# Optimizing the Selection of Product Recovery Options

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*Abstract* - **This paper investigates the problem of optimizing product recovery options within the reverse logistic context. A linear programming model is developed to find optimal allocation of returned products in different quality classes to certain recovery options. The objective is to maximize the profit. Qualities and quantities of returned products, demands, prices of the recovered products and costs for recovery are all considered in the model. The model is used to examine the effects of flexibility in product recovery allocation. Computation results show that flexible allocation between the returned products in different quality classes and the recovery options are beneficial.**

*Keywords*: **Reverse logistics; product recovery options; linear programming**

## I. INTRODUCTION

The reprocessing of used products (returned products) through various product recovery strategies has evolved from a mere necessity (legal requirements) to substantial effort in enhancing companies' profitability and competency. Product recovery as part of the reverse logistics is now viewed not only as part of the legal requirement but more importantly, to recover the economical as well as ecological value of used products, components and materials for as much as possible and thereby reducing quantities of waste to a minimum.

Legislation aimed at environment-benign production forces manufacturers to take back their products from end-users after they discard them [3]. After taking back products from their customers, manufacturers need to decide what to do with them and decide appropriate disassembly, recovery or disposal options. Basically there are five recovery options to choose: reuse, refurbish, remanufacture, cannibalize and recycle [9]. These options differ in terms of disassembly levels, the amount of repairs needed, replacement of modules, parts and materials, and the final recovered output.

Reference [3] is among the first research efforts addressing the choice of all product recovery options in one particular study. The study focuses on a problem in which the manufacturing company needs to determine to what extent that returned products should be recovered for reuse or if they should be disposed and to decide what sort of recovery options are suitable to use. Extending the study in [3], an improvised stochastic dynamic programming algorithm for determining the optimal disassembly and recovery strategy has been developed [4]. However, focus of this study is more on the disassembly strategy. Reference [5] developed a design decision model regarding component reuse, remanufacturing, recycling and disposal over several product lifecycles for a portfolio of products. The aim of the model is to maximize the overall utility of the entire product portfolio over several lifecycles. Study on multiple product recovery options is also illustrated by [1] that formulates a periodic review model to determine the structure of the optimal periodic review policy and addresses the stochastic remanufacturing problem with multiple reuse options.

Previous study on quality classification of returned products is fairly limited. Reference [6] addresses quality issues by assessing the cost effectiveness of quality-based categorization of return products. Another related study [7] presents an analytical approach towards production planning in a closed-loop supply chains using a mathematical programming model called Remanufacturing Aggregate Production Planning (RAPP). The study considers decisions on product recovery options (remanufacturing, disassembly and disposal) and incorporates inventory as well as purchasing and acquisition costs of products' modules and components into the model.

Meanwhile, study examining the effect of market demand towards product recovery decisions is also limited. Most of the study that includes market demand in the model normally incorporates it as a simple constraint requiring that the amounts of remanufactured or reused products cannot exceed the market demand [7], [8] or as known parameters which is can be obtained from industries databases [9]. Reference [10] treats demand as a linear function which is price-sensitive and incorporated in both the objective function and constraint.

As more companies now realize the importance of reverse logistics and product recovery management, the attention is shifted towards the way to utilize the recovery options to achieve business targets such as profit maximization, cost minimization, resource utilization and production efficiency. Normally returned products are inspected and classified into certain quality classes. Each returned product is then assigned to a particular recovery option based on its quality class. This paper tries to extend previous studies by allowing flexibility in the assignment between quality classes and the recovery options. The decisions on the assignment will depend on which options are more profitable under certain circumstances. The remainder of this paper is organized as follows. Section II describes the problem. Section III presents model formulation of the problem. Experiment results using the model are presented and analyzed in Section IV. Section V concludes the paper.

