Evaluating End-of-Life Recovery Profit by a Simultaneous Consideration of Product Design and Recovery Network Design

Minjung Kwak
Graduate Student
e-mail: kwak14@illinois.edu

Harrison M. Kim
Assistant Professor
e-mail: hmkim@illinois.edu

Department of Industrial and Enterprise Systems Engineering,
Enterprise Systems Optimization Laboratory,
University of Illinois at Urbana-Champaign,
Urbana, IL 61801

Product recovery has become a field of rapidly growing interest for product manufacturers as a promising solution for product stewardship as well as for economic viability. Because product recovery is highly dependent on the way a product is designed, it should be considered in the design stage so that the product is designed to have high recovery potential. To make a product easy to recover, manufacturers first need to understand the links between product design and recovery profit and be able to evaluate which design is better than others and why. This study proposes a framework for analyzing how design differences affect product recovery and what architectural characteristics are desirable from the end-of-life perspective. For better design evaluation, an optimization-based model is developed, which considers product design and recovery network design simultaneously. For illustration, a comparative study with cell phone examples is presented. Three cell phone handset designs that share the same design concept but have different architectural characteristics are created, and the recovery potential of each design variant is evaluated under three different recovery scenarios. The results show that the framework can highlight preferred design alternatives and their design implications for the economic viability of end-of-life recovery. [DOI: 10.1115/1.4001411]

1 Introduction

As environmental regulations urge stronger stewardship for product retirement, recovering used products has become a field of rapidly growing interest for product manufacturers. Recovery options, including reuse, repair, refurbishment, and recycling, enable companies to comply with legislation while also gaining some economic advantage. At comparatively little cost, companies can utilize many of the resources remaining in used products. As a result, more companies have been choosing product recovery instead of disposal as their primary retirement strategy. Accordingly, engineering methods for maximizing recovery profit have come into increasing demand from industry [1,2].

Product design is the most important factor in maximizing recovery profit [3–6]. As depicted in Fig. 1, product recovery is the process of collecting used products from their former users, sending recoverable units to recovery plants, reprocessing collected units to render them remarketable, and distributing recovered products, components, or materials to customers [7]. This recovery process is highly dependent on the way a product is designed. Product design features, including function, material, and structure, greatly affect what kinds of recovered items can be produced, what recovery operations are necessary to produce them, and how profitable the recovered units can be. Therefore, product recovery should be considered at the design stage in order to facilitate efficient and effective recovery at the end of the product's life.

This paper presents a study conducted to develop a design-for-recovery method. Improving the recovery potential of product design is achievable only by understanding the links between product design and recovery profit. However, the connection between product design (i.e., prelife) and the recovery process (i.e., end-of-life) has not been clear, hindering the movement toward design-for-recovery. Thus, this study suggests a framework that can analyze how design differences, particularly, architectural differences, affect product recovery and what design properties are desirable from the end-of-life perspective.

This paper consists of two parts. In the first part, a generic mathematical model is proposed for evaluating design alternatives. As input to the model, each design alternative is first represented in the form of a transition matrix before being evaluated in terms of the maximum recovery profit that corresponds to an optimal recovery plan.

In the second part, a comparative study based on the proposed model is conducted following the framework in Fig. 2. A cellular phone serves as the subject of the study, and three handset designs with the same concept but different architectural characteristics are created based on actual designs of cell phones in the market. We apply the evaluation model to each of three handset designs using a scenario that reflects the features of returned product, market parameters (e.g., demand), recovery network features (e.g., facility capacity and capability), and so on. Based on the evaluation results for the maximum expected recovery profit, the best design under a particular scenario is determined and the impact of design differences on recovery plans and recovery profit is analyzed.

The suggested framework and evaluation model can help manufacturing companies enhance their design competence. They enables a company to evaluate which design is better than others and why. Ultimately, they can support manufacturers to make an optimal product with maximum recovery potential in terms of cost, time, and materials recovered. Although being developed for product manufacturers, the framework and evaluation model can assist other recovery companies as well that work independently from manufacturers but use their products for recovery. For example, the framework can help independent remanufacturers to evaluate original manufacturers' products so as to analyze which model or brand is more profitable to recover and find what the optimal reprocessing strategy is for a product.

Contributed by the Design Automation Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received April 27, 2009; final manuscript received March 5, 2010; published online June 9, 2010. Assoc. Editor: Karthik Ramani.

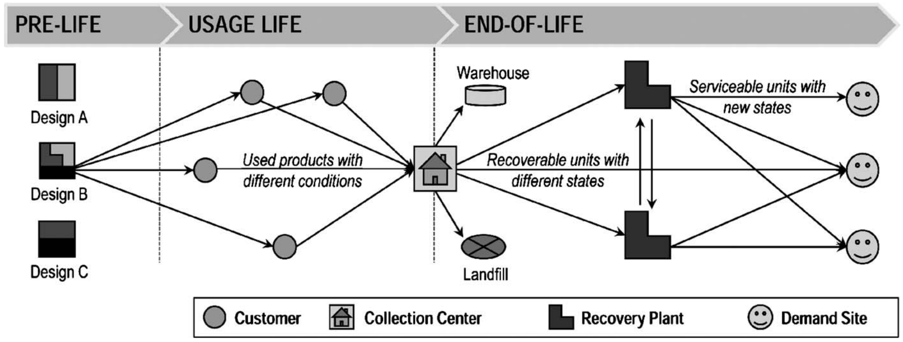


Fig. 1 General recovery structure [1,7]

The rest of this paper is organized as follows. Section 2 briefly explains the evaluation of recovery profit, which is the area of major difference between the proposed approach and previous work, and gives an overview of a product recovery logistics network. Section 3 follows with the transition matrix, a key design enabler. A mathematical model, a method of evaluating design alternatives, is presented in Section 4. Section 5 presents the comparative study, where the individual designs, multiple design and recovery scenarios, and the analysis results are described in detail, and the conclusion follows.

2 Recovery Profit Evaluation: Linking Product Design to Recovery Profit

In the area of design-for-disassembly [5,8–20], a number of methods have been developed to evaluate product design alternatives at the design stage based on their ease of disassembly and/or recovery. Similar to the current study, many of these studies selected recovery profit as the evaluation criterion and demonstrated a way to obtain profit value by finding an optimal recovery plan [5,17–20]. However, the existing literature has limitations in that it has overlooked the impact of recovery network design on recovery profit, since the recovery profit of a product is affected, not only by product design but also by the design of the recovery logistics network.

Recovery network design determines the feasibility of recovery operations as well as the profitability of possible recovery plans. Network features—what facilities are involved in the network, what sorts of recovery operations are performed and how well, which facility is assigned to do a particular job, what customers are included as end nodes of the network, and so on—affect recovery cost and/or recovery revenue. Thus, even if product designs are identical, recovery profits can differ depending on the recovery network design. Therefore, when decision makers evaluate the recovery profit of design alternatives, they should consider product design in conjunction with the design of the recovery network.

Earlier evaluation methods have dealt with product design and recovery network design separately by assigning logistics costs before finding the optimal recovery plan. They have regarded the network design as a parameter in optimizing the recovery plan. If there is a predefined fixed network design, this approach might be reasonable; however, it is more realistic that the logistics network applied and the corresponding cost differ based on changes in the recovery plan. Neglecting network features causes another problem in that these approaches consider only a single product, whereas, in reality, even the same products can be recovered differently in terms of both recovery procedures and final recovered outputs, based on facility capacity or market demand.

The proposed approach is distinguished from previous works by its evaluation model. In this approach, a generic method for optimizing a recovery network design was developed for the purpose of design evaluation. The model reflects the impact of product design during network optimization by using a transition matrix. Specifically, it regards network design as a set of decision variables that should be optimized simultaneously with the recovery plan. As a result, it identifies both the optimal network design and the optimal recovery plan for large numbers of products; thus, we can expect more realistic and reasonable evaluations of recovery profit from the proposed framework.

Figure 1 depicts a general recovery logistics network that the proposed model aims to optimize. Product recovery usually involves five types of facilities in its logistics network: collection centers, disposal sites, warehouses, recovery plants, and demand sites. Collection centers are central points where used products are collected from customers. After tests to assess the product's quality status, unrecoverable units are sent to disposal sites for landfill

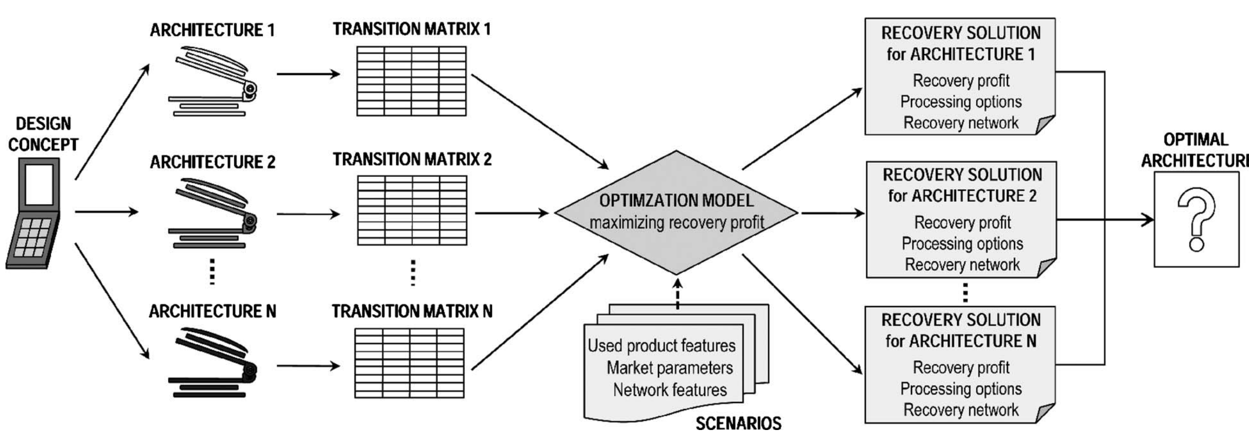


Fig. 2 Framework of proposed comparative study

Table 1 Example transition matrix for recovery modeling (the dot represents zero value)

	Operation 1	Operation 2	Operation 3	…	Operation p
State 1	−1	−1	1	.	.
State 2	1	.	.	.	.
State 3	.	1	−1	.	.
…	.	.	.	.	.
State s	.	1	−1	.	1
Type	(1 to 1)	(1 to N)	(N to 1)	…	(0 to 1)

or incineration, and recoverable products are transferred to recovery plants for reprocessing or to demand sites when a recoverable unit has sufficient resale value and additional reprocessing operations are not necessary. Some returned products may also be stored at a warehouse for later recovery, in which case the recovery decision is suspended.

The reprocessing options considered in this research include reuse, refurbishment, and recycling [1,7].

- Reuse: An item is used for its original purpose without repair.
- Refurbishment: An item maintains its identity and structure and is repaired or remanufactured as a like-new product. Disassembly, overhaul, replacement, and reassembly are parts of refurbishing a product.
- Recycling: An item is disassembled, shredded, and/or separated to recover raw materials. Incineration of parts that are not reusable produces heat and electricity.

Component recovery is another option that can be more worthwhile than product recovery, especially when parts or modules account for most of the residual value. In such cases, disassembly is first performed to turn a product into a set of "child" subassemblies. Individual child subassemblies then start their recovery as independent units, each with its own reprocessing option.

