International Journal of Environmentally Conscious Design & Manufacturing, Vol. 11, No. 4, 2003-04
Printed in the U.S.A.

REPACKAGING: AN OPPORTUNITY FOR ENVIRONMENTALLY CONSCIOUS MANUFACTURERS

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The environmentally conscious design and manufacturing hierarchy is an important component of sustainable development. One of the tenants of this hierarchy promotes waste minimization prior to recycling. For such products as electrical and electronic hardware, and for products, which contain hazardous materials, waste minimization is an important means of reducing the volume of life cycle waste and reducing the exposure of hazardous substances to the environment. Numerous integrated repair and recycling centers exist which seek to exploit opportunities to reuse products before recycling them. Nonetheless, in situations where products are of low value, little support exists in helping such integrated facilities to recover salvageable products from damaged products for repackaging or recycling. In this paper, we present a case study in which we apply a new decision-making tool to manage inventory, which may be either repackaged or recycled. With a collaborator who repackages fluorescent lamps salvaged from damaged packaging, we demonstrate the tool's ability to significantly reduce waste and simultaneously reduce the consumption and exposure of mercury to the environment.

INTRODUCTION

The environmentally conscious design and manufacturing hierarchy is prevention, minimization, extended use, reuse, materials recycling, incineration, and disposal [1]. Environmentally conscious design and manufacturing hinge upon the reduction or elimination of hazardous waste streams that return to the environment. This paper focuses on methods to minimize waste and decrease disposal through product take-back. A case study is presented for products containing hazardous materials. In this paper, recycling and recyclers refer to the process and companies respectively that focus on materials separation.

Currently, products are returned due to warranty returns, damage during distribution, customer dissatisfaction, expiration of leases, and end-of-customer-use. Extended producer responsibility legislation is being considered or implemented in several regions [2-4]. Due to increasing global distribution networks, products are transported further by multiple methods prior to their final point of sale. As a result, manufacturers have the opportunity to apply waste minimization by recovering products and materials from damage during distribution.

Product take-back centers receiving products damaged during distribution may repair, repackage, and/or separate materials for reuse. If a product take-back center only repairs and repackages products for resale, then it partners with materials recovery companies to process products that it cannot repair or sell. For example, recycling companies may specialize in recovering metals [5-7], plastics [8, 9], or glass [10, 11].

In practice, a significant number of reusable products are sent to disposal or materials recycling due to poor inventory management. Often, recyclers and refurbishers are not equipped to track inventory in detail. Since many of the products, which these facilities handle, are of low value, integrated repair and recycling centers have not installed advanced inventory management systems. As a result, the inventory that recyclers possess may be tracked by general product type such as 14” monitor, rather than the level of detail of each specific product model.

Unfortunately, a lack of good inventory information makes it difficult for operators to ensure that the products on hand are returned to the highest viable level of the environmentally conscious design and manufacturing hierarchy. Furthermore, even if sufficient historical data exists to identify or develop trends in inventory requirements, no tools exist for inventory management and production planning for low-value product returns. In order to manage more effectively the inventory awaiting processing within an integrated repackaging and recycling facility, a tool is needed to track this pre-processing inventory as it arrives, and make use of available historical data to quickly and inexpensively determine the most appropriate disposition of the arriving products. A new tool is needed to help manufacturers manage low-value returns inventory that does not warrant the installation of such inventory management equipment as barcode scanners and individual tracking numbers [12].

In this paper, we discuss the application of our tool as developed in [13] to an integrated repackaging and recycling operation that specializes in the recovery of mercury from fluorescent lamps. In the operation studied, end-of-life lamps arrive for recycling. In addition, new salvageable and non-salvageable lamps arrive mixed in casepacks damaged during forward distribution operations. An important term in packaging, the casepack, is defined as a sealed case of a single product type of a specified count designated by a unique stocking number within its product category. The objective in this paper is to demonstrate a new tool that will help manufacturers minimize waste by increasing the number of products repackaged in an integrated repackaging and recycling operation. The tool determines which salvageable lamps to store to await future new lamp arrivals in order to increase the number of full casepacks repackaged. This problem is similar to the repair problem that requires product storage until a spare part randomly arrives from another damaged product. In both cases, new spare parts may not be purchased. We demonstrate the ability of this tool to increase the repackaging of returned casepacks of fluorescent lamps.

