Bulk recycling is the wholesale processing of recyclables for material recovery in which some disassembly operation is performed to remove hazardous and valuable parts before the remainder of the product is shredded into flakes.
In the next section of this paper we provide a comprehensive model that addresses several key disposition decisions in the context of product recovery centers. Unlike the previous literature on end of life management of electronic assembly product recovery systems that only focuses on a few recovery options, this paper takes a comprehensive approach towards dealing with various recovery and disposition options for products that have been returned to the centralized return center sites. While the focus is on electronic assembly product recovery supply chain systems, this model could be applied to any industry that has to deal with product return disposition decisions.

3. PRODUCT RECOVERY IN SUSTAINABLE SUPPLY CHAINS

In general, product recovery sustainable supply chains have a number of options available to return a product to the consumer in useable condition. A recoverable system is essentially a closed-loop industrial system since discarded items are used in place of virgin materials to the greatest extent possible (Guide et al., 2000, Jayaraman et al., 2003). To manufacturers, once a product has been returned to a company, it has several disposal options from which to choose, including reuse, refurbish, remanufacture, recycle, and disposal to landfill. Figure 2 shows the various reverse logistics value chain channels that could be taken by a product that is returned by the customer.

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Insert Figure 2 about here

---

The first option is to sell the product as a used product if it meets sufficient quality levels. In this case, the product would need to be cleaned and repaired to working
order. Product repair involves fixing and replacement of broken parts. Repair operations can be performed at a manufacturer controlled repair center. The next option is to sell the product as a refurbished unit. The product does not lose its identity and is brought back to a specified quality level. Sometimes, refurbishing is combined with technology upgrading by replacing outdated modules and parts with technologically superior ones. Military and commercial aircrafts are good examples where the refurbishing significantly improves their quality and extends their service-life. The third option is to remanufacture. In this option the product will enter the reverse channel at the fabrication stage where it would be disassembled, remanufactured, and reassembled to flow back through the retail outlet back to the consumer as a remanufactured product. The purpose of remanufacturing is to bring the used products up to quality standards that are rigorous as those for new products. The fourth option is to recycle. In this option the product will most likely enter the reverse value channel in the raw material procurement stage where it may be reutilized with other raw materials to produce the virgin materials after some initial processing. In recycling, the identity and functionality of products and components is lost. The main purpose of recycling is to reuse materials from used components and products. The last option is disposal. The general goal for any value channel is to keep all materials within the channel and thus minimize any flow into the external environment. In this case, the only strategy that conflicts with this goal is that of disposal. This is the last option that has to be either eliminated or minimized. The correct choice may be dictated by economics and by the condition and age of the product being returned.

In the context of electronic product recovery supply chains, some of the common options include reuse, refurbishment, component recycling or material recycling that
involves some of the generic tasks associated with demanufacturing and remanufacturing. In demanufacturing, tasks include simple sorting, disassembly to various levels of subassemblies, or material separation to various purity levels (Ammons et al.). Remanufacturing includes the process of collecting a used product or component, assessing its condition, and replacing worn or obsolete parts with new or refurbished parts. In this case the identity and functionality of the original product is retained and the process of remanufacturing does not degrade the overall value of the materials used (Linton and Jayaraman, 2005). We now discuss an electronic assembly product recovery strategy at XYZ company and provide a comprehensive figure of the various disposition options that exist at this company.

3.1 Case study - Electronic Assembly Product Recovery at XYZ company

We now present a case study on XYZ company (We’ve disguised the name of the company due to the non-disclosure agreement that we’ve signed with this company) which is an international consumer electronics company that deals with product returns on a daily basis. The majority of product returns comes from overstocks and lack of customer satisfaction. The rationale for consumer returns includes factors such as lack of compatibility and consumer behavior (rentals, regret, or a lower price). The return rates are also strongly influenced by seasonality and end-of-life for individual product models. For XYZ, resellers and end users are major sources of product returns. Consumers may return products for a variety of reasons - this includes inadequate knowledge about the characteristics of the product purchased (speed, compatibility, quality, etc.), regret about purchase or due to manufacturing defect. Resellers also
return products because of overstocks and due to consumer returns. If a product is returned in an open carton (seal is broken), XYZ must treat this product as a defective item and assign it to testing and refurbishment. Major functions of the test and refurbishment facility include sorting, testing, repairing and refurbishing. A significant portion of items tested are found to be new items where the carton has been opened by a reseller to avoid stocking fees. If the product received at the test and repair facility is obsolete, then it is promptly dispatched to a scrap and recycling vendor for disposition.