According to chosen reprocessing options, recovery plants conduct a sequence of operations for returned products to transform them into marketable units. A reprocessing operation is regarded as a state change of a unit since, via reprocessing operations, a recoverable product transitions to a set of serviceable units with a new state in terms of quality and/or form. A product can be recovered not only in the form of a product but also of a module, a component, or a material. Multiple operations may be required to transform a unit into a desirable form, and different recovery plants can be required to accommodate necessary operations. After all reprocessing is complete, recovered units are sold to demand sites, such as manufacturing plants and used-product markets. When a company does not carry out any recycling on its own account, the company can regard recyclers as demand sites as well.

3 Transition Matrix for Modeling

3.1 Recovery Modeling Using Transition Matrix. A transition matrix is one that represents every possible recovery scenario a product design derives. Specifically, a transition matrix enables mathematical modeling of the relationship between product design and recovery processes. In previous research [5,20], a transition matrix has been used to model product disassembly. In this research, a transition matrix is modified so that its transitions can model various reprocessing operations including disassembly, part replacement, and reassembly.

Table 1 shows an example of a transition matrix. The rows of the matrix are related to product design. Every possible state a returned product can take on the recovery network is defined as a state, s. The entire set of feasible states constitutes the rows. The columns show feasible transitions, namely, recovery operations, p.

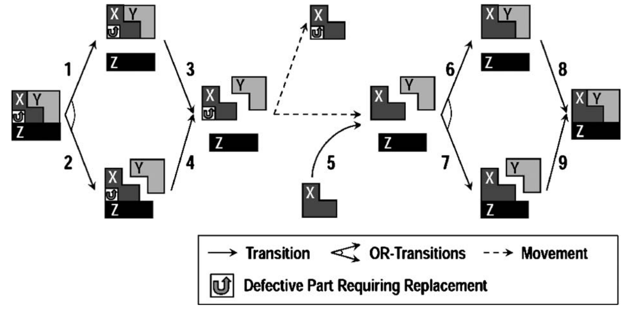


Fig. 3 Recovery operations for product *XYZ*

An operation p is regarded as a state change and the integer values in the relative column are used to indicate such state changes; the values in a column describe the input and output of the corresponding operation. If a cell (s,p) has a value of −1, a unit having state s is processed according to operation p. Alternatively, if a cell (s,p) has a value of 1, a unit having state s is generated according to operation p. If a cell (s,p) has a value of 0, represented as a dot in the table, that state has nothing to do with the operation p. In short, the transition matrix shows which operation is needed to transform a parent unit in a certain state into a certain set of child units in other states. This implies that different designs result in different transition matrices as the feasibility of a transition and every possible state that can result from transitions are affected by product design.

As shown in Table 1, four types of transitions are useful in modeling different recovery operations: (1 to 1), (1 to N), (N to 1), and (0 to 1). Transition (1 to 1) links an input unit with another single output unit. For example, a unit in state 1 is transformed into a unit in state 2 by means of operation 1; a repair operation that changes a failed unit into a functioning unit might be represented in this way. Transition (1 to N) links an input unit with multiple output units having different states. For instance, operation 2 changes a unit in state 1 into two units in states 3 and s; a disassembly operation can be represented in this manner. Transition (N to 1) is for an operation changing multiple units into a single item. Operation 3 belongs to this category. It converts two units in states 3 and s into a unit in state 1; a reassembly operation that occurs in remanufacturing can be represented as such. Finally, transition (0 to 1) represents the additional entrance of an input unit. For example, operation p adds a unit in state s with no changes in other units; supplying spare parts can be represented in this way.

By using these transitions, every possible recovery scenario of a returned product can be represented in a matrix form. Figure 3 and Table 2 illustrate this. A product XYZ with a defect in part X is assumed as the recovery target. In this case, the company can

Table 2 Transition matrix for product *XYZ*

	1	2	3	4	5	6	7	8	9	10
	Disassembly				Spare	Reassembly				Refurbishment
X^*YZ	−1	−1	.	.	.	.	.	.	.	−1
XYZ	.	.	.	.	.	.	.	1	1	1
X^*Y	1	.	−1	.	.	.	.	.	.	.
XY	.	.	.	.	.	1	.	−1	.	.
X^*Z	.	1	.	−1	.	.	.	.	.	.
XZ	.	.	.	.	.	.	1	.	−1	.
X^*	.	.	1	1	.	.	.	.	.	.
X	.	.	.	.	1	−1	−1	.	.	.
Y	.	1	1	.	.	−1	.	.	−1	.
Z	1	.	.	1	.	.	−1	−1	.	.

choose a plan from several recovery options for the product: They can reuse the product (reuse); they can refurbish the product by replacing the defective part, *X*, in order to sell the renewed product *XYZ* (refurbishment); or, they can disassemble the product with the intent to reuse or resell the resulting modules and/or components (component recovery). As for material recycling, it is assumed that the company does not perform recycling jobs but sells the product or disassembled components to third-party recyclers. Accordingly, there are ten possible states (asterisks are used to indicate the defective part) and nine feasible recovery operations, operations 1–9. In Fig. 3, recovery operations are represented by a solid line while movement without state change is represented by a dotted line. Depending on which operation is performed, an input product *XYZ* can be led to a different output.

Additionally, defining a transition and modeling the recovery is a matter of abstraction. In this example, refurbishment of *XYZ* can be represented by a combination of disassembly, replacement (spare), and reassembly operations. However, it is also possible to represent the same process by means of a single transition, operation 10.

3.2 Linking the Transition Matrix With Network Design. The capacity and capability of recovery plants are defined for each facility and for each transition. Each recovery plant has different capabilities as well as capacities for recovery operations. The capacity u_{jp} for plant j operation p indicates the maximum amount that a facility can handle at one time. In contrast, capability indicates whether a facility has the ability to do the operation, and if so, how well. Capability of plant j is reflected through the unit operation cost, c_{jp}. High capability is reflected through a low operation cost, and vice versa. If a facility cannot perform an operation, then capacity is set to zero; concurrently, the cost for that operation is set to $+\infty$.

The connection between the transition matrix and the facilities' capacity and capability information is represented by Eqs. (1)–(3), where z_{jp} is a decision variable indicating the number of times operation p is executed at recovery plant j. Equation (1) shows the capacity constraints and Eq. (2) shows the total operation cost of a network. Equation (3) pertains to the balance between inflow and outflow at a recovery plant j in terms of the volume of units. E_{js} and O_{js} represent the total volume of input and output units, respectively, in state s at plant j. A recovery operation changes an input's state into another state. The transition matrix entry T_{sp} indicates the input and output of operation p. When operation p uses a unit with state s as its input, T_{sp} has a value of -1; when operation p produces a unit with state s, T_{sp} has a value of 1; otherwise, T_{sp} is 0. Therefore, if plant j conducts a particular operation p z_{jp} times, the initial input amount E_{js} is changed by $z_{jp} \cdot T_{sp}$. Accordingly, the total changes due to recovery operations result in the summation of $z_{jp} \cdot T_{sp}$ with respect to all p. O_{js} should be equal to the remaining units reflecting the total changes. The details of the symbols used are described in the Nomenclature.

$$z_{jp} \leq u_{jp}, \quad \forall j \in J, \quad \forall p \in P \tag{1}$$

$$C_{\text{operation}} = \sum_{j=1}^{N_f} \sum_{p=1}^{N_o} c_{jp} \cdot z_{jp} \tag{2}$$

$$E_{js} + \sum_{p=1}^{N_o} z_{jp} \cdot T_{sp} = O_{js}, \quad \forall j \in J, \quad \forall s \in S \tag{3}$$

4 Mathematical Model

4.1 Problem Statement. The recovery profit of a design is obtained by a mathematical model. The model is summarized as the following optimization problem

(1) Given

- Transition matrix and the amount and quality of returned products.
- Location and distance of the potential recovery facilities.
- Cost of facility opening, recovery operations, and transportation; revenue from recovered items.

(2) Find

- Facilities to be opened or used and the volume of items flowing from one facility to another.
- Recovery operations performed by each facility and their frequency.

(3) Subject to

- *Flow balance feasibility*: An item must be sent only to an available facility that is open or in use; also, a facility should maintain its flow balance between input and output units.
- *Facility capacity*: Relative to a recovery operation, a plant has its own capacity and can deal with the input amount less than its capacity. A plant has zero capacity for unavailable operations.
- *Unit state change feasibility*: A recovery operation converts a single item into other unit(s). This state change should be feasible.
- *Avoiding excess fulfillment*: The supply of a recovered unit cannot exceed the demand for the unit.

(4) Maximizing

- Recovery profit expected from an amount of product with a given design.

(5) Supposition

- Deterministic parameter values; no penalty cost for not satisfying customer demand

4.2 Objective Function. The objective of this model is to maximize the profit from product recovery. Conversely, it is to minimize the total recovery cost after deduction in the total revenue. In this model, the total recovery cost is the sum of eight cost components (detailed descriptions are given below): cost for site opening (C_1), cost for disposal (C_2), cost for storage (C_3), cost for transportation (C_4, C_5, C_6), cost for recovery operation (C_7), and penalty cost (C_8) for unprocessed or discarded products. The objective function is modeled as shown in Eq. (4).

$$\min f\colon \sum_{n=1}^{8} C_n - R \tag{4}$$

4.2.1 Site Opening. A returned product reaching the collection point i is sent to another place in order for further recovery processes. There are three different types of site where the used product can be transported to: recovery plant, disposal site, and warehouse. What should be considered here is that a product can be transferred only to an available place. Perhaps, a site is constructed by the company. Or, a site can be used by the company under some contracts with the site owner. In such cases, the company should pay some fixed costs. Equation (5) represents this fixed cost, where Y is a binary variable indicating whether a site opens or not.

$$C_1 = c_j^f Y_j^f + c_l^{g_1} Y_l^g + c_r^{w_1} Y_r^w \tag{5}$$

4.2.2 Disposal From Collection Sites. A returned product can be thrown away at a disposal sites after it is tested/inspected at a collection site. The disposal cost consists of transportation cost and processing cost. The former is for moving a product from collection point to disposal site, and the latter is for doing actual jobs for disposal, such as landfill or incineration. Equation (6) represents disposal cost.

$$C_2 = \sum_{i=1}^{N_c} \sum_{l=1}^{N_g} \sum_{s=1}^{N_q} (c_{il}^{g_2} + c_{il}^{g_3}) X_{ils}^{g} \tag{6}$$

4.2.3 Storage. Instead of throwing a product into the recovery network, the company can suspend the decision and store the product for a while for some reasons. In this case, the company should pay the storage cost in Eq. (7) composed of transportation cost and warehousing cost.

$$C_3 = \sum_{i=1}^{N_c} \sum_{r=1}^{N_w} \sum_{s=1}^{N_q} (c_{ir}^{w_2} + c_{ir}^{w_3}) X_{irs}^{w} \tag{7}$$

4.2.4 Transportation. In the recovery network, products or disassembled units are transported between sites. Three types of transportation can exist: transportation from collection point i to recovery plant j and demand site k (C_4), transportation between recovery plants (C_5), and transportation from plant j to demand site k (C_6).