Approximately 550 million lamps are sold annually in the United States that contain mercury; over 90% of this volume consists of fluorescent lamps, and an equal volume of fluorescent lamps is discarded every year, representing 3.8% of the total mercury handled by the municipal solid waste stream in the U.S. [14]. A typical fluorescent lamp contains 15 to 25 mg of mercury, but newer low-mercury lamps contain only 5 to 7 mg. Nonetheless, the lamps disposed equate to approximately 26.9 tons landfilled annually, and another 15 tons per year emitted via the incineration of municipal solid waste [15]. Therefore, the repackaging, use and recycling of fluorescent lamps presents an opportunity to reduce the amount of mercury, which is not reclaimed from the solid waste stream in the U.S.

LITERATURE REVIEW

Most researchers have approached product take-back modeling by analyzing how to process a single product optimally. To analyze the level of disassembly for a specific product, researchers have developed cost models to determine the level of manual disassembly to recover subcomponents and materials [16-19]. A single product approach is extended to handle multiple products in [20]. [21] developed a goal programming approach to maximize profits for automotive disassemblers and shredders. [22-26] present inventory models for remanufacturing, manufacturing, and procurement. These data-intensive approaches are useful in analyzing high-value product returns such as aircraft engines, automobiles, or mainframe computers. However, they are not practical tools for low-value product returns.

Shahinpoor and Lantz propose a robotic method for recycling fluorescent lamps and contrast it with more common methods of crushing and separating lamps as part of a Life Cycle Analysis of fluorescent lamps [15]. Combining our proposed methodology for repackaging with the methodology for recycling in [15] will improve the use and recovery of mercury from fluorescent lamps.

The product take-back center should not make decisions about recovery by only considering the product's **intrinsic** characteristics. Rather, the product take-back center should also consider the current status of product inventory and recent history of product arrivals. In this paper, we present a case study demonstrating a new decision tool that allows the integrated product repackaging and recycling center to manage inventory and processing decisions from a **systems** perspective, but with practical levels of data and computation since the system may receive nearly a thousand different types of lamps each year. Next, a description is provided of the components of the new decision tool modeled in detail in [13].

With the decision tool illustrated in Figure 1, decisions are classified by two categories: tactical and operational. The tactical decision planning is based on the historical arrival frequencies and quantities, packaging sizes, and space constraint in the HF (high frequency) integer-programming model to determine the set of high frequency products F. The tactical decision to define set F may be updated monthly, quarterly, or annually depending on the truckload arrival frequency over time. The operational decisions are made by the SR (store versus recycle) algorithm based on the current arrival quantities, inventory, the set of high frequency products F, packaging sizes, and space constraint to determine which products to repackage, recycle, or store for future repackaging.