We now present a comprehensive figure that represents a variety of reverse flows occurring at different stages of the electronics assembly product recovery that was observed at XYZ company.

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Insert Figure 3 about here
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The various disposition decisions are marked along each arc (representing a flow) that connects a pair of locations. It is assumed that the product has already traveled through the forward supply chain phase and is currently in the hands of the customers to be returned. Some of the issues addressed by this comprehensive model include: 1) Which locations to use (from a given set) for the reverse logistics network? 2) Among these potential locations, which do you use for collection, storage, processing and sales to maximize net revenue?; 3) Which modes of transportation to use to ship product from one site to another?

The objective of this model is to maximize net profit. Once the product reaches the centralized returns center (CRC), it is processed at a sorting center that is operated by a
third party provider under contract. In the sorting center, the provider physically verifies the returns and either sends them as an "as is" product (products may be new and never used) or returned product to a sales site in a forward distribution channel to be sold to customers or sorts them into waste to be sent to a landfill. The first transaction that occurs at the XYZ company is issuance of credit where the returns are verified and credit is issued to the retailer. At the sorted facility, products are sorted by type and model, labeled and shipped to the appropriate facility. Upon sorting, the sorted waste is sent to the landfill or the sorted product is sent to a material refurbishing site for further processing and disposition. Diagnostic tests are performed to determine the appropriate disposition option that recovers the maximum value from the returned product. A significant portion of products tested (approximately 15 percent) is found to be new items where the carton has been opened by a reseller to avoid restocking fees. If found cost effective, products are remanufactured and sold in the secondary market to a consumer or segment that is unable or unwilling to purchase a brand new product. If products are not cost effective to be remanufactured, the parts are either recycled or sold as scrap in the marketplace. Considering the short life cycle for consumer electronics, the time spent to process and sort returned products and decide on the appropriate disposition option is quite lengthy. In the next section of the paper, we provide an efficient heuristic solution procedure to tackle the problem that a company such as XYZ faces in this reverse logistics environment.
4. HEURISTIC SOLUTION PROCEDURE

In this section, we provide the model parameters and data input for the model that appears in figure 3. All the base numbers were grounded on returns volume for XYZ company and other model parameters are varied over a wide range. Let set I represent the set of possible locations to conduct sorting, refurbishing and recycling; set J represent different product types; set T represent different time periods; set P represent different processes including sorting, refurbishing and remanufacturing; and set M represent different modes of transportation.

Heuristic development philosophy

A company such as XYZ has to handle a significant number of returns on a monthly basis. It is possible to model the above problem as a mathematical programming model that can incorporate all the key parameters and decision variables. Given the problem structure, it is highly unlikely that standard mathematical programming packages can currently find the optimal solution for this problem. Further, due to the large number of variables and constraints, any model might be intractable beyond a certain problem size. Therefore, a computationally efficient heuristic is necessary for solving large problems by exploiting some features of the problem in developing an efficient, albeit not guaranteed, optimal solution procedure. Solution speed is important in the sense that the analysts need to experiment with the formulation to gain insight.

Upon examining the problem structure, one can visualize that possible simplifications involve (1) aggregating across the time dimension and (2) aggregating
across the process dimension. Other possible aggregations—across products and sites—would destroy the most basic features of the problems structure and are therefore not considered. Aggregating across time implies a network flow formulation, whose solution times are very fast. Thus, our core approximation that is common to all of our heuristics involves converting the problem into a two-stage solution of continuous-variable linear programs that includes: (1) an LP model that finds the best transportation links to handle product flow from site-to-site (or, perhaps, recommending a site sells what it produces) based on some criteria, and (2) based on the optimal decision variables from (1), deductively determining which sites to open/close, and then through linear programming determining how much of each product type to flow amongst the sites.

In this section we provide three heuristic procedures (Transportation Problem (TP), Profit Max, and Circular Profit Max). One can simplify the problem structure into a transportation problem by viewing each site as both a source and sink node, and manipulating capacities to form supply and demand bounds for each site-product combination—the maximum of the collection, storage, and processing capacities becomes the supply upper bound, and the demand lower bound is a receiving site's sales capacity. Since a transportation problem is a cost minimizer, we ignore sales price and aggregate these costs to match the dimensions of our decision variable unit product flow from origin to destination site via a particular transportation mode. This includes the distance-based unit transportation cost, unit-based processing cost, unit-based collection costs and unit-based storage costs at both sites. The appendix provides the
details for the model parameters and decision variables that we use in the three heuristic procedures.