$$C_4 = \sum_{i=1}^{N_c} \sum_{j=1}^{N_f} \sum_{s=1}^{N_q} c_{ijs}^{\alpha} \cdot X_{ijs}^{\alpha} + \sum_{i=1}^{N_c} \sum_{k=1}^{N_d} \sum_{s=1}^{N_q} c_{iks}^{\beta} \cdot X_{iks}^{\beta} \tag{8}$$

$$C_5 = \sum_{j_m=1}^{N_f} \sum_{j_n=1}^{N_f} \sum_{s=1}^{N_q} c_{j_m j_n s}^{\delta} \cdot X_{j_m j_n s}^{\delta}, \quad j_m \neq j_n \tag{9}$$

$$C_6 = \sum_{j=1}^{N_f} \sum_{k=1}^{N_d} \sum_{s=1}^{N_q} c_{jks}^{\gamma} \cdot X_{jks}^{\gamma} \tag{10}$$

4.2.5 Recovery Operations. Each facility performs various recovery operations, such as reuse, repair, recycling, remanufacturing, disassembly, and others. Every operation for an input causes unit operation cost, and this cost has different value depending on the facility's capability. Equation (11) represents operation cost.

$$C_7 = \sum_{j=1}^{N_f} \sum_{p=1}^{N_o} c_{jp}^{o} \cdot Z_{jp} \tag{11}$$

4.2.6 Penalty for Unprocessed /Discarded Unit at Recovery Plants. In a recovery plant, some units can be discarded without further processing. Penalty cost for such units is calculated by Eq. (12).

$$C_8 = \sum_{j=1}^{N_f} \sum_{s=1}^{N_q} c_{js}^{h} \cdot X_{js}^{h} \tag{12}$$

4.2.7 Revenue. Besides cost, a recovery network brings about revenue by satisfying customer demand. For example, selling remanufactured products or recovered material returns income for the seller. Equation (13) describes the total revenue of a recovery network.

$$R = \sum_{k=1}^{N_d} \left(\sum_{i=1}^{N_c} X_{iks}^{\beta} + \sum_{j=1}^{N_f} X_{jks}^{\gamma} \right) \cdot r_{ks}^{d} \tag{13}$$

4.3 Constraints

4.3.1 Flow Balance at Collection Point. From a collection point, a returned product with state s should move to one of the following places: recovery plants, disposal sites, and warehouses. Constraint (14) represents this; here, E_{is} indicates the total volume of returned product with state s at collection point i.

$$E_{is} = \sum_{j=1}^{N_f} X_{ijs}^{\alpha} + \sum_{l=1}^{N_g} X_{ils}^{g} + \sum_{r=1}^{N_w} X_{irs}^{w} + \sum_{k=1}^{N_d} X_{iks}^{\beta}, \quad \forall\, i \in I, \quad \forall\, s \in S \tag{14}$$

4.3.2 Facility Feasibility. A returned product can be treated only by available facilities. Recovery operations can be performed only by open plants. Constraints (15)–(17) constrain this feasibility condition in terms of disposal sites, warehouses, and recovery plants, respectively; here, ω is an extremely large number.

$$\sum_{i=1}^{N_c} \sum_{s=1}^{N_q} X_{ils}^{g} \leq \omega \cdot Y_{l}^{g}, \quad \forall\, l \in L \tag{15}$$

$$\sum_{i=1}^{N_c} \sum_{s=1}^{N_q} X_{irs}^{w} \leq \omega \cdot Y_{r}^{w}, \quad \forall\, r \in R \tag{16}$$

$$\sum_{i=1}^{N_c} \sum_{s=1}^{N_q} X_{ijs}^{\alpha} + \sum_{j_m=1}^{N_f} \sum_{s=1}^{N_q} X_{j_m js}^{\delta} + \sum_{j_n=1}^{N_f} \sum_{s=1}^{N_q} X_{jj_n s}^{\delta} + \sum_{k=1}^{N_d} \sum_{s=1}^{N_q} X_{jks}^{\gamma} + \sum_{s=1}^{N_q} X_{js}^{h} \leq \omega \cdot Y_{j}^{f}, \quad j_m \neq j, \quad j \neq j_n, \quad \forall\, j \in J \tag{17}$$

4.3.3 Input Flow Balance at Recovery Plants. Every input unit of a recovery plant is either from collection points or other recovery plants. Thus, E_{js}, the total volume of input unit in state s at a facility j, is the sum of input flows from collection points and input flow from recovery plants.

$$E_{js} = \sum_{i=1}^{N_c} X_{ijs}^{\alpha} + \sum_{j_m=1}^{N_f} X_{j_m js}^{\delta} \quad j_m \neq j, \quad \forall\, j \in J, \quad \forall\, s \in S \tag{18}$$

4.3.4 Unit State Change Feasibility at Recovery Plants. A recovery operation changes an input's state into another state. As explained in Eq. (3), the left-hand side represents the total number of units with state s that remain at plant j after all recovery operations. This number should be non-negative according to constraint (19). For example, when operation p uses a unit with state s as its input (T_{sp}=−1), the number of operations for the unit in state s cannot exceed the number of inputs with s.

$$E_{js} + \sum_{p=1}^{N_o} Z_{jp} \cdot T_{sp} \geq 0, \quad \forall\, j \in J, \quad \forall\, s \in S \tag{19}$$

4.3.5 Capacity of Recovery Plants. There is a set of operations a facility can do, and the facility can perform only the activities in the set. As for an activity, a facility has the upper bound of input amount, that is, capacity. The facility can deal with only the amount of inputs less than capacity. Capacity for unavailable operation is set as 0.

$$Z_{jp} \leq u_{jp}^{f}, \quad \forall\, j \in J, \quad \forall\, p \in P \tag{20}$$

4.3.6 Output Flow Feasibility at Recovery Plants. The output in state s at the recovery plant j is equal to the remaining units, changing from the initial input amount due to recovery operation. The output, O_{js}, increases if the plant j performs any recovery operation generating unit with state s. In contrast, it decreases if the plant operates recovery operation transforming unit's state into other states.

$$O_{js} = E_{js} + \sum_{p=1}^{N_o} Z_{jp} \cdot T_{sp}, \quad \forall\, j \in J, \quad \forall\, s \in S \tag{21}$$

4.3.7 Output Flow Balance at Recovery Plants. An output unit in state s should move to either one of other recovery plants or demand sites. Or, a plant could stop to recover the unit even accepting some penalty cost for giving up the recovery. Equation (22) represents this output balance constraints.

$$O_{js} = \sum_{j_n=1}^{N_f} X^{\delta}_{jj_n s} + \sum_{k=1}^{N_d} X^{\gamma}_{jks} + X^{h}_{js}, \quad j_n \neq j, \quad \forall\, j \in J, \quad \forall\, s \in S \tag{22}$$

4.3.8 Demand Satisfaction and Avoidance of Excess Fulfillment. Each of demand sites requires an amount of unit in state s, and this demand can be satisfied by the input from collection points and recovery plants. This supply of recovered units at the demand site k is controlled not to exceed the corresponding demand, v^{d}_{ks}, by constraint (23).

$$\sum_{i=1}^{N_c} X^{\beta}_{iks} + \sum_{j=1}^{N_f} X^{\gamma}_{jks} \leq v^{d}_{ks}, \quad \forall\, k \in K, \quad \forall\, s \in S \tag{23}$$

4.3.9 Variable Condition. Y is a binary variable indicating whether a site opens or not. X represents the volume of items moving on the network; thus, every X should have nonnegative integer value. Also, Z_{jp} indicating the number of operation should be a non-negative integer. Constraints (24) and (25) restrain these variable conditions.

$$Y^{f}_{j}, Y^{g}_{l}, Y^{w}_{r} = 0 \text{ or } 1 \quad \text{(binary)} \tag{24}$$

$$X^{g}_{ils}, X^{w}_{irs}, X^{\alpha}_{ijs}, X^{\beta}_{iks}, X^{\gamma}_{jks}, X^{\delta}_{j_m j_n s}, X^{h}_{js}, Z_{jp} = \text{non-negative integer} \tag{25}$$

5 Comparative Study

To illustrate how to apply the proposed framework and how it benefits product design and recovery decision making, this section presents a comparative study with cellular phone design alternatives.

5.1 Overview of Cellular Phone Recovery. As the number of discarded cellular phones (cell phones) per year rapidly increases, recovering cell phones has become a great concern worldwide. Because cell phones are small, both the environmental impact and the economic value of an obsolete unit are also perceived to be small. However, when large numbers of discarded products are considered, the impact and value of those phones become significant. Short market cycles and high product variety are also characteristic of cell phones, making their need for recovery inevitable.

Following is the design-recovery scenario considered in the comparative study. Suppose that there is a cell phone manufacturer (the decision maker) who has interests in recovery business. Currently, the company conducts take-back of used cell phones but does not perform any recovery activities in-house. Instead, the company sends collected phones to a recycling partner for recovery. However, if the company can carry out recovery as an in-house business, it will be possible to reuse or refurbish used phones (i.e., fixing defects) and resell them as refurbished phones. Recycling partners will also be available if recycling is more profitable than reuse or refurbishment. Now, the manufacturer is developing a new cell phone model, for which there are currently three design alternatives to be considered. If the company decides to start recovery business, this model will be the first one recovered by the company. In order to make a decision, the manufacturer needs to know whether undertaking in-house recovery would be profitable or not. Especially, the manufacturer seeks the answers to following questions: Can cell phone recovery make a profit that surpasses its anticipated negative side effects? Does cell phone design affect recovery profit? If so, among the three design alternatives, which one would be the best from the end-of-life perspective? Given this situation, this comparative study aims to demonstrate following two points. First, the proposed framework can help the manufacturer to find the answers to those questions. Second, the framework can support the manufacturer to consider not only product design but also recovery network design, which leads to better evaluation of recovery profit.

The general recovery process for used cell phones starts with segregating handsets from their accessories, including battery, charger, and hands-free devices. It is the handset recovery that carries considerable portion relative to the entire profit from cell phone recovery. Thus, this research accounts only for the handset design in their differences and the effect on the profit. We also assume that the company can discern the condition of a handset accurately without any disassembly operations. During the test at a collection center, every part passes through function tests, and the handset is given a state s based on the test result. In this paper, a component's condition is a binary parameter: functioning and nonfunctioning. Finally, the cell phone designs and parameter values used here—such as plant location and capacity, operation costs, and resale revenues—are simulated and controlled. Every data have been created to approximate reality. Three individual handset designs and market parameter values are established based on previous literature [21,22] as well as market research [23].

5.2 Three Handset Designs. To analyze whether architectural differences can make one handset design more profitable than others, three design variants (Handset α, β, and γ) were created based on actual cell phones on the market. The handsets were designed to have identical functions and the same clamshell-type appearance, which makes it reasonable to assume same amounts of returned units and same prices for recovered handsets for all three handsets.

A clamshell (or folding) handset considered here is composed of upper and lower blocks (Fig. 4). The upper block comprises the main and sub-LCD, UI board, camera, and earpiece, all contained by cover A (outside upper cover) and cover B (inside upper cover). In the lower block the key mat, dome sheet, main PWB, antenna, and microphone are positioned, contained by cover C (inside upper cover) and cover D (outside lower cover). Covers B and C compose the main frame constructing the folding structure of the handset and are fastened by a hinge module. The PWB flex connects the UI board and main PWB through the folding frame. Detailed component information used here is described in Table 3, where "cost" represents the price for a new component that the recovery company should pay for a new spare part, and "resale" indicates the revenue from a used component in working condition in a cell phone market. The company can gain resale values by selling the components resulting from handset disassembly. Resale values are assumed to be half of new part cost.

The three handsets in this study share identical components, except for the display-related parts. Table 3 gives detailed information about the part composition of each handset. Each design is differentiated from the others in terms of modular design in three ways: (1) display parts, (2) folding structure, and (3) key mat. Figure 4 represents the three handset designs and their architectural characteristics.