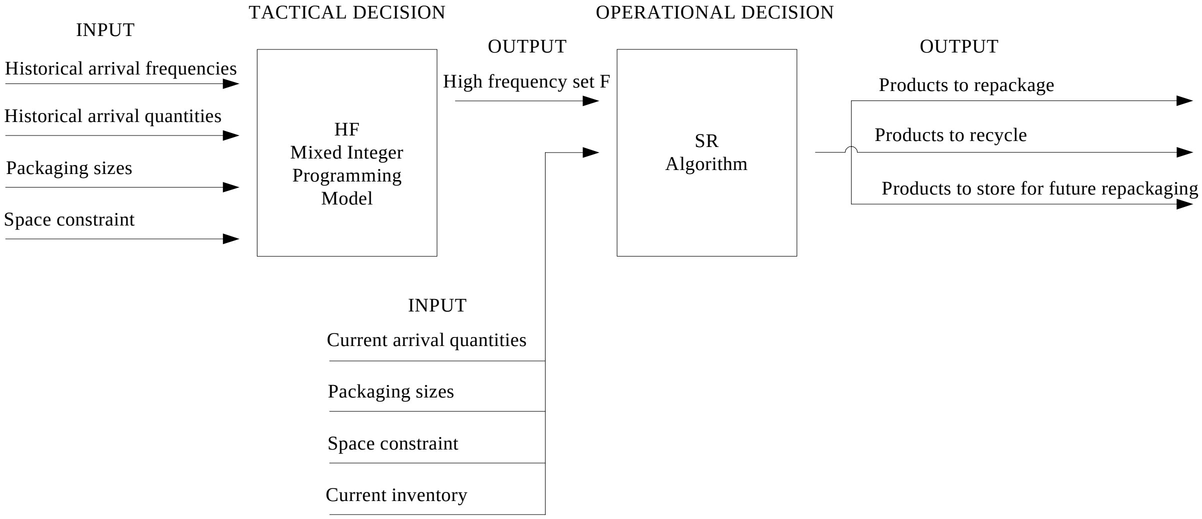


Figure 1: Decision Tool for Repackaging Inventory

To test the decision tool, the authors conducted a computational study using data from an industrial collaborator who repackages lamps for manufacturers. The industrial collaborator expressed interest in testing the tool on its regular operation. In the next section, the construction of the decision tool and the test results are presented.

DEMONSTRATION OF NEW METHODOLOGY

For this study, the authors collaborate with an industrial recycler of fluorescent lamps. The firm specializes in retorting fluorescent lamps to remove mercury; the remainder of the base materials is also recovered and recycled. The collaborator receives used lamps from many different customers for recycling. In addition, the collaborator also receives damaged casepacks of new lamps from manufacturers, salvages the remaining operable lamps, and in turn places those lamps into new packaging. The facility receives truckload quantities of pallets, which contain a random assortment of stock-keeping units (SKU) of lamps; a detailed inventory of the shipment containing SKU and quantity information known as a "bill of lading" is also included. The facility handles over 800 different product

SKUs for lamps. Additionally, the arriving product SKUs vary greatly in kind and quantity with every shipment. As a result of this variability in arriving shipments and the customers' requirement that only full casepacks of each product be returned, the potential for salvageable lamps varies widely between shipments.

Due to space constraints and the desire to maximize the number of lamps salvaged for use, if an insufficient number of salvageable lamps of a given product arrive in a shipment, the decision must be made whether to store that product until the next inbound shipment is received, or to send that product to recycling. Currently, the collaborator has no formal procedure for deciding which products to store and which to recycle. Decisions are made at the operator level relying exclusively upon personal knowledge and experience. Operator experience is sufficient that they are able to judge approximately how many returned casepacks of a given product are needed to produce one full casepack of salvageable lamps. As a result, the operators can efficiently sort out those products, which are not present in sufficient quantity to be repackaged for use. Commonly, personnel save all of the incomplete casepacks as long as space is available in storage regardless of the product's arrival history. Once the storage space is full, however, any new arrivals are generally recycled, again without regard to arrival history.

Besides the previously-mentioned arriving truckload bills of lading, the collaborator also produces outbound bills of lading for all products which have been salvaged and repackaged. Unfortunately, while such historical data is available for all of the products seen to date within the repackaging and recycling operation, no decisions are made using the information. In the next section, we will use the collaborator's data in our decision tool to demonstrate how it may increase the level of reuse and decrease handling and holding costs without requiring capital investments for space or processing capacity.