4.1 Transportation Problem (TP) Heuristic

The TP heuristic first solves a transportation problem, which is less cumbersome compared to other types of similar problems, and uses the resultant decision variable flows to fix the binary variables for a solution to the original problem. For instance, processing will not be allowed at a site if the transportation problem indicates that no flow will pass either in or out of that site-product combination. Let set I represent the set of all potential facility sites, set J represent the product type, set T represent the time period, set P represent the set of processes and set M represent the set of transportation modes. The appendix describes the set of parameters that were used for this section.

**Step 1:** Solve the transportation subproblem

**TRANSPORTATION SUBPROBLEM**

\[
\begin{align*}
\text{MIN} & \sum_j \sum_i \sum_{i'} \sum_m \text{Cost}_{ijm} \ast X_{i'jm} \\
\text{subject to} & \sum_{i'} \sum_m X_{i'jm} \leq \text{Supply}_{ij} \quad \text{(for all } i,j) \\
& \sum_{i'} \sum_m X_{i'jm} \geq \text{Demand}_{i'j} \quad \text{(for all } i',j) \\
& X_{i'jm} \geq 0
\end{align*}
\]

In this formulation,

\[
\text{Supply}_{ij} = \{ \sum_i \text{CAPCOL}_{ij}, \sum_i \text{CAPSTR}_{ij}, \sum_i \sum_p \text{CAPPROC}_{ijp} \}
\]

\[
\text{Demand}_{ij} = \text{CAPDEM}_{ij}
\]
\[ \text{Cost}_{ii'm} = (\text{COSTSTR}_i + \text{COSTSTR}_{i'}) + (\text{COSTCOL}_i + \text{COSTCOL}_{i'}) + \sum_p (\text{COSTPROC}_{p_i} + \text{COSTPROC}_{p_{i'}}) + (\text{COSTTRAN}_{ii'm} * \text{DIST}_{ii'm}) \]

(for \( i \neq i' \))

**Step 2:** We convert the problem into an LP and solve by fixing its binary variables, based on output from step 1:

for all \( i \)

for all \( i' \ (i' \neq i) \)

for all \( m \)

\[
z = \sum_j X_{i'ijm}
\]

if \( z < 1 \)

\[
\text{YTRANS}_{ii'm} = 0
\]
\[
\text{YTRANSFEAS}_{ii'm} = 0
\]

else

\[
\text{YTRANS}_{ii'm} = 1
\]
\[
\text{YTRANSFEAS}_{ii'm} = 1
\]

for all \( i \)

for all \( p \)

\[
y = \sum_{i' \neq i} \sum_j \sum_m X_{i'ijm}
\]

\[
z = \sum_{i'} \sum_j \sum_m X_{i'ijm}
\]

if \( y < 1 \) and \( z < 1 \)

\[
\text{YPROC}_{ip} = 0
\]
\[
\text{YPROCFEAS}_{ip} = 0
\]

else

\[
\text{YPROC}_{ip} = 1
\]
\[
\text{YPROCFEAS}_{ip} = 1
\]

for all \( i \)

for all \( j \)

\[
z = \sum_{i' \neq i} \sum_m X_{i'jm}
\]

if \( z < 1 \)

\[
\text{YSOLD}_{ij} = 0
\]
\[
\text{YSOLDFEAS}_{ij} = 0
\]

else

\[
\text{YSOLD}_{ij} = 1
\]
YSOLDFEAS_{ij} = 1

for all i

\[ z = \sum_{i \in I'} \sum_{j \in J'} \sum_{m} X_{i'j'm} \]

\[ y = \sum_{i \in I'} \sum_{j \in J'} \sum_{m} X_{ij'm} \]

if \( z < 1 \) and \( y < 1 \)