5.2.1 Integrated Design of Display Parts. For the display, a handset requires four components: a main liquid crystal display (LCD), a sub-LCD (or caller ID LCD), a user-interface (UI) Board, and a printed wiring board (PWB) flex connector. These components can be integrated into a handset in three ways, as shown in Fig. 4: They can be designed as four distinctive parts: the main LCD and sub-LCD can be combined as a dual LCD component, or all four can be integrated into a single LCD module. The last method of integration tends to be lighter, since less

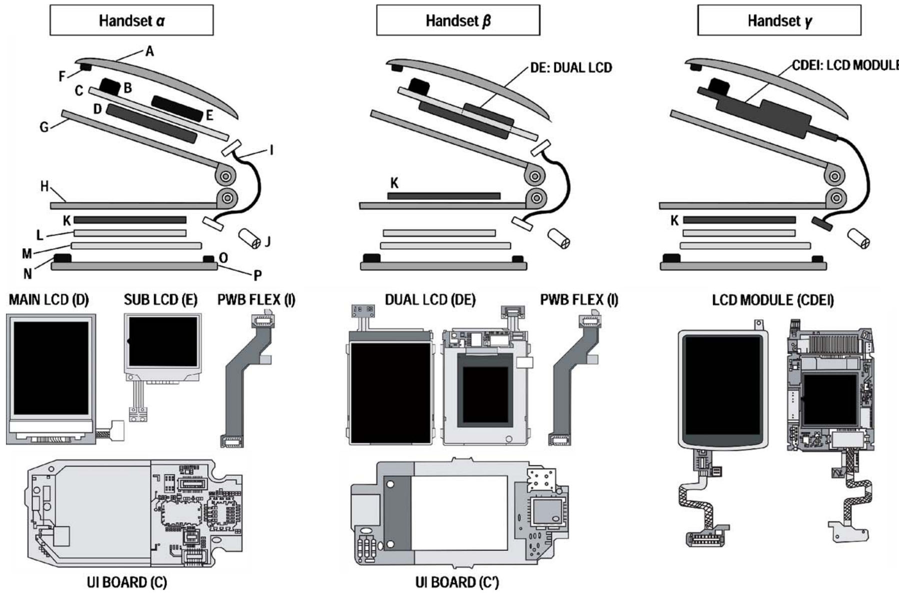


Fig. 4 Three design variants for a clamshell-type handset

material is used. In this work, Handsets α, β, and γ follow different ways and have four distinctive parts, a dual LCD, and a LCD module, respectively.

5.2.2 Disassemblability of the Folding Structure. Whether display parts are integrated into a module affects the disassemblability of the folding structure, when a handset contains an integrated display part, i.e., a LCD module, the handset can be disassembled only from the lower cover. In order to dismantle the upper block, the lower block must be disassembled. However, in other cases, a handset can be disassembled from either the upper block or the lower block, so there is no precedence between two blocks.

5.2.3 Detachability of Key Mat. There are two possible alternatives for designing the connection between the key mat and the remaining lower block: The key mat can be easily detachable from the entire handset without any prerequisite disassembly or the key mat is blocked by other parts in the lower block, thus requiring another disassembly process in order to be detached. In this study, Handset β has a key mat that can be disassembled at any time, unlike other handsets.

To evaluate the three handset designs, we need to convert each design into a transition matrix. Three transition matrices for Handsets α, β, and γ appear in the Appendix.

5.3 Design and Recovery Scenarios. There are several factors besides product design that influence recovery profit: the number and quality of returned product, market parameters (e.g., demand size and potential resale revenue), and recovery network features (e.g., possible locations and expected capacity of recovery facilities, operation cost, and transportation rate). In order to

Table 3 Handset component information (the O's indicate the parts included in each of the handsets)

Part information					Handset information		
Part ID	Part name	Cost ($)	Resale ($)	Weight (lb)	Handset α	Handset β	Handset γ
A	Cover A (upper cover)	4	2	0.01	O	O	O
B	Camera	5	2.5	0.01	O	O	O
C	UI board	5	2.5	0.02	O		
C′	UI board (with an opening)	5	2.5	0.01		O	
D	Main LCD	15	7.5	0.02	O		
E	Sub LCD	8	4	0.02	O		
(DE)	Dual LCD	23	11.5	0.04		O	
(CDEI)	LCD module	30	15	0.05			O
F	Earpiece speaker	1	0.5	0.0025	O	O	O
G	Cover B (inner upper cover)	5	2.5	0.02	O	O	O
H	Cover C (inner lower cover)	3	1.5	0.01	O	O	O
I	PWB flex	2	1	0.02	O	O	
J	Hinge module	0.5	0.25	0.02	O	O	O
K	Key mat	3	1.5	0.005	O	O	O
L	Dome sheet	1	0.5	0.005	O	O	O
M	Main PWB	20	10	0.08	O	O	O
N	Antenna	2	1	0.005	O	O	O
O	Microphone	1	0.5	0.0025	O	O	O
P	Cover D (lower cover)	5	2.5	0.01	O	O	O
	Weight of handset (lb)				0.26	0.25	0.23

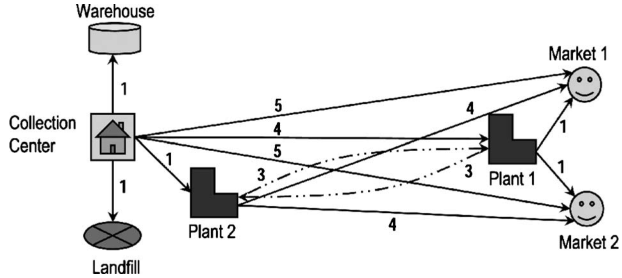


Fig. 5 Logistics network assumption for handset recovery (numbers represent the distance between two facilities; 1 represents a unit distance)

evaluate handsets α, β, and γ impartially, we need to assume such network conditions and parameters identical if they are independent of design differences. For example, possible locations of facilities and basic transportation rate should be controlled to be identical for all three handsets because they are insensitive to the presumed architectural differences. In contrast, if network conditions and parameters are dependent on design differences so that they need to be differentiated, such values are assigned based on an estimating equation and same basic data. For instance, transportation rate for a unit s is estimated by multiplying the basic transportation rate ($/lb per unit distance) by distance between facilities and weight of unit s. A scenario in this paper defines a set of values for the network conditions and parameters and proposes circumstances under which the three subject designs can be compared fairly so as to reveal the meaningful design implications in terms of product recovery.

Three scenarios used in this paper assume different quality (i.e., defect condition) of the returned handsets. Defect conditions decide which part must be disassembled and replaced in refurbishment. They also determine which part can be (or cannot be) sold to the market for component recovery. Therefore, defect conditions are important when evaluating different designs for parts and disassembly structures. Specifically, an important design issue relates to how different part designs and disassembly structures react to a specific defect condition (i.e., what designs are better than others under the defect condition) and how different defect conditions affect the result. Thus, three scenarios are defined to have different defect conditions and used to examine Handsets α, β, and γ with different display parts and disassembly structures.

Scenario 1 assumes that every returned handset has a defect in the main LCD and examines different designs for that part. Scenario 2 assumes defects in the key mat and compares the handsets focusing on different disassembly structures. Finally, scenario 3 assumes a defect in the microphone. Because the three handsets have the same microphone and the design differences are not related to microphone disassembly, the defect has a negligible effect on handset refurbishment. If the proposed model works well, the evaluated recovery profits in scenario 3 for handsets α, β, and γ should be similar. While these scenarios do not provide an exhaustive analysis, each highlights distinctively different design implications and can validate the proposed framework.

Except the defect condition, all three scenarios share the same network conditions and parameters. As Fig. 5 depicts, the company has one main collection center and sells the recovered handsets to a cell phone market (market 1) and to a recycling center (market 2). Both markets are assumed to have unlimited demand for any working unit. For nonworking units, however, market 1 has no demand, while market 2 has unlimited demand. The revenue from each market that the company can expect for selling a used or refurbished item is shown in the Appendix.

There are two potential locations for recovery plants. Plant 1 is located much closer to the markets, while plant 2 is located closer to the collection center. Except for location, both plants have identical features and are assumed to have unlimited capacity. There is also one disposal site and one warehouse available, and the capacity of each facility is assumed to be unlimited. In summary, the scenarios have values of $i=1$, $j=2$, $k=2$, $l=1$, and $r=1$.

The site-opening costs for plants 1 and 2, the disposal site, and the warehouse are set as $100,000, $10,000, and $50,000, respectively. Transportation costs are assigned based on the distance and unit weight; for simplification, "unit distance" is defined as a measure of the relative distance between two facilities; $0.385/lb is assigned for unit distance, which is represented as 1 in Fig. 5. (Dotted lines in the figure distinguish the flow between recovery plants.) Unit weights are also used to assign other costs: the disposal and storage cost as well as the penalty cost at recovery plants. All these unit cost data appear in the Appendix, along with the unit operation cost of each recovery plant.

5.4 Analysis Results. *Scenario 1*. All returned products have a defect in the LCD. Design Implication: A high-cost part has different designs. Best design: Handset α.

Regardless of the handset type, suppose that all returned handsets have problems with their main LCDs—broken LCDs, for example—while other components are in working condition. In this scenario, three handset designs are evaluated one by one under the same condition. The number of returned items for each handset is given as 5000, and every recovery plant has enough capacity to accommodate the items. While market 2 has unlimited demand for any type of item, market 1 has no demand for items containing defective LCDs. Optimization was conducted using EXCEL PREMIUM SOLVER PLATFORM (Version 9.5). Table 4 shows

Table 4 Evaluation results with three scenarios

Scenario		(1) Defect in LCDs			(2) Defect in key mats			(3) Defect in MICs		
No. of returned units=5000		Handset α	Handset β	Handset γ	Handset α	Handset β	Handset γ	Handset α	Handset β	Handset γ
Total cost		178,138	218,081	253,857	118,310	117,423	118,021	108,365	108,269	108,076
C_1	Site opening	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000
C_2	Disposal	-	-	-	-	-	-	-	-	-
C_3	Storage	-	-	-	-	-	-	-	-	-
C_4	Transportation from i	2,000	1,923	1,769	2,000	1,923	1,769	2,000	1,923	1,769
C_5	Transportation between js	-	-	-	-	-	-	-	-	-
C_6	Transportation from j to k	538	558	538	510	490	452	505	486	447
C_7	Recovery operation	75,600	115,600	151,550	15,800	15,010	15,800	5,860	5,860	5,860
	(Disassembly)	(150)	(150)	(375)	(150)	(5)	(150)	(180)	(180)	(180)
	(Part replacement)	(75,000)	(115,000)	(150,000)	(15000)	(15000)	(15000)	(5000)	(5000)	(5000)
	(Reassembly)	(450)	(450)	(1175)	(650)	(5)	(650)	(680)	(680)	(680)
C_8	Penalty	-	-	-	-	-	-	-	-	-
Revenue		375,038	375,077	375,096	375,010	375,010	375,010	375,005	375,005	375,005
Net profit		196,900	156,996	121,239	256,700	257,587	256,989	266,640	266,736	266,929

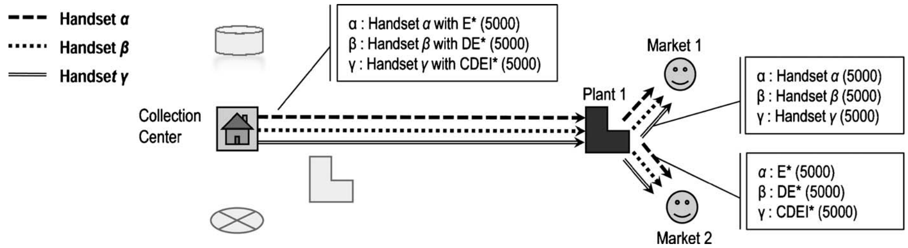


Fig. 6 Optimal network design with scenario 1

the optimization result, and Fig. 6 represents the corresponding optimal recovery network.