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## II. PROBLEM DESCRIPTION

In this study returned products are graded into five quality classes based on the physical and functionality conditions. The five classes from the highest to the lowest quality are 1: repairable, 2: refurbishable, 3: remanufacturable, 4: cannibalizable, and 5: recyclable. This type of quality classification is practiced by some remanufacturers albeit not 100% similar. The classification is also inspired by the work of [7] and the implementation can be done by professional judgment (quality controller). After quality classification, returned products are sent to the recovery facility and to specific recovery options. Five recovery options are considered – 1: repair, 2: refurbish, 3: remanufacture, 4: cannibalize and 5: recycle. It is possible for a returned product of a higher quality to be recovered using a lower option, and vice versa. However, a lower quality returned products that are recovered using a higher recovery option will involve higher recovery costs. Therefore, each class of returned products is not restricted to only one designated recovery option as currently practiced. Here we allow flexibility in terms of the relationships between quality of returned products and the recovery options. Nonetheless, this flexibility is allowed as long as it is technically feasible. In cases where certain lower quality returned products are not technically possible to be assigned to some higher recovery options, we can consider the cost for such assignments as infinitely high.

Recovering returned products in the same quality class would incur different recovery costs depending on the recovery option used. It is also understandable that if a returned product that is only good enough to be cannibalized may be recovered using the remanufacturing option (upgrade), then the recovery cost will be higher. However, the quality of the output from the remanufacturing option is also much better and commanding higher selling price.

In terms of the recovery processes, we consider a situation where the company has facilities to carry out all five recovery methods in-house. We assume the unit processing times for returned product in each quality class using each recovery option is known. The capacity of the facility for each recovery option is limited and known. For this study, recovery capacity of the facility for an option is represented by the maximum number of available hours for that facility. In our analysis, we consider different selling prices for the outputs of different recovery options. It is assumed that recovered products from the remanufacturing activities have the highest quality followed by refurbished and repaired products. Therefore, remanufactured products command highest selling price followed by refurbished and repaired products. Selling prices for retrieved parts and components are lower than selling price for repaired products but higher than recycled materials. It is also assumed that there is a demand for each recovery option's outputs. The in-house product recovery activities involve processing costs as well as collection and handling costs.

The company is considered to be operating in an environment where product take-back is mandated and they have to meet a minimum recovery target set by the government. A minimum recovery target is a minimum proportion of collected used products that must be recovered either for reuse, recycled or resell.

The problem is then to determine the amount of returned products in each quality classes that should be allocated into each recovery options considering all the aforementioned issues. The objective is to maximize the profit.

## III. MODEL FORMULATION

In this section, a mathematical model is developed to find optimal allocation of returned products in different quality classes to product recovery options. The model considers amounts of returned products, demands of recovered products, recovery targets set by regulations, and recovery capacities.

*Parameters*

$I = \{1, 2, \ldots, n\}$ : the set of returned product types;
$R = \{1, 2, \ldots, 5\}$ : the set of recovery options;
$Q = \{1, 2, \ldots, 5\}$ : the set of quality class;
$T_{iq}$ : The amount of returned product $i$ in quality class $q$;
$TA_i$: Total amount of returned product $i$, so, $\sum_{q=1}^{5} T_{iq} = TA_i$;
$G_i$ : Recovery target of item $i$ expressed in terms of proportion of $TA_i$;
$K_{iqr}$: Capacity needed to recover item $i$ from quality class $q$ using option $r$;
$TK_r$: Maximum capacity of recovery option $r$;
$CD_{ir}$: Committed demand for product $i$ recovered using option $r$;
$MD_{ir}$: Market demand for product $i$ recovered using option $r$;
$P_{iqr}$: Profit (per unit) of item $i$ in quality class $q$ assigned to recovery option $r$, where $P_{iqr} = S_{ir} - (C_{iqr} + PC_i + CH_i)$. $S_{ir}$ is the selling price (per unit) of item $i$ recovered using option $r$, $C_{iqr}$ is the direct recovery cost per unit of item $i$ in quality class $q$ recovered using option $r$, $PC_i$ is the purchasing cost per unit of returned product $i$, $CH_i$ is the collection and handling cost per unit of returned product $i$.