YS\text{TOR}_{i} = 0

YS\text{TORF}\text{EAS}_{i} = 0

YCOLL_{i} = 0

YCOLL\text{FEAS}_{i} = 0

Y\text{OPEN}_{i} = 0

else

YS\text{TOR}_{i} = 1

YS\text{TORF}\text{EAS}_{i} = 1

YCOLL_{i} = 1

YCOLL\text{FEAS}_{i} = 1

Y\text{OPEN}_{i} = 1

4.2 Profit Maximization Heuristic

The cost minimizing simplification is dropped to generate the next heuristic, Profit Max. The formulations for the two-stage structure of TP are kept, with these exceptions: (1) the first-stage objective function is profit maximization, where an average unit sales price per site-product combination is obtained by averaging across the time periods, and (2) the demand constraint is treated as a lower bound. In TP, the demand constraint had to be a lower bound to conform to a transportation problem structure. But this constraint should not generate as much profit as an upper bound, which is permitted if we drop the transportation problem requirement as we do here. Since supply should never exceed demand. But it might be more profitable for supply to be less than demand when the cost to deliver a product to a site is high relative to the
sales price. Thus, in this new heuristic, relative to TP, there is a trade-off between solution speed and accuracy.

**Step 1:**

Let \( SPRICE_{ijt} = \frac{\sum_{t} SPRICE_{ijt}}{|T|} \)

where \( SPRICE_{ijt} \) is the selling price of product type \( j \) at site location \( i \) in time period \( t \).

Solve the optimization in Step 1 from the TP heuristic with these changes:

1. Let the objective function be \( \text{MAX} \sum_{j} \sum_{i} \sum_{r} \sum_{m} \left( SPRICE_{ijr} - Cost_{im} \right) * X_{irjm} \)
2. Convert the demand constraint to be an \( \leq \) constraint

**Step 2:** Identical to Step 1 in the TP heuristic

### 4.3 Circular Profit Max Heuristic

The most comprehensive heuristic, *Circular Profit Max*, builds on Profit Max by allowing a site to sell what it collects and/or produces. Otherwise, the same structure as Profit Max is used, with appropriate modifications. This is the most realistic heuristic that can be conceived in the sense that all of the problem features are modeled. All transportation cost-time elements, all site-specific elements (storage, collection and processing) and all revenue elements are modeled.

**Step 1:**

Identical to Profit Max, with these changes:

1. Permit \( i' \) to equal \( i \) everywhere
2. \( DIST_{ir} = 0 \) whenever \( i' = i \)
(3) \( \text{COSTCOL} = 0 \) whenever \( i' = i \) for both \( i' \) and \( i \)

**Step 2:** Convert the problem into an LP and solve by fixing its binary variables per the following, based on Step 1 output:

for all \( i \)
  for all \( i' \)
    for all \( m \)
      if \( (i' \neq i) \)
        \[
        z = \sum_{j} X_{i'jm}
        \]
        if \( z < 1 \)
        \[
        \begin{align*}
        \text{YTRANS}_{ii'm} &= 0 \\
        \text{YTRANSFEAS}_{ii'm} &= 0
        \end{align*}
        \]
      else
      \[
      \begin{align*}
      \text{YTRANS}_{ii'm} &= 1 \\
      \text{YTRANSFEAS}_{ii'm} &= 1
      \end{align*}
      \]

Else (don’t want to count transportation costs for a circular flow)
\[
\begin{align*}
\text{YTRANS}_{ii'm} &= 0 \\
\text{YTRANSFEAS}_{ii'm} &= 0
\end{align*}
\]

for all \( i \)
  for all \( p \)
\[
\sum_{i'} \sum_{j} \sum_{m} X_{i'jm}
\]
\[
\sum_{i'} \sum_{j} \sum_{m} X_{i'jm}
\]

if \( y < 1 \) and \( z < 1 \)
\[
\begin{align*}
\text{YPROC}_{ip} &= 0 \\
\text{YPROCFEAS}_{ip} &= 0
\end{align*}
\]

else (can now process at a site if its only out/inflow is to itself)
\[
\begin{align*}
\text{YPROC}_{ip} &= 1 \\
\text{YPROCFEAS}_{ip} &= 1
\end{align*}
\]

for all \( i \)
  for all \( j \)
\[
\sum_{i} \sum_{m} X_{ii'jm}
\]

if \( z < 1 \)
\[
\begin{align*}
\text{YSOLD}_{ij} &= 0 \\
\text{YSOLDFEAS}_{ij} &= 0
\end{align*}
\]

else (can now sell at a site if its only outflow is to itself)
\[
\begin{align*}
\text{YSOLD}_{ij} &= 1
\end{align*}
\]
YSOLDFEAS_i = 1