Our results show no difference among the three handsets in terms of reprocessing options and recovery network design. In order to achieve maximum recovery profit, 5000 units of defective handsets should be sent to plant 1 for refurbishment. At plant 1, the defective LCD part in the handset—the main LCD for handset α, the dual LCD for handset β, and the LCD module for handset γ—is detached from other components and sent to market 2 for recycling. The other components are reassembled with a new LCD part, and the units are sold as refurbished handsets in market 1. Although two plants do not differentiate the total distances from the collection center to the markets, the optimal network design always chooses plant 1 since choosing plant 2 means earlier refurbishment than plant 1, and the refurbished handsets with new spare parts will move a farther distance to market 1 after reprocessing. Since the weight from the spare parts is added earlier, plant 2 requires more transportation costs than plant 1, so plant 2 is never used when plant 1 has enough capacity to deal with the returned units.

Under this scenario, Handset α demonstrates the best design and a maximum profit of $196,900. The design difference in LCD parts results in sharp differences among the three handsets, especially concerning operation cost (C_7). Although the defect exists in the main LCD, the whole dual LCD unit must be replaced in handset β, making the required replacement cost higher than that of handset α. Handset γ shows the least profit for two reasons. First, similar to handset β, handset γ should replace the LCD modules, rather than just the main LCD. Moreover, during the refurbishment, handset γ needs more steps for disassembly and reassembly than the other two since its folding structure requires the lower block to be disassembled first before the LCD module is removed.

Scenario 2: All returned products have a defect in the key mat. Design Implication: The disassembly structure differs for an identical part. Best design: Handset β.

Instead of the main LCD, scenario 2 presents problems with key mats, and refurbishing the handsets required that their key mats be replaced. As in scenario 1, 5000 handsets are returned items, there is unlimited demand at market 2 for any type of items, and market 1 has no demand for any items containing nonworking key mats. Table 4 provides the results of the evaluation.

The results seem similar to those in scenario 1. Five thousand defective handsets are sent to Plant 1 for refurbishment, where they are disassembled into defective key mats and other components. While defective key mats are sent to market 2 for recycling, the other components are reassembled into a refurbished handset by virtue of new key mat supplies, and then sent to market 1 for resale.

However, the best design in scenario 2 differs from the one in scenario 1 in that, although the profit differences are small, handset β is the most profitable design. Handset β requires fewer disassembly and reassembly operations because it allows the key mat to be detached first without precedence constraints. The magnitude of the revenue value, however, diminishes the impact of savings in the disassembly process. In addition, handset γ's lower weight reduces the differences between handset β and γ since the lighter unit has a lower transportation cost.

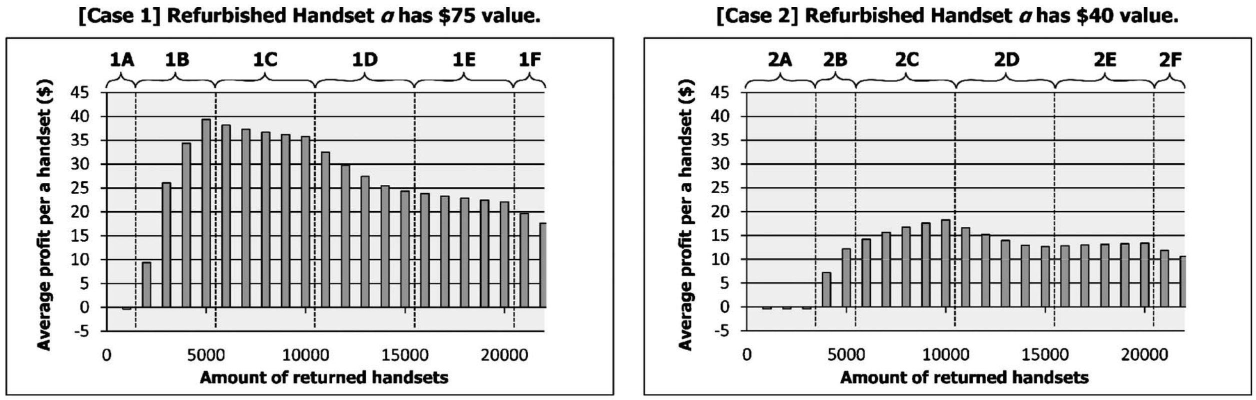
Scenario 3: All returned products have a defect in the MIC. Design Implication: Designs are identical for a part, but the product weights differ. Best design: Handset γ.

Scenario 3 assumes a defect in the microphone, but all other assumptions and conditions from the previous scenarios are the same. With respect to the microphone, the three designs are identical; all of them place the microphone in the same location in the lower blocks. Thus, it is expected that the three designs are comparable in terms of the recovery profit.

The results from the reprocessing option and logistics network are similar to those of scenarios 1 and 2. Regardless of the handset type, the optimal recovery plan for the 5000 returned handsets involves detachment and recycling of defective microphones, followed by handset refurbishment by means of a new microphone supply. As expected, the three handset designs show similar recovery profits (Table 4). Although slight differences in recovery profits exist because of differences in transportation costs related to weight features, the operation costs are exactly the same for the three designs. Since handset γ is the lightest, it shows better performance than others, but the profit gap is very small compared with that in the other two scenarios.

5.5 Discussion: Influences of Recovery Network Conditions and Parameters. In the three previous scenarios, the returned product's condition significantly changes the recovery profit. As Table 4 shows, the recovery profit in scenario 3 was higher than that in the other two scenarios. Since the microphone is a low-cost part, scenario 3 requires less replacement cost than scenarios 1 and 2. This result illustrates that variations in network conditions and parameters can lead to significantly different recovery profit, even when the product design is the same. Viewed in this light, understanding how network conditions and parameters are associated with product recovery becomes important in achieving design-for-recovery. The optimization model proposed in this work supports such approaches that consider both product design and network features simultaneously.

5.5.1 Sensitivity Analysis. In order to demonstrate how network conditions and parameters affect the recovery decision, two sensitivity analyses are conducted by increasing the number of used Handsets α from 0 to 22,000 by increments of 1000 (Fig. 7). All returned handsets are assumed to have a defect in the LCD part, as in scenario 1. Two sensitivity analyses, cases 1 and 2, assume that the resale prices from a refurbished handset in market 1 are $75 (as before) and $40, respectively. In both cases, all other resale revenues are the same: the volume of demand in market 1 is limited to 5000 for all working units, market 2 maintains unlimited demand, and the capacity of every operation in plants 1 and 2 is limited to 5000. Other network conditions and parameters are identical with previous scenarios. The analysis results are represented in Fig. 7, which shows how the average unit profit changes with the increase in quantity of the input units. These results clarify how various network features influence the link between



Section	Description
1A	None of recovery plants opens. No reprocessing operation is performed. **All handsets are sent to Market 2 for recycling.**
1B	Plant 1 opens and handset resale in Market 2 stops. **All handsets are refurbished and sold at Market 1.** Defective LCDs are sold at Market 2.
1C	For 5,000 units, it is the same as 1B. Demand for refurbished handset in Market 1 is fulfilled. For excess units, **component resale in Market 1 is conducted.** Defective LCDs are sold at Market 2.
1D	For 10,000 units, it is the same as 1C. All excess handsets are sent to Market 2 for recycling.
1E	For 15,000 units, it is the same as 1D. Plant 2 opens and handset resale in Market 2 stops. Component resale in Market 1 increases.
1F	For 20,000 units, it is the same as 1E. Most demand in Market 1 is satisfied. Resale in Market 2 restarts.

Section	Description
2A	None of recovery plants opens. No reprocessing operation is performed. **All handsets are sent to Market 2 for recycling.**
2B	Plant 1 opens and Handset resale at Market 2 stops. All handsets are disassembled into components. **Component resale in Market 1 is conducted.**
2C	For 5,000 units, it is the same as 2B. Demand for some components in Market 1 is fully fulfilled. For excess units, **handset refurbishment is conducted.** Defective LCDs are sold at Market 2.
2D	For 10,000 units, it is the same as 2C. All excess handsets are sent to Market 2 for recycling.
2E	For 15,000 units, it is the same as 2D. Plant 2 opens and handset resale in Market 2 stops. Component resale at Market 1 increases.
2F	For 20,000 units, it is the same as 2E. Most demand in Market 1 is satisfied. Resale in Market 2 restarts.

Fig. 7 Sensitivity analysis results (handset α)

product design and its recovery solution. Although various network features affect product recovery, here we focus on three features: (1) new-site-opening cost, (2) price of the remanufactured product, and (3) facility capacity and demand volume.

New-site-opening cost. The site-opening cost of a recovery plant serves as a barrier to entry and makes an in-plant recovery option less attractive until the number of used handsets exceeds a certain level. This observation emphasizes the importance of economies of scale in product recovery. In case 1, when the number of used handset is 1000, none of recovery plants opens because of the $100,000 site-opening cost, and thus, no reprocessing operation—whether disassembly, reassembly, or replacement—appears in the optimal plan. Instead of reprocessing, then, selling all the returned units in market 2 is the optimal solution. However, when there are enough returned units to make the site opening affordable and profitable, handset refurbishment is chosen as the optimal solution, which significantly raises the recovery profit. A similar result is found in section 2A of case 2; the only difference is the threshold amount at which the optimal plan changes. Case 2 has a higher threshold (4000 units) than case 1 does (2000 units) because a returned handset in Case 2 generates less profit, and more units are required to offset the site-opening cost. Before plant 2 opens, the impact of economies of scale reappears in sections 1D and 2D.

Price of remanufactured product. Resale prices of recovered items determine the priority of reprocessing options. In the sequence of reprocessing options added in sections B and C of cases 1 and 2, when a refurbished handset has a price of $75, the preferred reprocessing option in the optimal plan is handset refurbishment, and the next most preferred option is component resale in market 1. This result reflects the profitability of the reprocessing options. However, when the refurbished phone has a price of $40 in market 1, component resale in market 1 is preferred first, followed by handset refurbishment. Because refurbishment requires high-cost operations including part supply, when a refurbished handset has lower resale price, the most profitable option becomes component resale, which requires disassembly operations only.

Facility capacity and demand volume. Facility capacity and the volume of demand are related to setting the number of returned handsets, that is, points that divide sections in Fig. 7. Between sections B, C, D, E, and F, the optimal recovery solution changes whenever the number of returned handset reaches a certain level; a new reprocessing option is added in order to deal with excess units. There are two possible reasons for this result: facilities cannot afford the additional operations required for the additional units to use the current reprocessing option, or the demand for the item recovered is fully satisfied, so an additional unit recovered has no place to be sold. In this respect, facility capacity and/or demand size establish the upper limit of the number of used handsets that can follow a specific reprocessing option.