*Decision variables*

$A_{iqr}$ : the amount of item $i$ in quality class $q$ that should be recovered using option $r$.

Using the above notion the problem can be formulated as the following linear programming model.

$$\text{Maximize } \sum_{i=1}^{n}\sum_{q=1}^{5}\sum_{r=1}^{5} P_{iqr}\, A_{iqr}$$

Subject to:

$$\sum_{q=1}^{5} A_{iqr} \ge CD_{ir}\,,\ i \in I, r \in R \tag{1}$$

$$\sum_{q=1}^{5} A_{iqr} \le MD_{ir}\,,\ i \in I, r \in R \tag{2}$$

$$\sum_{r=1}^{5} A_{iqr} \le T_{iq}\,,\ i \in I, q \in Q \tag{3}$$

$$\sum_{i=1}^{n}\sum_{q=1}^{5} K_{iqr} \cdot A_{iqr} \le TK_r\,,\ r \in R \tag{4}$$

$$\sum_{q=1}^{5}\sum_{r=1}^{5} A_{iqr} \ge TA_i G_i\,,\ i \in I \tag{5}$$

$$A_{iqr} \ge 0,\ i \in I, q \in Q, r \in R \tag{6}$$

The objective of this model is to maximize the total profit made from recovering the returned products. Constraints (1) require that the committed orders for all types of recovered products must be satisfied. Constraints (2) state that the amount of each product recovered by each option cannot exceed the total market demand for that type of product. Constraints (3) ensure that the sum of the amounts of returned product *i* in quality class *q* assigned to different recovery options *r* must not exceeds the total amount of returned product *i* in quality class *q*. Constraints (4) require that the sum of capacities of each recovery option required by all returned products in all quality classes must not exceed the available capacity of this recovery option. Constraints (5) guarantee that the amount of all recovered products must meet the recovery target. Constraints (6) require that all variables must be non-negative.

## IV. COMPUTATIONAL EXPERIMENT

The above model allows flexibility in allocating returned products to recovery options. To demonstrate the potential benefits of this flexibility, we use this model to test the effect of flexibility on an example problem. In this example, we assume that the company collects three different used products (products 1, 2 and 3) and uses them to produce recovered products. Table I gives the total amount of each product returned, its recovery target, purchasing cost and handling cost. The selling prices of recovered products are listed in Table II. Tables III and IV list the unit recovery costs and capacity related parameters, respectively.

Using the above data we examine the impact of flexible recovery assignments under different supply and demand environments. On the supply side we consider three different distributions of quality classes for each returned product types: the amount of returned products in every quality class equal to $TA_i/5$, from uniform distribution $[0.7*TA_i/5,\ 1.3*TA_i/5]$, from uniform distribution $[0.4*TA_i/5,\ 1.6*TA_i/5]$. These represent three different levels of quality variability of returned products. On the demand side, we consider three different levels of demand constraints using different pairs of uniform distributions of $CD_{ir}$ and $MD_{ir}$. Table V summaries these supply and demand environments.

TABLE I
TOTAL RETURN, $TA_i$, RECOVERY TARGET, $G_i$, PURCHASE COST, *PC*, AND HANDLING COST, *CH*, FOR EACH PRODUCT TYPE

| *i* | $TA_i$ | $G_i$ | *PC* | *CH* |
|---|---|---|---|---|
| 1 | 100000 | 0.9 | 15 | 10 |
| 2 | 130000 | 0.85 | 7 | 5 |
| 3 | 90000 | 0.8 | 8 | 10 |

TABLE II
UNIT SELLING PRICE OF RECOVERED PRODUCTS, $S_{ir}$

| *r* \ *i* | 1 | 2 | 3 | 3 | 3 |
|---|---|---|---|---|---|
| 1 | 150 | 50 | 180 | 180 | 180 |
| 2 | 200 | 70 | 200 | 200 | 200 |
| 3 | 250 | 90 | 220 | 220 | 220 |
| 4 | 50 | 30 | 45 | 45 | 45 |
| 5 | 30 | 20 | 20 | 20 | 20 |

