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A Multiphase Fuzzy Logic Approach to Strategic Planning of a Reverse Supply Chain Network

Kishore K. Pochampally and Surendra M. Gupta

Abstract—**Strategic planning (also called designing) is a challenging aspect of a reverse supply chain network. To effectively satisfy drivers such as profitability, environmental regulations, and asset recovery, only the most economical used products must be reprocessed in only the recovery facilities that have the potential to efficiently reprocess them. Due to uncertainties in supply, quality, and reprocessing times of used products, the cost-benefit function in the literature that selects the most economical product to reprocess from a set of used products is not appropriate for direct adoption. Moreover, due to the same uncertainties, any traditional forward supply chain approach to identify potential manufacturing facilities cannot be employed to identify potential recovery facilities. This paper proposes a three-phase fuzzy logic approach, taking the above uncertainties into account, to design a reverse supply chain network. Application of the approach is detailed through an illustrative example in each phase.**

Index Terms—**Analytic hierarchy process (AHP), fuzzy, reverse supply chain, strategic planning.**

I. Introduction

A reverse supply chain can be defined as a series of activities required to retrieve a used product from a customer and either recover its left-over market value or dispose it of. Besides asset recovery and environmental regulations [6], [8], [25], an important driver for companies to engage in a reverse supply chain is that many used products, especially electronic ones [7], [9], [14], [19], [20], represent a resource for recoverable value. Though direct reuse of used products is infeasible in most cases, remanufacturing and recycling are the major recovery options applied in the reverse supply chain. While this process is common in European companies, it is still in relative infancy in American companies. In the USA, cities and towns are responsible for retrieval of used electronic goods and properly disposing of the potentially environmentally dangerous components (also called e-waste). Recently, there was a report [2] that in the state of Massachusetts, support is building for a refiled bill that would require manufacturers of electronic goods to pay for retrieval and recycling of their equipment. If passed, the statewide take-back program would be the first of its kind in the nation and would relieve cities and towns, which are bracing for local aid cuts, from the costs associated with retrieving and disposing of the e-waste. The bill's supporters say that cities and towns in the USA spend between \$6 million and \$21 million a year on such endeavors.

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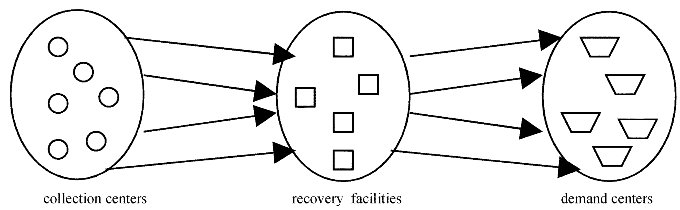

Fig. 1. Generic reverse supply chain.

Implementation of any reverse supply chain network (RSCN) requires at least three parties: collection centers where consumers return used products, recovery facilities where reprocessing (remanufacturing or recycling) is performed, and demand centers where customers buy reprocessed products, *viz.*, outgoing goods from recovery facilities. Fig. 1 shows a generic reverse supply chain network.

While there are many strategic, tactical, and operational aspects that are considered in an RSCN, this paper concentrates on strategic planning (also called designing) that ideally should involve the following phases:

1) Selection of the most economical product to reprocess, from a set of different used products (this step in turn leads to the identification of potential collection centers and potential demand centers in the region where an RSCN is to be designed);
2) identification of potential facilities in a set of candidate recovery facilities operating in the region;
3) Minimization of overall cost, i.e., sum of the costs of retrieval, inventory, remanufacturing, and transportation of products (used and remanufactured) across the RSCN.

In this paper, we propose mathematical models for each of the above three phases. Practitioners who are interested in recovering components and materials from used electronic products, such as computers, copiers, and cell phones that contain components of considerable resale value and materials of high recyclability, may apply our models to 1) select the most economical used electronic product to reprocess, 2) select recovery facilities where the selected used electronic product will be reprocessed, and 3) minimize overall cost across the reverse supply chain.