Setting up the Decision Tool

Building the decision tool first requires classifying products as high or low frequency. The HF model, a mixed integer programming model illustrated in Figure 1, aids this tactical decision. The HF model seeks to maximize the number of lamps repackaged subject to the historical product arrival data and the space capacity. We use the output from the HF model to define a high frequency set of lamps.

Our industrial collaborator supplied data for six truckloads which arrived at approximately one truckload per month. We treat each truckload as a period in the HF model. In the historical data, 400 products arrived zero times in the six-month period so they were automatically assigned to the low frequency set. With space capacity for 750 lamps and six months of historical data on arrival frequency and quantity, the HF model selected 170 products as high frequency. Model HF assigned 230 products arriving at least once in the six-month period to the low frequency set. The results of the tactical decision model are summarized in Tables 1a and 1b.

Table 1a: Breakdown of Product Frequency Classifications from Model HF with Space Capacity 750

Product frequency classification	Arrival frequency in six truckloads	**No. of products assigned**
"High Frequency" Set	≥ 2	170
"Low Frequency" Set	≤ 2	630

Table 1b: Breakdown of "Low Frequency" Set with Space Capacity 750

Arrival frequency in six truckloads	**Number of products**
2	38
1	192
0	400

We further analyze the bills of lading data for the six truckloads using the high-frequency product set F defined by model HF at a storage capacity of 750 in Table 2. We find that the low-frequency lamp arrivals were 18% of total salvageable lamp arrivals. When completed casepacks from each truckload are subtracted from the salvageable lamp arrivals, less-than-casepack low-frequency lamp arrivals were 53% of the total less-than-casepack lamp arrivals. The data in Table 2 demonstrate that low-frequency lamp arrivals pose a significant problem for the original approach since they result in storage of lamps without regard to expected duration of stay.

Table 2: Bills of Lading Data Summary for 6 Truckloads

Description	**No. lamps**
Total number of salvageable lamps received	38976
Total number of salvageable lamps received that are classified high frequency by Model HF when storage capacity is 750	32102
Total number of salvageable lamps received that are classified low frequency by Model HF when storage capacity is 750	6874
Total number of less-than-casepack arrival quantities of salvageable lamps	9331
Total number of less-than-casepack arrival quantities of salvageable lamps that are classified high frequency by Model HF when storage capacity is 750	4397
Total number of less-than-casepack arrival quantities of salvageable lamps that are classified low frequency by Model HF when storage capacity is 750	4934

Once the high frequency set is defined, the operators may use the SR algorithm to make each store versus recycling disposition decision. Table 3 summarizes the logic for our decision algorithm. All products arriving are considered for repackaging according to their arrival quantity. Less-than-casepack arrivals for the high frequency products are subject to a storage-versus-recycling disposition decision. Less-than-casepack arrivals that are classified low frequency are automatically sent to recycling. Storage decisions are subject to storage space availability. Further details of the SR Algorithm are discussed in [13].

Table 3: Summary of SR Algorithm Logic for Storage vs. Recycling Decisions

Logic for each salvageable product	**Disposition decision**
Question 1: Is each product from truckload in sufficient quantity to repackage?	Yes → Send to repackaging
	No → Go to question 2
Question 2: Is product in the high frequency set F?	No → Send to recycling
	Yes → Go to question 3
Question 3: Is there empty storage space?	No → Send to recycling
	Yes → Go to question 4
Question 4: Rank products from set F in ascending order by number of lamps required to join with existing inventory to complete a casepack.	Send set F products to storage in ranked sequence until storage space is filled; send remaining products to recycling.

Even if the process personnel attempt to make storage decisions from memory, they would have to be familiar with 170 different products by SKU. Furthermore, as practice has shown, when no intelligent storage decisions are made, the 630 different products that are classified as low frequency quickly block the storage space over the long run.