When the influences of network features are considered during decision making about recovery options, the optimal recovery solution is greatly affected. As shown in scenario 2, handset β shows better performance than the other two handsets when all returned handsets have a defect in the key mat. Because this result is predictable without considering any network variables and parameters, it is tempting to conclude that it is unnecessary to consider network features in decision making. However, Fig. 8, which presents the results of three different evaluations conducted under the same assumptions on defective key mats, suggests a counterargument. In the three cases, network conditions and parameters were differentiated, resulting in the changes in the optimal reprocessing option and shifts in the ranking of designs as the optimal reprocessing option changes. Figure 8(*a*) represents scenario 2, for which handset β is the best design. Figure 8(*b*) shows the case in which the resale price is $40, under which the optimal reprocess-

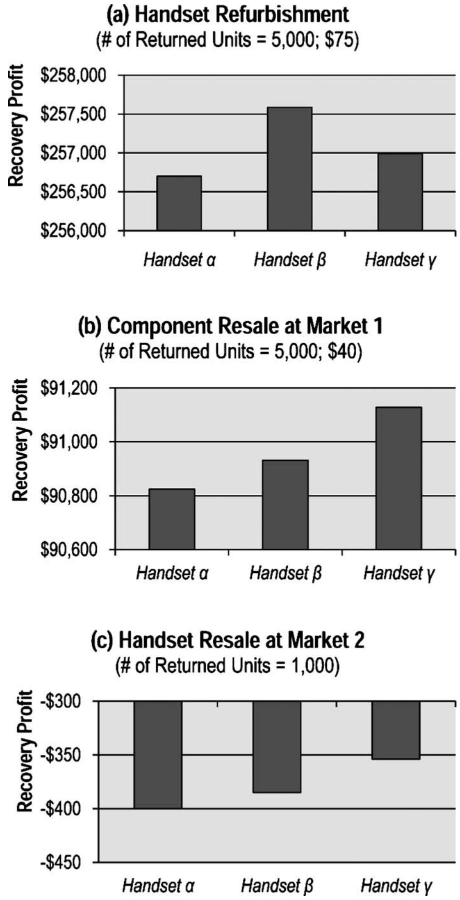


Fig. 8 Change in the rank of designs with the shift of optimal recovery plan (defect in key mats)

ing option is component resale and handset γ is most profitable. Figure 8(*c*) shows the case in which the volume of returned units is 1000, under which the optimal reprocessing option is handset resale at market 2 and handset γ is the design that loses the least amount of money. In summary, handset β's superiority in scenario 2 shifts to other designs in the second and third cases.

6 Conclusion

Product recovery has become of great concern to manufacturers who take responsibility for product end-of-life decisions, and product design is an essential part of achieving maximum recovery profit. However, the links between product design and the recovery process have not been clear, and this knowledge gap has hindered the movement toward design-for-recovery and economically viable end-of-life recovery. In this paper, we clearly established the link between products' prelife and end-of-life by showing how different product designs affect end-of-life recovery. In order to demonstrate the influences of product architecture on product recovery, we developed an optimization model for recovery profit evaluation and applied it to a design alternative so as to evaluate its recovery potential. Unlike previous models, the model used here considers both product design and recovery network design simultaneously. In doing so, recovery profit is estimated based on the optimal reprocessing options for a product, as well as on the optimal recovery network design. Also, various recovery situations can be accommodated, which are differed by changes in product design and network conditions.

To illustrate the link, we performed a comparative study for three different handset designs with different architectural characteristics. The result of this study confirms that differences in product design have a great influence on potential profit from product recovery. In a given scenario, different designs result in different recovery profits. On the other hand, if three designs share a common structure, they generate similar recovery profits. When one design is better than others, the result provides clue to preferred product design that improves economic viability of end-of-life recovery. For instance, the handset study shows that modular design (handset α) is more preferred than integrated design when high rate of defects in LCD is expected. Also, the study shows that he scenario using differences in part designs (scenario 1) reveals considerably greater differences in recovery profits than does a scenario using differences in the disassembly structures (scenario 2) or weight (scenario 3). This result implies that part composition has a greater impact on handset recovery profit than does assembly structure or weight, especially when the part is relatively high cost.

The comparative study also demonstrates that it is worthwhile to incorporate recovery network design into end-of-life decision making model. The results of this study do not suggest that the best design in one scenario is always the best in all cases. The evaluation results for different scenarios show that identifying the best design is not a simple problem since the best design changes depending on the situation considered, particularly when it is linked to end-of-life decisions. This means that it is critical to involve network conditions and parameters in linking product design and recovery profit. For example, handset α is better than the others in scenario 1 but not in scenario 2. Sensitivity analyses also support the importance of network features since changes in a returned product's quantity and condition, the size of demand in a market, expected revenue values, plant capacity, and capability, and other parameter values such as site-opening costs, can shift the evaluation results significantly, changing the designs' rankings.

It should be reminded that the purpose of this research is to provide a generic framework that simultaneously considers product design and recovery processes and network designs. In a sense, the results of three scenarios match well with the intuition, which validates that the proposed model captures the real world well and can serve various situations reliably. In the future, the framework can be extended or improved in several points. The influences of environmental regulations on recovery profit can be involved in the proposed framework. External costs or penalties due to environmental regulations (e.g., WEEE, RoHS, ELV, and REACH) are big issues in recovery industry. Thus, including such legislative driving forces in the model will lead to a more advanced framework. Uncertainty is also an important point worth being improved. Many network features are uncertain and inherently changeable. Such uncertainty should also be considered in the product design stage in order to find an optimal design that is robust to possible changes. Future work can involve developing a framework that can deal with such uncertainties. Finally, the mathematical model suggested here is for single product and single period. The mathematical model can be extended to a model for multiple types of products and multiple periods.

Acknowledgment

This material is based on the work supported by the National Science Foundation under Award No. 0726934.

Nomenclature

Index Sets

$I=\{1,\ldots,N_c\}$ = collection points, $i \in I$
$J=\{1,\ldots,N_f\}$ = potential locations of recovery plant, $j \in J$
$K=\{1,\ldots,N_d\}$ = fixed demand locations, $k \in K$
$L=\{1,\cdots,N_g\}$ = potential locations of disposal site, $l \in L$
$R=\{1,\ldots,N_w\}$ = potential locations of warehouse, $r \in R$

Table 5 Transition matrix for handset α

ID	Feasible state	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	*ABCDE*FGHIJKLMNOP*	−1	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	*ABCDEFGHIJK*LMNOP*	0	0	−1	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	*ABCDEFGHIJKLMNO*P*	0	0	0	0	−1	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	*ABCDEFGHIJKLMNOP*	0	0	0	0	0	0	−1	−1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
5	*GHIJK*LMNOP*	0	0	1	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	*GHIJKLMNO*P*	0	0	0	0	1	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	*GHIJKLMNOP*	1	0	0	0	0	0	1	0	0	0	−1	0	0	0	0	0	0	0	−1	0	1	0	0	0	0	0	0	0	0
8	*ABCDE*FGHIJ*	0	1	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	*ABCDEFGHIJ*	0	0	0	1	0	1	0	1	0	0	0	0	−1	0	0	0	0	0	0	−1	0	1	0	0	0	0	0	0	0
10	*GHIJ*	0	0	0	0	0	0	0	0	1	1	1	1	1	−1	0	0	0	0	0	0	−1	−1	1	0	0	0	0	0	0
11	*NO*P*	0	0	0	0	0	1	0	0	0	1	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	*NOP*	0	1	0	1	0	0	0	1	1	0	1	0	0	0	0	−1	0	0	0	−1	−1	0	0	1	0	0	0	0	0
13	*CD*	1	0	1	0	1	0	1	0	0	0	0	1	1	0	0	0	−1	0	−1	0	0	−1	0	0	1	0	0	0	0
14	*LM*	0	1	0	1	0	1	0	1	1	1	1	0	0	0	0	0	0	−1	0	−1	−1	0	0	0	0	1	0	0	0
15	*A*	1	0	1	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	−1	0	0	−1	0	0	0	0	0	0	0
16	*B*	1	0	1	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	−1	0	0	−1	0	0	0	0	0	0	0
17	*C*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−1	0	0	0	0
18	*D*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−1	0	0	0	0
19	*E**	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	*E*	0	0	1	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	−1	0	0	−1	0	0	0	0	1	0	0
21	*F*	1	0	1	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	−1	0	0	−1	0	0	0	0	0	0	0
22	*G*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0
23	*H*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0
24	*I*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0
25	*J*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0
26	*K**	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	*K*	0	1	0	0	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	−1	−1	0	0	0	0	0	0	1	0
28	*L*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−1	0	0	0
29	*M*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−1	0	0	0
30	*N*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	−1	0	0	0	0	0
31	*O**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	*O*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−1	0	0	0	0	1
33	*P*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	−1	0	0	0	0	0

Table 6 Transition matrix for handset β

ID	Feasible state	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
1	$ABC'(DE)^*FGHIJKLMNOP$	−1	−1	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	$ABC'(DE)FGHIJK^*LMNOP$	0	0	0	−1	−1	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	$ABC'(DE)FGHIJKLMNO^*P$	0	0	0	0	0	0	−1	−1	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	$ABC'(DE)FGHIJKLMNOP$	0	0	0	0	0	0	0	0	0	−1	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	$ABC'(DE)^*FGHIJLMNOP$	1	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	$ABC'(DE)FGHIJLMNO^*P$	0	0	0	0	0	0	1	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	$ABC'(DE)FGHIJLMNOP$	0	0	0	1	0	0	0	0	0	1	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
8	$GHIJK^*LMNOP$	0	0	0	0	1	0	0	0	0	0	0	0	0	0	−1	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	$GHIJKLMNO^*P$	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−1	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	$GHIJKLMNOP$	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	−1	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	1	1	0	0	0	0	0	0	0	0	0
11	$ABC'(DE)^*FGHIJK$	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	$ABC'(DE)FGHIJK^*$	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	$ABC'(DE)FGHIJK$	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
14	$ABC'(DE)^*FGHIJ$	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	$ABC'(DE)FGHIJ$	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	0	−1	0	0	0	0	0	0	0	0	0	0	0	−1	−1	0	0	1	0	0	0	0	0	0	0	0
16	$GHIJLMNO^*P$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	$GHIJLMNOP$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	1	0	0	0	0	0	0	0
18	$GHIJK^*$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	$GHIJK$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	−1	0	0	1	0	0	0	0	0	0
20	$GHIJ$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	−1	0	0	0	0	0	0	0	0	0	0	−1	−1	−1	1	0	0	0	0	0
21	NO^*P	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	NOP	0	0	1	0	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	−1	0	0	−1	0	−1	0	0	−1	0	−1	0	0	1	0	0	0	0
23	$(DE)^*$	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	(DE)	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	−1	0	0	0	0	0	1	0	0
25	LM	0	0	1	0	0	1	0	0	1	0	0	1	1	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	0	0	0	0	−1	0	−1	0	−1	0	0	−1	0	−1	0	0	0	1	0	0	0
26	A	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	−1	0	0	0	0	0	0	0	0
27	B	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	−1	0	0	0	0	0	0	0	0
28	C'	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	−1	0	0	0	0	0	0	0	0
29	F	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	−1	0	0	0	0	0	0	0	0
30	G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0
31	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0
32	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0
33	J	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0
34	K^*	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	K	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	−1	0	0	0	−1	−1	0	0	0	−1	0	0	0	0	1	0
36	L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0
37	M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0
38	N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0
39	O^*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	1
41	P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0