for all $i$

$$z = \sum_{i'} \sum_{j} \sum_{m} X_{ii'jm}$$

$$y = \sum_{i'} \sum_{j} \sum_{m} X_{ijjm}$$

$$z_1 = \sum_{i(j = i')} \sum_{j} \sum_{m} X_{ii'jm}$$

$$y_1 = \sum_{i(j = i')} \sum_{j} \sum_{m} X_{ijjm}$$

if $z < 1$ and $y < 1$

YSOR_i = 0
YSFAS_i = 0
YOPEN_i = 0

else

YSOR_i = 1
YSFAS_i = 1
YOPEN_i = 1

if $z_1 < 1$ and $y_1 < 1$

YCOLL_i = 0
YCOLLFEAS_i = 0

else (still allowed to collect if the only flows are circular)

YCOLL_i = 1
YCOLLFEAS_i = 1

In the next section, we provide the experimental data design to test the performance of the three heuristic procedures.

### 4.4 Experimental data design

All input data for application of the heuristic solution procedures are representative averages from our research base of companies dealing with end-of-life electronic assembly product recovery. In this experiment, we consider 3 potential facility sites, 2 product types, 2 modes of transportation, 3 different types of processes and 3 different time periods. The base case data for product price (SPRICE[I][J][T]) has significant variation over time, by product, and across the sites. Price in time period two is 80% of
the price time in time period 1 and the price in period three is 80% of the price in period two. Storage charges vary by site. \(\text{COSTSTR}[I]\) is 2, 2.4, and 1.6 for sites 1, 2, and 3, respectively. Collection charges \(\text{COSTCOLL}[I]\) equals the storage charges by site. Processing charge \(\text{COSTPROC}[P][I]\) by site is equal to site's storage charge. The per unit distance transportation cost varies by transportation mode. We consider location 1 to be 10 units away from location 2 and 20 units away from location 3 while location 2 is 15 units away from location 3.

The test cases were selected to test the heuristics on the two areas of simplification upon which they were built: time and process aggregation. The stage one formulation is the foundation for all of the heuristics. In the heuristic, we use three different setting for \(\text{CAPPROC}_{ipt}\) (represent the maximum capacity for processing at site \(i\) using process \(p\) in a certain time period \(t\)) in order to perform some sensitivity analysis on the problem parameters. The three settings are (1) all 5s for the base; (2) 1-5-9 as the time period increases; and (3) 9-5-1 as the time period increases. The 1-5-9 sequence was selected to induce maximum variability with respect to time on capacities—the capacity in the last period is nine times the first period’s capacity, with the middle period having a mid-range capacity. The 9-5-1 sequence has the same capacity spread, but in reverse time sequence. Increased variability of exogenous variables with respect to process type was accomplished via multiplying the base case \(\text{COSTPROC}_{pi}\) (represents the processing charge per unit at site \(i\) per unit time period) parameters by 0.8, 1.5, and 1.0 as the process type moves from 0 to 2, respectively.
Thus, to summarize, case 1 is the base case. Cases 2-3 represent the 1-5-9 and 9-5-1 representations of CAPPROC_{ipr}. Case 4 represents the 0.8-1.5-1.0 representation of COSTPROC_{pi}. Thus, cases 2-3 represent varying the process capacity variable, holding all else constant while case 4 represents varying the process unit cost variable, holding all else constant. Finally, cases 5-6 combine the process capacity and process unit cost factors in interactive ways. Case 5 is like case 4 with respect to process unit costs and case 2 with respect to process capacity; however, the process capacity variability is increased even further by applying the specific process multipliers from Case 4 to each process represented in the capacities. Case 6 does the same as case 5 except process capacity that is similar to case 3. In summary, this sensitivity analysis over key parameters is similar to a full factorial design with two factors in which all main effects and interactions are accounted for.

4.5 Computational results

The heuristic solution was coded in Microsoft Visual C++ 6.0 and CPLEX 9.0 was used for the network and linear programming solutions. The Windows XP operating system was used. The series of computational experiments was carried out using all three heuristic procedures. In this paper, we report the results for all three heuristics across the six cases that were reported in the experimental design section.
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<th></th>
<th>TP</th>
<th>Profit Max</th>
<th>Circular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>218,355</td>
<td>136,475</td>
<td>136,475</td>
</tr>
<tr>
<td>Case 2</td>
<td>209,472</td>
<td>95,272</td>
<td>147,275</td>
</tr>
<tr>
<td>Case 3</td>
<td>234,144</td>
<td>52,456</td>
<td>125,675</td>
</tr>
<tr>
<td>Case 4</td>
<td>231,125</td>
<td>79,140</td>
<td>76,690</td>
</tr>
<tr>
<td>Case 5</td>
<td>221,463</td>
<td>102,917</td>
<td>96,637</td>
</tr>
<tr>
<td>Case 6</td>
<td>240,786</td>
<td>55,902</td>
<td>53,742</td>
</tr>
</tbody>
</table>