Constructing the Decision Tool

The operational decision tool can be constructed and updated within an Excel spreadsheet or program. If the tool is implemented in a spreadsheet, then a database may be constructed within the spreadsheet to store all available information that can be tracked by product in a dedicated record for that product. By formatting the database in this manner, a single query returns all of the values necessary for assigning disposition, plus any other desired information pertinent to that product. The query is performed automatically as information is entered into the spreadsheet, and the operator needs only to record the part number and received quantity of unit loads associated with each product. For this study, the operational decision tool is programmed in Java [27]. The tactical decision model, Model HF, is successfully run on a desktop PC running Windows ME with a 1.0 GHz Pentium 3 processor while the original and SR algorithms are successfully run on a desktop PC running Windows XP with a 2.52 GHz Pentium 4 processor.

Results

We run our program for the new decision tool with the data summarized in Table 2. There are eight possible disposition scenarios for high and low frequency products.

1 - a high frequency product arrives in exactly salvageable casepack quantities that are repackaged

2 - a high frequency product arrives in both salvageable casepack quantities that are repackaged and a less-than-casepack quantity that is recycled due to the space constraint

3 - a high frequency product arrives in both salvageable casepack quantities that are repackaged and a less-than-casepack quantity that is stored

4 -a high frequency product arrives in only less-than-casepack quantity that is recycled due to the space constraint

5 -a high frequency product arrives in only less-than-casepack quantity that is combined with inventory for repackaging and/or stored

6 -a low frequency product arrives in exactly salvageable casepack quantities that are repackaged

7 -a low frequency product arrives in both salvageable casepack quantities that are repackaged and a less-than-casepack quantity that is recycled

8 -a low frequency product arrives in only salvageable less-than-casepack quantity that is recycled

Table 4 illustrates seven of the eight scenarios as they occur for the fifth truckload. Since the arrival rates are approximately one truckload per month in the operation we studied, Table 4 also illustrates the results for the fifth month. The frequency class is designated low or high. The inventory represents the lamps in storage at the end of the fourth truckload (or month). In Table 4, the operator mod( ) represents the remainder from a division operation. For example, $\mathrm{mod}\left(\frac{9}{4}\right)=1$. A storage versus recycle decision is indicated when there is a less-than-casepack quantity remaining after repackaging incoming lamps and lamps stored from the previous truckloads. Scenarios 1-5, 7 and 8 are illustrated in Table 4; scenario 6 did not occur for the fifth truckload.

Table 4: Examples of Storage vs. Recycling Disposition Decisions with the New Tool

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Product No.	Case-pack Size	Frequency Class	Inventory at the end of the fourth truckload	Total lamps arriving in truckload 5	Cases repacked from (5)	Cases repacked from (4) and (5)	Storage decision if $\bmod\left(\frac{(4)+(5)}{(2)}\right)>0$	Scenario
36	15	High	0	105	7	0	----	1
13	30	High	0	168	5	0	Recycle	2
27	15	High	14	49	3	1	Store	3
52	24	High	0	11	0	0	Recycle	4
119	25	High	8	23	0	1	Store	5
138	30	Low	0	56	1	0	Recycle	7
192	25	Low	0	12	0	0	Recycle	8
63	25	High	0	140	5	0	Recycle	2
136	15	High	0	28	1	0	Store	3
249	40	High	0	19	0	0	Recycle	4
177	15	High	0	14	0	0	Store	5
149	15	Low	0	35	2	0	Recycle	7
261	24	Low	0	11	0	0	Recycle	8