Table 7 Transition matrix for handset γ

ID	Feasible state	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	$AB(CDEI)^{*}FGHJKLMNOP$	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	$AB(CDEI)FGHJK^{*}LMNOP$	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	$AB(CDEI)FGHJKLMNO^{*}P$	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	$AB(CDEI)FGHJKLMNOP$	0	0	0	−1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
5	$AB(CDEI)^{*}FGHJ$	1	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	$AB(CDEI)FGHJ$	0	1	1	1	0	−1	0	0	0	0	0	−1	1	0	0	0	0	0	0
7	$AB(CDEI)^{*}FG$	0	0	0	0	1	0	−1	0	0	0	0	0	0	0	0	0	0	0	0
8	$AB(CDEI)FG$	0	0	0	0	0	1	0	−1	0	0	0	0	−1	1	0	0	0	0	0
9	$(CDEI)^{*}$	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
10	$(CDEI)$	0	0	0	0	0	0	0	1	0	0	0	0	0	−1	0	0	1	0	0
11	$NO^{*}P$	0	0	1	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0
12	NOP	1	1	0	1	0	0	0	0	0	−1	0	−1	0	0	1	0	0	0	0
13	LM	1	1	1	1	0	0	0	0	0	0	−1	−1	0	0	0	1	0	0	0
14	A	0	0	0	0	0	0	1	1	0	0	0	0	0	−1	0	0	0	0	0
15	B	0	0	0	0	0	0	1	1	0	0	0	0	0	−1	0	0	0	0	0
16	F	0	0	0	0	0	0	1	1	0	0	0	0	0	−1	0	0	0	0	0
17	G	0	0	0	0	0	0	1	1	0	0	0	0	0	−1	0	0	0	0	0
18	H	0	0	0	0	1	1	0	0	0	0	0	0	−1	0	0	0	0	0	0
19	J	0	0	0	0	1	1	0	0	0	0	0	0	−1	0	0	0	0	0	0
20	K^{*}	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	K	1	0	1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	1	0
22	L	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	−1	0	0	0
23	M	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	−1	0	0	0
24	N	0	0	0	0	0	0	0	0	1	1	0	0	0	0	−1	0	0	0	0
25	O^{*}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
26	O	0	0	0	0	0	0	0	0	0	1	0	0	0	0	−1	0	0	0	1
27	P	0	0	0	0	0	0	0	0	1	1	0	0	0	0	−1	0	0	0	0

Table 8 Operation cost information: c_{jp}^{o}

		Transition No.													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Handset α	Plant 1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.015
	Plant 2	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.015
Handset β	Plant 1	0.001	0.03	0.03	0.001	0.03	0.03	0.001	0.03	0.03	0.001	0.03	0.03	0.03	0.03
	Plant 2	0.001	0.03	0.03	0.001	0.03	0.03	0.001	0.03	0.03	0.001	0.03	0.03	0.03	0.03
Handset γ	Plant 1	0.03	0.03	0.03	0.03	0.015	0.015	0.03	0.03	0.006	0.006	0.003	0.13	0.015	0.09
	Plant 2	0.03	0.03	0.03	0.03	0.015	0.015	0.03	0.03	0.006	0.006	0.003	0.13	0.015	0.09
		15	16	17	18	19	20	21	22	23	24	25	26	27	28
Handset α	Plant 1	0.006	0.006	0.003	0.003	0.09	0.13	0.13	0.09	0.015	0.006	0.006	0.006	15	3
	Plant 2	0.006	0.006	0.003	0.003	0.09	0.13	0.13	0.09	0.015	0.006	0.006	0.006	15	3
Handset β	Plant 1	0.001	0.001	0.001	0.03	0.03	0.03	0.001	0.001	0.001	0.03	0.03	0.03	0.03	0.001
	Plant 2	0.001	0.001	0.001	0.03	0.03	0.03	0.001	0.001	0.001	0.03	0.03	0.03	0.03	0.001
Handset γ	Plant 1	0.006	0.006	30	3	1									
	Plant 2	0.006	0.006	30	3	1									
		29	30	31	32	33	34	35	36	37	38	39	40	41	42
Handset α	Plant 1	1													
	Plant 2	1													
Handset β	Plant 1	0.001	0.015	0.006	0.006	0.006	0.001	0.13	0.09	0.13	0.001	0.001	0.13	0.09	0.13
	Plant 2	0.001	0.015	0.006	0.006	0.003	0.001	0.13	0.09	0.13	0.001	0.001	0.13	0.09	0.13
		43	44	45	46	47	48	49							
Handset β	Plant 1	0.001	0.015	0.006	0.006	23	3	1							
	Plant 2	0.001	0.015	0.006	0.006	23	3	1							

Table 9 Cost and revenue parameters (handset α)

Feasible state	c_{il}^{g2}	c_{il}^{g3}	c_{ir}^{w2}	c_{ir}^{w3}	$c_{j_1s}^{h}$	$c_{j_2s}^{h}$	$r_{k_1s}^{d}$	$r_{k_2s}^{d}$
$ABCDE^{*}FGHIJKLMNOP$	0.100	1.500	0.100	0.500	3.000	3.000	20.00	0.100
$ABCDEFGHIJK^{*}LMNOP$	0.100	1.500	0.100	0.500	3.000	3.000	25.00	0.100
$ABCDEFGHIJKLMNO^{*}P$	0.100	1.500	0.100	0.500	3.000	3.000	25.00	0.100
$ABCDEFGHIJKLMNOP$	0.100	1.500	0.100	0.500	3.000	3.000	75.00	0.100
$GHIJK^{*}LMNOP$	N/A	N/A	N/A	N/A	2.048	2.048	12.00	0.068
$GHIJKLMNO^{*}P$	N/A	N/A	N/A	N/A	2.048	2.048	12.00	0.068
$GHIJKLMNOP$	N/A	N/A	N/A	N/A	2.048	2.048	16.00	0.068
$ABCDE^{*}FGHIJ$	N/A	N/A	N/A	N/A	1.760	1.760	0.00	0.059
$ABCDEFGHIJ$	N/A	N/A	N/A	N/A	1.760	1.760	8.00	0.059
$GHIJ$	N/A	N/A	N/A	N/A	0.269	0.269	4.00	0.027
$NO^{*}P$	N/A	N/A	N/A	N/A	0.067	0.067	0.00	0.007
NOP	N/A	N/A	N/A	N/A	0.067	0.067	2.00	0.007
CD	N/A	N/A	N/A	N/A	0.462	0.462	6.00	0.015
LM	N/A	N/A	N/A	N/A	0.981	0.981	10.00	0.033
A	N/A	N/A	N/A	N/A	0.038	0.038	2.00	0.004
B	N/A	N/A	N/A	N/A	0.038	0.038	2.50	0.004
C	N/A	N/A	N/A	N/A	0.231	0.231	2.50	0.008
D	N/A	N/A	N/A	N/A	0.231	0.231	4.00	0.008
E^{*}	N/A	N/A	N/A	N/A	0.231	0.231	0.00	0.008
E	N/A	N/A	N/A	N/A	0.231	0.231	7.50	0.008
F	N/A	N/A	N/A	N/A	0.010	0.010	0.50	0.001
G	N/A	N/A	N/A	N/A	0.077	0.077	2.50	0.008
H	N/A	N/A	N/A	N/A	0.038	0.038	1.50	0.004
I	N/A	N/A	N/A	N/A	0.077	0.077	1.00	0.008
J	N/A	N/A	N/A	N/A	0.077	0.077	0.25	0.008
K^{*}	N/A	N/A	N/A	N/A	0.019	0.019	0.00	0.002
K	N/A	N/A	N/A	N/A	0.019	0.019	1.50	0.002
L	N/A	N/A	N/A	N/A	0.019	0.019	0.50	0.002
M	N/A	N/A	N/A	N/A	0.923	0.923	10.00	0.031
N	N/A	N/A	N/A	N/A	0.019	0.019	1.00	0.002
O^{*}	N/A	N/A	N/A	N/A	0.010	0.010	0.00	0.001
O	N/A	N/A	N/A	N/A	0.010	0.010	0.50	0.001
P	N/A	N/A	N/A	N/A	0.038	0.038	2.50	0.004

Table 10 Cost and revenue parameters (handset γ)

Feasible state	c_{il}^{g2}	c_{il}^{g3}	c_{ir}^{w2}	c_{ir}^{w3}	$c_{j_1s}^{h}$	$c_{j_2s}^{h}$	$r_{k_1s}^{d}$	$r_{k_2s}^{d}$
$AB(CDEI)^{*}FGHJKLMNOP$	0.088	1.327	0.088	0.442	2.654	2.654	20.00	0.088
$AB(CDEI)FGHJK^{*}LMNOP$	0.088	1.327	0.088	0.442	2.654	2.654	25.00	0.088
$AB(CDEI)FGHJKLMNO^{*}P$	0.088	1.327	0.088	0.442	2.654	2.654	25.00	0.088
$AB(CDEI)FGHJKLMNOP$	0.088	1.327	0.088	0.442	2.654	2.654	75.00	0.088
$AB(CDEI)^{*}FGHJ$	N/A	N/A	N/A	N/A	1.413	1.413	0.00	0.047
$AB(CDEI)FGHJ$	N/A	N/A	N/A	N/A	1.413	1.413	8.00	0.047
$AB(CDEI)^{*}FG$	N/A	N/A	N/A	N/A	1.067	1.067	0.00	0.036
$AB(CDEI)FG$	N/A	N/A	N/A	N/A	1.067	1.067	8.00	0.036
$(CDEI)^{*}$	N/A	N/A	N/A	N/A	0.577	0.577	0.00	0.019
$(CDEI)$	N/A	N/A	N/A	N/A	0.577	0.577	15.00	0.019
$NO^{*}P$	N/A	N/A	N/A	N/A	0.067	0.067	0.00	0.007
NOP	N/A	N/A	N/A	N/A	0.067	0.067	2.00	0.007
LM	N/A	N/A	N/A	N/A	0.327	0.327	10.00	0.033
A	N/A	N/A	N/A	N/A	0.038	0.038	2.00	0.004
B	N/A	N/A	N/A	N/A	0.038	0.038	2.50	0.004
F	N/A	N/A	N/A	N/A	0.010	0.010	0.50	0.001
G	N/A	N/A	N/A	N/A	0.077	0.077	2.50	0.008
H	N/A	N/A	N/A	N/A	0.038	0.038	1.50	0.004
J	N/A	N/A	N/A	N/A	0.077	0.077	0.25	0.008
K^{*}	N/A	N/A	N/A	N/A	0.019	0.019	0.00	0.002
K	N/A	N/A	N/A	N/A	0.019	0.019	1.50	0.002
L	N/A	N/A	N/A	N/A	0.019	0.019	0.50	0.002
M	N/A	N/A	N/A	N/A	0.923	0.923	10.00	0.031
N	N/A	N/A	N/A	N/A	0.019	0.019	1.00	0.002
O^{*}	N/A	N/A	N/A	N/A	0.010	0.010	0.00	0.001
O	N/A	N/A	N/A	N/A	0.010	0.010	0.50	0.001
P	N/A	N/A	N/A	N/A	0.038	0.038	2.50	0.004

Table 11 Cost and revenue parameters (handset β)