On the surface, the TP dominance over Profit Max seems unusual since Profit Max models provide more realism—adding revenue to the objective. But this profit reduction is due to the fact that the revenues in Profit Max are based on average sales prices across the entire time horizon. Since there is much variability in these prices over time, making decisions based on average prices is very misleading: incorporating price into the heuristics makes the results worse since the prices are very time-dependent and the heuristics ignore the time dimension. Thus, it is better to focus on cost minimization rather than incorporating time-averaged prices into a profit maximization. This time-averaging problem also explains why the Circular heuristic procedure is outperformed by Profit Max for Cases 5-6; allowing more origin-destination options in Circular is more than offset by analyzing these options with misleading prices.

5. MANAGERIAL INSIGHTS

There are several managerial insights that we gained from our interaction with company XYZ in addition to the results that we obtained from the application of the heuristic solution procedure. It is clear that in any reverse logistics flow, it is critical to obtain the highest value possible for the products that are returned in the reverse supply chain. It is also important to pick and choose between various disposition
policies the one that is going to provide any company the “bang for the buck.” One key insight is to build centralized return centers. Centralized return centers seem to be a popular reverse logistics strategy where all products returned are sorted, processed and then shipped to their next destination. There are several benefits that companies can accrue by using this strategy. They include, **Consistency**: By collecting returns at a central depot, the company can make more consistent decisions about product disposition. This would lead to more standardized processes and efficient sorting processes for products; **Improved customer service**: The centralized return depots can speed the reconciliation process, improve material authorization and issuance of credit and also serve as a good marketing strategy to gain customer loyalty; **Compacting of disposition time**: Centralized return centers tend to expedite flow of materials in the reverse logistics pipeline. The disposition of returned products to a centralized return centers makes it somewhat easy to determine whether a returned product may be reused as is, remanufactured, disassembled for components and parts or recycled.

The most effective way to avoid any costs of product returns is of course to prevent returns from occurring. Since product returns are unlikely to be eliminated, companies such as XYZ need to effectively design their reverse logistics and recoverable processes. One factor to focus on is perhaps the cycle time required to identify, transport and make disposition decisions. The key objective is to have a returns facility where returned products are unloaded, entered into the database and disposed, all in one continuous step. The current strategy required the products to wait until the boxes are opened, resealed and reopened. Products are often waiting for protracted periods of time in large inventory holding areas. It is important to realize that such product returns are perishable assets. Hence the percentage of value that can be recovered from
such assets is directly proportional to the speed of disposition and recovery of returned products. Hence, companies such as XYZ need to make time the key performance metric.

The objective of asset recovery is to recover as much of the economic value as is reasonably possible. This would lead to reduction in the amount of products that go to a landfill. There are several criteria to consider: a) Economic best use – Companies such as XYZ need to design a program that can quickly recover and resell the returned products as refurbished, recover and use the products in various support processes, disassemble the products into components for internal use such as spare parts, resell “as is” and recycle the remaining products’ b) Product life cycle – Companies and businesses in this environment have just begun to learn that the largest portion of their profits is derived from the early stages of the product life cycle. This key insight makes proper disposition even more critical as an option such as reuse generates more profits across the entire lifecycle of the product. The product development cycle for consumer electronics is diminishing at a rapid pace and is placing significant demands on the product returns process. It is important for companies in this industry to decrease the lead time that it takes to process returns so they can maximize the value that can be obtained from such returns. Product returns process cannot be designed as an afterthought. While the volume of product returns is bound to grow worldwide, partly due to laws pertaining to producer responsibility and customer service considerations, it is critical for companies to explicitly consider requirements for product reuse and product return channels during the design phase of new product development.
6. **SUMMARY AND CONCLUSIONS**