TABLE III
UNIT RECOVERY COSTS, $C_{iqr}$,

| *i, q* \ *r* | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1, 1 | 20 | 25 | 45 | 20 | 15 |
| 1, 2 | 20 | 20 | 40 | 20 | 15 |
| 1, 3 | 55 | 40 | 45 | 20 | 15 |
| 1, 4 | 160 | 140 | 120 | 20 | 15 |
| 1, 5 | 100 | 125 | 150 | 40 | 15 |
| 2, 1 | 10 | 20 | 40 | 8 | 5 |
| 2, 2 | 20 | 20 | 40 | 8 | 5 |
| 2, 3 | 45 | 30 | 35 | 8 | 5 |
| 2, 4 | 80 | 70 | 60 | 8 | 5 |
| 2, 5 | 50 | 65 | 80 | 25 | 5 |
| 3, 1 | 20 | 25 | 45 | 20 | 15 |
| 3, 2 | 20 | 20 | 40 | 20 | 15 |
| 3, 3 | 65 | 40 | 45 | 20 | 15 |
| 3, 4 | 120 | 100 | 80 | 20 | 15 |
| 3, 5 | 140 | 120 | 100 | 30 | 15 |

TABLE IV
CAPACITY COEFFICIENTS, $K_{iqr}$, AND CAPACITIES AVAILABLE, $TK_r$

| *i, q* \ *r* | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1,1 | 0.25 | 0.35 | 0.4 | 0.3 | 0.15 |
| 1,2 | 0.3 | 0.25 | 0.4 | 0.2 | 0.15 |
| 1,3 | 0.35 | 0.3 | 0.35 | 0.2 | 0.15 |
| 1,4 | 0.35 | 0.4 | 0.45 | 0.2 | 0.15 |
| 1,5 | 0.4 | 0.45 | 0.55 | 0.25 | 0.15 |
| 2,1 | 0.25 | 0.35 | 0.4 | 0.3 | 0.15 |
| 2,2 | 0.3 | 0.25 | 0.4 | 0.2 | 0.15 |
| 2,3 | 0.35 | 0.3 | 0.35 | 0.2 | 0.15 |
| 2,4 | 0.35 | 0.4 | 0.45 | 0.2 | 0.15 |
| 2,5 | 0.4 | 0.45 | 0.55 | 0.25 | 0.15 |
| 3,1 | 0.25 | 0.35 | 0.4 | 0.3 | 0.15 |
| 3,2 | 0.3 | 0.25 | 0.4 | 0.2 | 0.15 |
| 3,3 | 0.35 | 0.3 | 0.35 | 0.2 | 0.15 |
| 3,4 | 0.35 | 0.4 | 0.45 | 0.2 | 0.15 |
| 3,5 | 0.4 | 0.45 | 0.55 | 0.25 | 0.15 |
| $\boldsymbol{TK_r}$ | 25000 | 25000 | 30000 | 20000 | 15000 |

TABLE V
SUPPLY AND DEMAND ENVIRONMENTS

| Level | Quality distribution of returned products, $T_{iq}$ | Tightness of demand constraints | |
|---|---|---|---|
| | | $CD_{ir}$ | $MD_{ir}$ |
| 1 | $ta_i^*$ | $[0.8ta_i, 0.9ta_i]$ | $[1.1ta_i, 1.2ta_i]$ |
| 2 | $[0.7ta_i, 1.3ta_i]$ | $[0.6ta_i, 0.8ta_i]$ | $[1.2ta_i, 1.4ta_i]$ |
| 3 | $[0.4ta_i, 1.6ta_i]$ | $[0.4ta_i, 0.7ta_i]$ | $[1.3ta_i, 1.6ta_i]$ |

$^* ta_i = TA_i/5$

For each combination of supply level and demand level, we generate 50 problem instances using the corresponding distributions. The allocation of returned products to recovery options are then done for each problem instance in two different ways: ***flexible*** allocation using the model in Section III, and the conventional ***fixed*** allocation. All the linear programming models are solved using Xpress-MP.