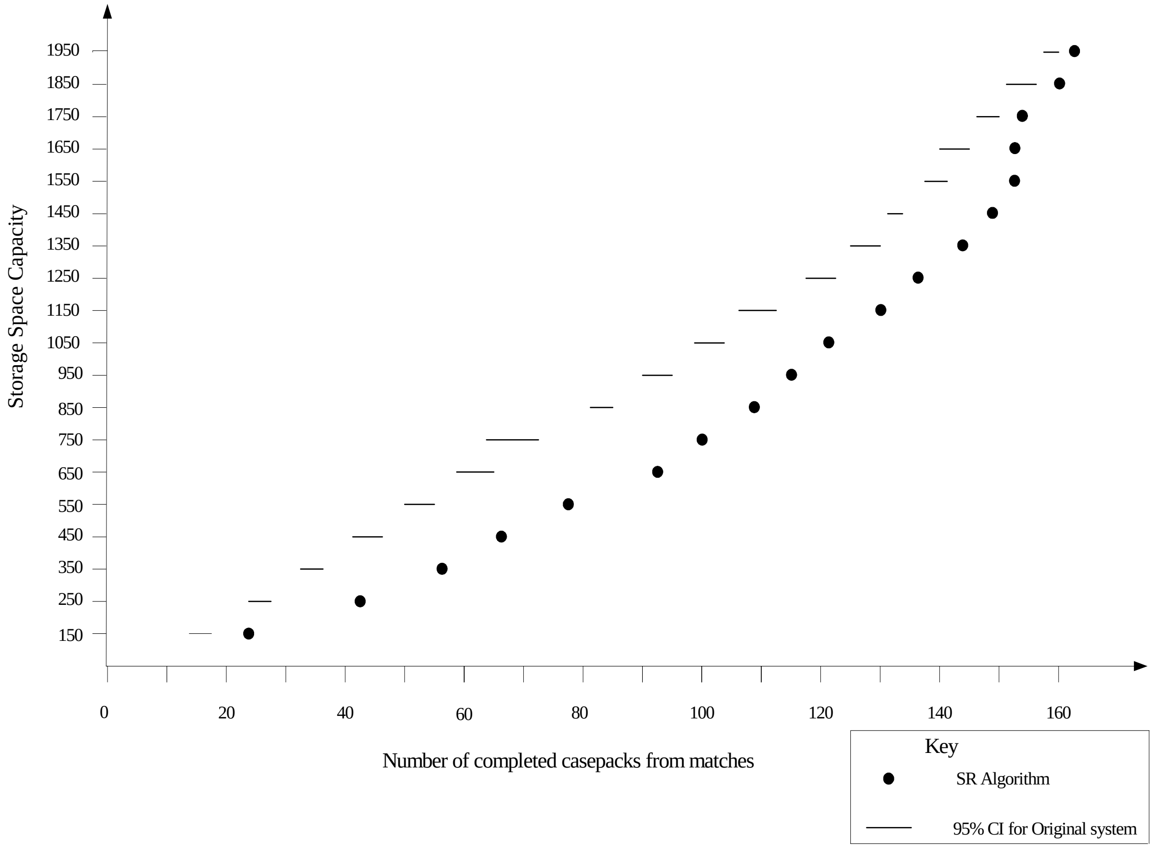
We compare the original and new approaches in Table 5. For the original method in Table 5, storage versus recycling decisions are made on a truckload of products in a random order. The minimum, mean, maximum, and standard deviation are calculated from 20 replications with the Original approach because the storage decisions are random with the operator-guided approach. For our new decision tool, denoted "New" in Table 5, we apply the approach outlined in Figure 1. Because the storage decision is deterministic with the "New" approach, no standard deviation is reported. The results for the number of lamps and casepacks repackaged from matches of the inventory with the less-than-casepack arrivals are summarized in Table 5. The decision tool increases the number of casepacks repackaged by as much as 185% when compared to the worse replication with the original method. On average, the new approach increases the number of casepacks repackaged from inventory 48%. The results indicate that an environmentally conscious manufacturer can decrease life cycle waste with efficient repackaging operations for casepacks partially damaged in transit.