Feasible state	c_{il}^{g2}	c_{il}^{g3}	c_{ir}^{w2}	c_{ir}^{w3}	$c_{j_1s}^{h}$	$c_{j_2s}^{h}$	$r_{k_1s}^{d}$	$r_{k_2s}^{d}$
$ABC'(DE)^{*}FGHIJKLMNOP$	0.096	1.442	0.096	0.481	2.885	2.885	20.00	0.096
$ABC'(DE)FGHIJK^{*}LMNOP$	0.096	1.442	0.096	0.481	2.885	2.885	25.00	0.096
$ABC'(DE)FGHIJKLMNO^{*}P$	0.096	1.442	0.096	0.481	2.885	2.885	25.00	0.096
$ABC'(DE)FGHIJKLMNOP$	0.096	1.442	0.096	0.481	2.885	2.885	75.00	0.096
$ABC'(DE)^{*}FGHIJLMNOP$	N/A	N/A	N/A	N/A	2.827	2.827	0.00	0.094
$ABC'(DE)FGHIJLMNO^{*}P$	N/A	N/A	N/A	N/A	2.827	2.827	24.55	0.094
$ABC'(DE)FGHIJLMNOP$	N/A	N/A	N/A	N/A	2.827	2.827	50.00	0.094
$GHIJK^{*}LMNOP$	N/A	N/A	N/A	N/A	2.048	2.048	12.00	0.068
$GHIJKLMNO^{*}P$	N/A	N/A	N/A	N/A	2.048	2.048	12.00	0.068
$GHIJKLMNOP$	N/A	N/A	N/A	N/A	2.048	2.048	16.00	0.068
$ABC'(DE)^{*}FGHIJK$	N/A	N/A	N/A	N/A	1.702	1.702	0.00	0.057
$ABC'(DE)FGHIJK^{*}$	N/A	N/A	N/A	N/A	1.702	1.702	8.00	0.057
$ABC'(DE)FGHIJK$	N/A	N/A	N/A	N/A	1.702	1.702	9.00	0.057
$ABC'(DE)^{*}FGHIJ$	N/A	N/A	N/A	N/A	1.644	1.644	0.00	0.055
$ABC'(DE)FGHIJ$	N/A	N/A	N/A	N/A	1.644	1.644	8.00	0.055
$GHIJLMNO^{*}P$	N/A	N/A	N/A	N/A	2.048	2.048	4.00	0.068
$GHIJLMNOP$	N/A	N/A	N/A	N/A	2.048	2.048	12.00	0.068
$GHIJK^{*}$	N/A	N/A	N/A	N/A	0.288	0.288	4.00	0.029
$GHIJK$	N/A	N/A	N/A	N/A	0.288	0.288	5.00	0.029
$GHIJ$	N/A	N/A	N/A	N/A	0.269	0.269	4.00	0.027
$NO^{*}P$	N/A	N/A	N/A	N/A	0.067	0.067	0.00	0.007
NOP	N/A	N/A	N/A	N/A	0.067	0.067	2.00	0.007
$(DE)^{*}$	N/A	N/A	N/A	N/A	0.462	0.462	0.00	0.015
(DE)	N/A	N/A	N/A	N/A	0.462	0.462	11.50	0.015
LM	N/A	N/A	N/A	N/A	0.981	0.981	10.00	0.033
A	N/A	N/A	N/A	N/A	0.038	0.038	2.00	0.004
B	N/A	N/A	N/A	N/A	0.038	0.038	2.50	0.004
C'	N/A	N/A	N/A	N/A	0.115	0.115	2.50	0.004
F	N/A	N/A	N/A	N/A	0.010	0.010	0.50	0.001
G	N/A	N/A	N/A	N/A	0.077	0.077	2.50	0.008
H	N/A	N/A	N/A	N/A	0.038	0.038	1.50	0.004
I	N/A	N/A	N/A	N/A	0.077	0.077	1.00	0.008
J	N/A	N/A	N/A	N/A	0.077	0.077	0.25	0.008
K^{*}	N/A	N/A	N/A	N/A	0.019	0.019	0.00	0.002
K	N/A	N/A	N/A	N/A	0.019	0.019	1.50	0.002
L	N/A	N/A	N/A	N/A	0.019	0.019	0.50	0.002
M	N/A	N/A	N/A	N/A	0.923	0.923	10.00	0.031
N	N/A	N/A	N/A	N/A	0.019	0.019	1.00	0.002
O^{*}	N/A	N/A	N/A	N/A	0.010	0.010	0.00	0.001
O	N/A	N/A	N/A	N/A	0.010	0.010	0.50	0.001
P	N/A	N/A	N/A	N/A	0.038	0.038	2.50	0.004

$P=\{1,\ldots,N_o\}$ = possible recovery operation, $p \in P$
$S=\{1,\ldots,N_q\}$ = possible states of recovery target unit, $s \in S$

Variables

X_{ils}^{g} = volume of unit in state s flowing from i to disposal site l
X_{irs}^{w} = volume of unit in state s flowing from i to warehouse r
X_{ijs}^{α} = volume of unit in state s flowing from i to recovery plant j
X_{iks}^{β} = volume of unit in state s flowing from i to demand site k
X_{jks}^{γ} = volume of unit in state s flowing from j to demand site k
$X_{j_mj_ns}^{\delta}$ = volume of unit in state s flowing from j_m to j_n, $j_m \neq j_n$
X_{js}^{h} = volume of unit in state s not proceeded further and discarded at j
Y_j^f = indicator opening recovery plant j
Y_l^g = indicator opening disposal location l
Y_r^w = indicator opening warehouse r

Z_{jp} = number of times operation p is executed at plant j

Parameters

T_{sp} = entity value of transition matrix
E_{is} = total volume of returned product with state s at i
v_{ks}^{d} = volume of demand for unit in state s at site k
u_{jp}^{f} = maximum capacity of plant j for recovery operation p
r_{ks}^{d} = revenue from providing a unit in state s at demand site k
c_j^f = fixed cost for opening recovery plant j
c_l^{g1} = fixed cost for opening disposal location l
c_r^{w1} = fixed cost for opening warehouse r
c_{il}^{g2} = transportation rate from i to disposal location l for a unit s
c_{ir}^{w2} = transportation rate from i to warehouse r for a unit s
c_{il}^{g3} = processing cost at disposal location l for a unit s
c_{ir}^{w3} = processing cost at warehouse r for a unit s
c_{ijs}^{α} = transportation rate from i to plant j for a unit s
c_{iks}^{β} = transportation rate from i to demand site k for a unit s

c_{jks}^{γ} = transportation rate from j to demand site k for a unit s

$c_{j_m j_n s}^{\delta}$ = transportation rate from plant j_m to j_n, $j_m \neq j_n$ for a unit s

c_{jp}^{o} = unit processing cost for recovery operation p at plant j

c_{js}^{h} = penalty cost for the discarded unit at plant j for a unit s

Appendix

Tables 5–7 show the transition matrix for handsets α, β, and γ, while Table 8 shows the operation cost information. Tables 9–11 list the cost and revenue parameters of handsets α, β, and γ.

References

[1] Kwak, M. J., and Kim, H. M., 2009, "Simultaneous Consideration of Product Design and End-of-Life Recovery Network Design," Proceedings of the International Conference on Engineering Design, Stanford, CA.

[2] Mangun, D., and Thurston, D. L., 2002, "Incorporating Component Reuse, Remanufacture, and Recycle into Product Portfolio Design," IEEE Trans. Eng. Manage., **49**(4), pp. 479–490.

[3] Fixson, S. K., 2004, "Assessing Product Architecture Costing: Product Life Cycles, Allocation Rules, and Cost Models," Proceedings of the ASME 2004 Design Engineering Technical Conferences, Salt Lake City, UT.

[4] Zhang, Y., and Gershenson, J. K., 2002, "Questioning the Direct Relationship between Product Modularity and Retirement Cost," The Journal of Sustainable Product Design, **2**(1–2), pp. 53–68.

[5] Kwak, M. J., Hong, Y. S., and Cho, N. W., 2009, "Eco-Architecture Analysis for End-of-Life Decision Making," Int. J. Prod. Res., **47**(22), pp. 6233–6259.

[6] Dekker, R., Fleischmann, M., Inderfurth, K., and Van Wasswnhove, L. N., 2004, *Reverse Logistics*, Springer-Verlag, Berlin.

[7] Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J. M., and Van Wassenhove, L. N., 2001, "The Impact of Product Recovery on Logistics Network Design," Production and Operations Management, **10**(2), pp. 156–173.

[8] Dowie, T., and Kelly, P., 1994, *Estimation of Disassembly Times. Unpublished Technical Report*, Manchester Metropolitan University, Manchester, UK.

[9] Kroll, E., and Carver, B. S., 1999, "Disassembly Analysis Through Time Estimation and Other Metrics," Rob. Comput.-Integr. Manufact., **15**(3), pp. 191–200.

[10] Das, S., Yedlarajiah, P., and Narendra, R., 2000, "An Approach for Estimating the EOL Product Disassembly Effort and Cost," Int. J. Prod. Res., **38**(3), pp. 657–673.

[11] Marks, M. D., Eubanks, C. F., and Ishii, K., 1993, "Life-Cycle Clumping of Product Designs for Ownership and Retirement," Proceedings of the ASME Design Theory and Methodology, Albuquerque, NM, pp. 83–90.

[12] Veerakamolmal, P., and Gupta, S. M., 1999, "Analysis of Design Efficiency for the Disassembly of Modular Electronic Products," J. Electron. Manuf., **9**(1), pp. 79–95.

[13] Hula, A., Jalali, K., Hamza, K., Skerlos, S. J., and Saitou, K., 2003, "Multi-Criteria Decision-Making for Optimization of Product Disassembly Under Multiple Situations," Environ. Sci. Technol., **37**(23), pp. 5303–5313.

[14] Shalaby, M. and Saitou, K., 2008, "Design for Disassembly With High-Stiffness Heat-Reversible Locator-Snap Systems," ASME J. Mech. Des., **130**(12), p. 121701.

[15] Shalaby, M. and Saitou, K., 2009, "High-Stiffness, Lock-and-Key Heat-Reversible Locator-Snap Systems for the Design for Disassembly," ASME J. Mech. Des., **131**(4), p. 041005.

[16] Collado-Ruiz, D. and Capuz-Rizo, S.F., 2010, "Modularity and Ease of Disassembly: Study of Electrical and Electronic Equipment," ASME J. Mech. Des., **132**(1), p. 014502.

[17] Gonzalez, B., and Adenso-diaz, B., 2005, "A Bill of Materials-Based Approach for EOL Decision Making in Design for the Environment," Int. J. Prod. Res., **43**(10), pp. 2071–2099.

[18] Pnueli, Y., and Zussman, E., 1997, "Evaluating the EOL Value of a Product and Improving It by Redesign," Int. J. Prod. Res., **35**(4), pp. 921–942.

[19] Erdos, G., Kis, T., and Xirouchakis, P., 2001, "Modeling and Evaluating Product EOL Options," Int. J. Prod. Res., **39**(6), pp. 1203–1220.

[20] Lambert, A. J. D., 2002, "Determining Optimum Disassembly Sequences in Electronic Equipment," Comput. Ind. Eng., **43**(3), pp. 553–575.

[21] Seliger, G., Basdere, B., Ciupek, M., and Franke, C., 2003, CIRP Seminar on Life Cycle Engineering, Contribution to Efficient Cellular Phone Remanufacturing, Copenhagen, Denmark.

[22] Gupta, S. M., Erbis, E., and McGovern, S. M., 2004, "Disassembly Sequencing Problem: A Case Study of a Cell Phone," SPIE International Conference on Environmentally Conscious Manufacturing IV, Philadelphia, PA, pp. 43–52.

[23] http://www.tessco.com