II. Literature Review

In the literature for designing an RSCN, while many location models deal with the transportation issue (see [3] and [5] for good reviews), no paper addresses the problem of either selecting the most economical product from a set of used products or identifying potential recovery facilities in the region where an RSCN is to be designed. In the case of discrete location models (for example, [13]), *all* the recovery facilities are assumed to be potential and in the case of continuous location models (for example, [12]), it is assumed that potential recovery facilities were already established or can be established at the locations solved for. Also, each of these location models deals with a used product that is *given* to be economical. Evidently, though every location model realizes the importance of reprocessing only an economical used product in potential recovery facilities, it does not show either how to select that used product from a set of many economical used products or how to identify those potential recovery facilities in the region where the RSCN is to be designed.

Although one paper [23] proposes a cost-benefit function that assesses the feasible combinations (set of components) of retrieval from the design of a used product and compares the combination with the highest benefit from one design against those from the others, the function assumes that every component selected for reuse will be in a reusable state after dismantling the product. It also assumes that all the components in the retrieved used product are in their original multiplicities. It is inappropriate to adopt that benefit function for selecting the most economical product to reprocess from a set of used products because neither of the above assumptions is universally valid in a reverse supply chain scenario.

Although identification of potential manufacturing facilities is widely addressed in a forward supply chain (the series of activities required to produce and distribute a new product to a customer), the corresponding approaches (for example, [22]) are unsuitable for employment in a reverse supply chain. This is due to the problems associated with reprocessing, which include: 1) uncertainties in supply and timing of used products, and 2) unknown quality and quantity of components in used products.

III. Techniques Used in This Paper

For the convenience of the reader, in this section, we briefly introduce the fuzzy set theory [24] that is used in all the three phases (Sections IV–VI) of our approach to strategic planning of an RSCN, and the analytic hierarchy process (AHP) [17] that is used in the second phase (Section V) of the approach.

A. *Fuzzy Set Theory*

Expression such as "not very clear," "probably so," "approximately," and "very likely" are often heard in daily life. The commonality in such expressions is that they are tainted with imprecision. This imprecision or vagueness of human decision-making is called "fuzziness" in the scientific literature. Since Zadeh [24] first proposed fuzzy set theory, an increasing number of studies have dealt with imprecision (fuzziness) in problems. This paper too makes use of the theory, in the formulation of the benefit function for selecting economical used products (Section IV), in the employment of the analytic hierarchy process for identifying potential recovery facilities (Section V), and in the example for the transshipment model for minimizing overall cost (Section VI) across the RSCN. The concepts of the fuzzy set theory, which we utilize in this paper, are as follows.

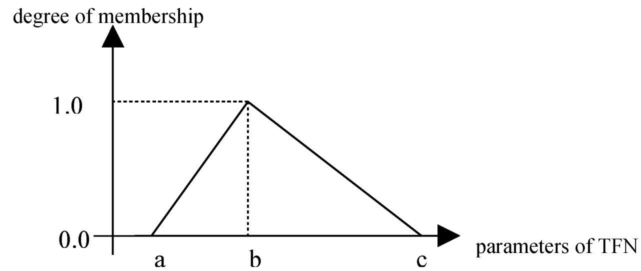

Fig. 2. Triangular fuzzy number.

1) Linguistic Values and Fuzzy Sets: By using *linguistic* (vague) values like "high," "low," "good," "medium," "cheap," etc., people are usually attempting to describe factors with uncertain or imprecise values. To deal with quantifying vagueness, Zadeh [24] proposed a membership function which associates with each quantified linguistic value a grade of membership belonging to the interval [0, 1]. Thus, a fuzzy set is defined as:

$$\forall x \in X, \mu_{\mathrm{A}}(x) \in [0,1]$$

where $\mu_{\mathrm{A}}(x)$ is the degree of membership, ranging from 0 to 1, of a quantity x of the linguistic value, A, over the universe of quantified linguistic values, X. X is essentially a set of real numbers. The more x fits A, the larger the degree of membership of x. If a quantity has a degree of membership equal to 1, this reflects a complete fitness between the quantity and the vague description (linguistic value). On the other hand, if the degree of membership of a quantity is 0, then that quantity does not belong to the vague description.

2) Triangular Fuzzy Numbers: A triangular fuzzy number (TFN) is a fuzzy set with three parameters, each representing a quantity of a linguistic value associated with a degree of membership of either 0 or 1. It is graphically depicted in Fig. 2. The parameters a, b, and c, respectively, denote the smallest possible quantity, the most promising quantity, and the largest possible quantity that describe the linguistic value.