Companies operating in this environment must have an effective, responsive reverse logistics strategy incorporated into its traditional supply chain system because of the short life cycles of their products. The reverse flow of products is more difficult to manage owing to the inherent uncertainty and the critical need for timely, cost efficient operations. Because products being returned for any reason must be treated as perishable assets, delays in handling such returns may limit the options for such returned products, and as a result, reduce cash flows. For many companies, product returns process has been designed as an afterthought. Since product returns are bound to grow in volume in part due to customer service considerations and laws pertaining to producer responsibility, this requires firms across such industries to consider the requirements for product reuse and product channel returns during the initial design phase of new product development. Efficient reverse logistics strategies should be part of the overall business strategy for any manufacturer or retailer. Electronic assembly product recovery centers face complex materials separation decisions while there is an urgent need to balance between holding and processing costs and fluctuating commodity markets for recovered materials from electronic products. In this paper, we have provided an effective procedure to tackle a problem faced by the electronics industry. We have shown that reverse product flow offer unique opportunities for firms to create additional shareholder wealth. It is important to recognize the significant value remaining in product returns and their sensitivity to time that exists in such
reverse logistics supply chains. We hope that this study provides the basis for future research into more effective reverse supply chain systems.

References


6) EPA - U.S. Environmental Protection Agency, 1997, EPA 530-R-97-015


APPENDIX

Let $\text{CAPCOL}_{ijt}$ represent the upper bound capacity for collecting a product $j$ at site $i$ in a certain time period $t$, $\text{CAPSTR}_{ijt}$ represent the maximum capacity for storing product $j$ at
site i in time period t, CAPPROC_{ipt} represent the maximum capacity for processing at site i using process p in a certain time period t and CAPDEM_{ij} represent the maximum capacity for selling product of type j at site location i. Let COSTSTR_i represent the storage cost per unit at site i per unit time period, COSTCOL_i represent collection charge per unit at site location i per unit time period. COSTPROC_{pi} and COSTPROC_{pi'} represent the collection charge per unit for process p at site i per unit time period and at site \text{i'} respectively, COSTTRAN_{i'i'm} represent the transportation cost per unit time from site i to site \text{i'} using transportation mode m (this will also apply to the materials and parts extracted from product j and transported to a different site) and DIST_{i'i'm} represent distance traveled from site i to site \text{i'} using transportation mode m. The decision variables for this problem include: $X_{i'jt}$ that represents the quantity of product flow j from site i to site \text{i'} using transportation mode m, $Y_{TRANS_{i'i'm}}$ that is a binary variable which is equal to 1 if transportation is performed between i and \text{i'} using transportation mode m, $Y_{TRANSFEAS_{i'i'm}}$ is a binary variable which is equal to 1 if product flow is allowed between site i and \text{i'} using transportation mode m, $Y_{PROC_{i'p}}$ is a binary variable which is equal to 1 if process p occurs at site i and $Y_{PROCFEAS_{i'p}}$ is a binary variable which is equal to 1 if process p is allowed to occur at site i, $Y_{SOLD_{ij}}$ is a binary variable which is equal to 1 if product j is sold at facility site i, $Y_{SOLDFEAS_{ij}}$ is a binary variable which is equal to 1 if product j can be sold at facility i, $Y_{STOR_{i}}$ is a binary variable which is equal to 1 if we store the product at site location i, $Y_{STORFEAS_{i}}$ is a binary variable which is equal to 1 if products can be stored at location i, $Y_{COLL_{i}}$ is a binary variable which is equal to 1 if site location i collects the products, $Y_{COLLFEAS_{i}}$ is a binary variable which is equal to 1 if site location i is a collection center, and $Y_{OPEN_{i}}$ is another binary variable which is equal to 1 if site location i is open.
Figure 1: The Electronics Supply Chain

Source: U.S. Bancorp Piper Jaffray Equity research - Electronics Manufacturing Supply Chain
Figure 2: Different reverse logistics value chain channels for product returns
Figure 3 - Flow Diagram - Disposition decisions

Reverse Logistics Process Steps
1. Collection (at the origin site)
2. Collection (at the collection sites)
3. Sorting (at the collection sites)
4. Disposition

Disposition Decisions
1. Return to vendor
2. Sell as New
3. Sell via Outlet, Discount, or Secondary Markets (Symetecnished product or parts)
4. Sell recycled materials
5. Refurbish
6. Recycle
7. Landfill

Model Inputs
1. All Costs (transportation, storage, fixed, etc.)
2. Potential site locations (collection, sales, refurbish, vendor, disposal, etc.)
3. Potential modes of transportation
4. Capacities (transportation and storage)
5. Sales prices (new, used, parts, and materials)