Table 5: Comparison of Original Approach and New Approach
with Storage Capacity 750 for Six Truckloads

		Completed Casepacks from Matches of Inventory with Less-than-Casepack Arrivals for Six Truckloads	
Description		**Number of Lamps Repackaged**	**Number of Casepacks Repackaged**
Original	**Minimum**	1195	77
	Mean	1417	83
	Maximum	1634	92
	Standard Dev.	70	4
New		1976	100
% Increase from Minimum to New		65%	185%
% Increase from Mean to New		39%	48%

A sensitivity analysis was conducted on the relationship between the improvement in lamps repackaged and the size of the storage space. All parts are assumed to occupy equal space when stored in inventory while waiting for repackaging. For a given instance, if the size of the storage space is increased, then the number of casepacks repackaged will also increase. Since the majority of lamps are low frequency and space utilization of low-value, low-frequency lamps cannot be economically justified, we constrain the storage of lamps. When the space constraint is tight, our method will improve the number of casepacks repackaged as illustrated in Figure 2. In Figure 2, we vary the storage space in increments of 100 lamps. We use Model HF to determine the size of the high frequency set F for each of the storage space capacities. Model HF selects a high frequency set F which ranges from 132 products to 176 products for storage space capacities 150 to 1950 respectively. We compare the original and proposed approaches in Figure 2 by examining the number of casepacks completed from matches between inventory and salvageable less-than-casepack arrival quantities. Figure 2 illustrates a significant increase in the number of completed casepacks when inventory is controlled using the SR Algorithm.

Figure 2: Number of Casepacks Completed from Matches between Inventory and Less-than-Casepack Arrivals at Various Capacities



CONCLUSIONS

Manufacturers could more efficiently repackage and recycle large volumes of low-value products from damaged casepacks in transit at integrated repackaging and recycling centers. If an intelligent method for storing inventory does not exist, what is essentially a lack of planning can result in either unreasonably large inventories of low-frequency products queued awaiting matches for repackaging or a significant loss in the quantity repackaged if the storage space is tightly constrained.

Unfortunately, for many facilities which recycle products, especially those of low value, additional products or parts cannot be ordered to increase the number repackaged. Therefore, the only way to increase the number of salvageable products repackaged is either to store all salvageable products or to select products to store with the shortest expected duration of stay. The method demonstrated in this paper is to base the duration of stay on the frequency of historical arrivals. It is important to note that the expected duration of stay is not singularly focused on the historical quantity of arrivals but rather the historical frequency of arrivals. This important insight is the basis for the success of the new decision tool studied in this paper.

By actively deciding which products should be stored, the overall quantity of repacked products reclaimed for use by consumers can be increased. Additionally, the potential exists to yield a substantial savings in space and handling costs, as well as an improvement in inventory tracking and control, by allowing certain low-frequency products to be sent directly to the recycling function. Together, these factors can also help to enhance the financial viability of an otherwise environmentally sensible process.

This paper tests a new decision making tool which assists in making the store-versus-recycle selection for an integrated repackaging and recycling operation based exclusively upon historical data. As demonstrated within the study, it allows a considerable improvement in the number of lamps repackaged when storage space is constrained. The decision tool presented here also has the added benefit of relying upon metrics that can be quickly and easily calculated without using sophisticated software or by collecting additional data. These features make for an inexpensive tool that is easy to maintain and update for a variety of products and functions. Our methodology also serves to provide a qualitative framework that guides in assessing what is a reasonable investment of time and technology for managing inventory within an integrated repackaging and recycling operation. The value of a product and its revenue stream in the product life cycle need to be balanced against the investment required to construct such a decision tool. An environmentally conscious manufacturer can use this tool or partner with a third party recycler to use this tool to reduce the life cycle waste of their casepacks partially damaged during transit.

ACKNOWLEDGEMENTS

The authors are grateful for the insights and discussions provided by Recyclights, Inc., a division of Superior Special Services, IBM Asset Recovery Center, and colleagues Tito Homem-de-Mello of The Ohio State University and Arnold L. Sweet of Purdue University. This material is based upon work supported by the National Science Foundation under Grants No. BES-0124761 and DMII-0049074. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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