Each TFN P has linear representations on its left and right side such that its membership function can be defined as

$$\mu_P = 0, \qquad x < a \tag{1}$$
$$= \frac{(x-a)}{(b-a)} \qquad a \leq \mathrm{x} \leq \mathrm{b} \tag{2}$$
$$= \frac{(c-x)}{(c-b)} \qquad b \leq x \leq \mathrm{c} \tag{3}$$
$$= 0, \qquad x \geq \mathrm{c}. \tag{4}$$

The TFN is mathematically easy to implement, and more importantly, it represents the rational basis for quantifying the vague knowledge in most decision making problems. The basic operations on triangular fuzzy numbers are as follows.

For example, $P_1 = (a,b,c)$ and $P_2 = (d,e,f)$:

$$P_1 + P_2 = (a+d, b+e, c+f) \quad \text{addition} \tag{5}$$
$$P_1 - P_2 = (a-f, b-e, c-d) \quad \text{subtraction} \tag{6}$$
$$P_1 * P_2 = (a*d, b*e, c*f) \text{ where } a \geq 0 \text{ and } d \geq 0 \quad \text{multiplication} \tag{7}$$

TABLE I
SCALE FOR PAIR-WISE JUDGMENTS

Comparative Importance	Definition
1	Equally important
3	Moderately more important
5	Strongly important
7	Very strongly more important
9	Extremely more important
2, 4, 6, 8	Intermediate judgment values

$$\frac{P_1}{P_2} = \left(\frac{a}{f}, \frac{b}{e}, \frac{c}{d}\right) \text{ where } a \geq 0 \text{ and } d > 0$$
division. (8)

3) Defuzzification: Defuzzification is a technique to convert a fuzzy number into a crisp real number. One of the several methods converts a fuzzy number $P = (a, b, c)$ into a crisp real number Q where

$$Q = \frac{(c - a) + (b - a)}{3} + a. \tag{9}$$

Defuzzification might become necessary in two situations: 1) When comparison between two or more fuzzy numbers is difficult to perform, and 2) when a fuzzy number to be operated on, has negative parameters (for example, squaring TFN $(-1,\ 0,\ 1)$ using (7) will lead to (1, 0, 1) that is not a fuzzy number).

B. AHP

The AHP is a tool, supported by simple mathematics, which enables decision makers to explicitly weigh tangible and intangible criteria against each other for the purpose of resolving conflict or setting priorities. The process has been formalized by Saaty [17] and is used in a wide variety of problem areas (e.g., siting landfills, evaluating employee performance, and ranking city livability).

In a large number of cases (for example, [16]), the tangible and intangible criteria are considered as independent, i.e., those criteria do not in turn depend upon subcriteria and so on. The AHP in such cases is conducted in two steps: 1) weigh independent criteria, each of which can compare two or more decision alternatives, using pair-wise judgments, 2) compute the relative ranks of decision alternatives using pair-wise judgments with respect to each independent criterion.

1) *Computation of relative weights of criteria*: AHP enables a person to make pair-wise judgments of importance between independent criteria with respect to the scale shown in Table I. The resulting matrix of comparative importance values is used to weigh the independent criteria by employing mathematical techniques like eigenvalue, mean transformation, or row geometric mean. In our paper, we employ the eigenvalue technique for computing the relative weights of the criteria.
2) *Computation of the relative ranks*: Pair-wise judgments of importance using the scale shown in Table I are computed for the decision alternatives too. These judgments are obtained with respect to each independent criterion considered in step 1. The resulting matrix of comparative importance values is used to rank the decision alternatives by employing mathematical techniques like eigenvalue, mean transformation, or row geometric mean. Here again, we employ the eigenvalue technique for computing the ranks of decision alternatives.

TABLE II
RANDOM INDEX VALUE FOR EACH n VALUE

n	1	2	3	4	5	6	7	8	9	10
R	0	0	0.58	0.90	1.12	1.24	0.32	1.41	1.45	1.49

The degrees of consistency of pair-wise judgments in steps 1 and 2 are measured using an index called the consistency ratio (CRatio). Perfect consistency implies a value of zero for CRatio. However, perfect consistency cannot be demanded since, as human beings, we are often biased and inconsistent in our subjective judgments. Therefore, it is considered acceptable if CRatio is less than or equal to 0.1. For CRatio values greater than 0.1, the pair-wise judgments must be revised before the weights of criteria and the ranks of decision alternatives are computed. CRatio is computed using the following formula:

$$\text{CRatio} = \frac{(\lambda \max - n)}{(n-1)(R)} \tag{10}$$

where $\lambda \max$ is the principal eigenvalue of the matrix of comparative importance values, n is the number of rows (or columns) in the matrix, and R is the random index [17] given for each n value that is greater than or equal to one. Table II shows R values for n ranging from 1 to 10.