In the fixed allocation, products of a quality class must be assigned to the corresponding recovery option, i.e., $A_{iqr}$ takes nonzero values only when $q = r$. When the quality distribution of returned products does not match with the demand requirements for some problem instances, this fixed allocation is infeasible. For all the problem instances tested the flexible allocation method always gives a feasible solution.

For each instance for which both methods generate feasible solutions, let *Flex* be the total profit achieved by the flexible allocation and *Fix* be the total profit achieved by the fixed allocation. The benefit of flexible allocation can be represented using the relative difference between the two total profits:

$$\frac{Flex - Fix}{Fix} \times 100\%$$

For each group of problem instances (each combination of supply level and demand level), we calculated the average of the benefit for the feasible instances in the group. Table VI shows the results.

The overall average benefit is 9.56%. This shows that for the problems tested, allowing flexibility in allocation can increase almost 10% of profit on average. From the results in Table VI we can also clearly see that when the demand constraint tight, the benefit is relatively small. This is because in this case there is not much flexibility allowed. The benefit increases significantly as the demand constraint is relaxed.

TABLE VI
AVERAGE BENEFIT OF FLEXIBLE ALLOCATION IN DIFFERENT SUPPLY AND DEMAND ENVIRONMENTS

| Level of variability on supply quality | Level of tightness of demand constraints | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| 1 | 4.45% | 8.83% | 12.86% |
| 2 | 4.50% | 8.83% | 12.93% |
| 3 | –* | 8.89% | 12.98% |

* Fixed allocation is infeasible for all the instances in this group

TABLE VII
NUMBER OF INFEASIBLE INSTANCES FOR FIXED ALLOCATION IN DIFFERENT SUPPLY AND DEMAND ENVIRONMENTS

| Level of variability on supply quality | Level of tightness of demand constraints | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| 1 | 0 | 0 | 0 |
| 2 | 17 | 0 | 0 |
| 3 | 50 | 40 | 1 |

Intuitively if the variability in the quality distribution of returned product increases, the benefit of flexible allocation would be increase because higher variability would make the fixed allocation difficult. From the results in Table VI, however, we do not see much difference in the average benefit when variability of supply quality changes. This is partially due to the fact that we calculated the average of only the instances for which the fixed allocation is feasible.

Looking at the detailed results we find that as the variability of supply quality increases the number of infeasible instances in the group also increases. Table VII gives the number of infeasible instance in each group. If we consider penalties for not satisfying demand constraints, then the benefit of flexible allocation will be more significant when the variability of supply quality is large. Nevertheless, being able to find feasible solutions in difficult situations is already a huge benefit for the flexible allocation method.

## V. CONCLUSIONS

This paper studies the problem of selecting recovery options for returned products. A linear programming model is formulated to determine the optimal amount of recoverable returned products in different quality classes into certain recovery options so that the profit will be maximized. The model is used to demonstrate the potential impact of flexibility in the assignment of returned products to recovery options.

Using a set of cost and capacity parameters, we generated a large number of problem instances representing different supply quality and demand constraint situations. The result shows that considering flexibility in recovery allocation is beneficial as compared to the fixed allocation approach. For the problem instance tested, the flexible allocation can increase profit by almost 10% on average. Another major benefit is that flexible allocation can find feasible recovery plans under difficult supply and demand conditions where fixed allocation cannot handle. It should be noted that flexible allocation is possible only when returned products are classified in detailed categories so that the possible options for each quality class is clear. This means the simple classification into “good” and “bad” products is not enough. With increasing environment awareness and tighter regulations, companies need to make more effort in the inspection, classification of returned products and in optimizing the product recovery options.

In practice, complete flexibility of allocating returned products to recovery options may not be technically possible. Returned products in certain quality class may only be recovered using a subset of options. The proposed model can be easily modified to handle such situation. Further research may be done incorporating other practical factors such as outsourcing, indirect recovery costs and multiple planning periods.

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