The AHP is illustrated in the form of a hierarchy of three levels where the first level contains the primary objective, the second level contains the independent criteria, and the last level contains the decision alternatives. Also, as mentioned earlier, an important feature of the AHP is that the tangible and intangible criteria in the second level must be chosen in such a way that they can somehow help the decision maker in comparing two or more decision alternatives.

We use the AHP in our approach to identify potential recovery facilities, because it enables the decision maker to structure a complex problem in the form of a simple hierarchy and evaluate quantitative and qualitative factors in a systematic manner [1]. It must be noted that AHP does have some limitations [4]; primarily, AHP assumes linear independence of criteria and alternatives. If there is dependence among the criteria, analytic network process (ANP) [18] is more appropriate.

IV. PHASE-I (SELECTION OF USED PRODUCT)

A benefit function-based technique provides for a more understandable approach of economic analysis than techniques involving rate of return, present worth, and future worth. The benefit function, in our context, can be defined as the ratio of the equivalent value of benefits associated with the object of interest to the equivalent value of costs associated with the same object. The equivalent value can be present worth, annual worth, future worth, etc. In this phase, the object of our interest is a used product to be reprocessed. The benefit function (F) is formulated as

$$F = \frac{B}{C} \tag{11}$$

where B represents the equivalent value of the benefits (revenues), and C represents the equivalent value of the costs. An F value greater than 1.0 indicates that the object is economically advantageous. A notable point here is that due to uncertainties in supply, quality, and disassembly times [11] of used products, decision makers must rely on experts' knowledge to obtain fuzzy data for calculating B, C, and hence, F values [hence, F will hereafter be called fuzzy benefit function (*FCB*)].

Our *FCB* of a used product of interest consists of equivalent values of the following terms: reuse revenue (revenue from direct-sale/usage-in-remanufacturing of usable components of the used product), recycle revenue (revenue from selling material obtained from recycling of unusable components of the used product), collection cost (cost to collect the used product from consumers), reprocessing cost (cost to remanufacture/recycle the used product), disposal cost (cost to dispose of the material left over after remanufacturing and/or recycling of the used product), loss-of-sale cost (cost due to loss of sale, which might occur every now and then, due to lack of supply of the used product), and investment cost (capital required for the recovery facility (and its machinery) where the used product will be reprocessed).

We make the following assumptions while formulating the *FCB*.

1) The approach considers recovery (not repair) of components and materials. Hence, the used product of interest will be completely and nondestructively disassembled. However, since complete and nondestructive disassembly is not required in all recovery processes (see [10]), the authors plan to relax this assumption in their future research.
2) All reusable components of the used product of interest will be reused immediately (for direct sale or in remanufacturing), and all the remaining ones will be recycled or disposed of immediately.

A. Nomenclature

b_{ij}	Probability of bad quality (broken, worn-out, low-performing, etc) of component j in used product i.
CC_i	Total collection cost of used product i per period (\$).
CD	Cost of reprocessing per unit time (\$/unit time).
CF	Recycling revenue factor (\$/unit weight).
CR_i	Total recycle revenue of used product i per period (\$).
CO_i	Cost to collect one used product i (\$).
DC_i	Total disposal cost of used product i per period (\$).
DI_{ij}	Disposal cost index of component j in used product i (index scale $0 =$ lowest, $10 =$ highest).
DF	Disposal cost factor (\$/unit weight).
E_{ik}	Subassembly k in used product i.
FCB_i	Fuzzy benefit function for used product i.
i	Used product type.
IC_i	Investment cost of used product i (\$).
j	Component type.
LC_i	Loss-of-sale cost of used product i (\$).
M_i	Total number of subassemblies in used product i.
m_{ij}	Probability of missing component j in used product i.
N_{ij}	Multiplicity of component j in used product i.
P_{ij}	Component j in used product i.
RCP_{ij}	Percentage of recyclable contents by weight in component j of used product i.
RC_i	Total reprocessing (remanufacturing/recycling) cost of product i per used period (\$).
RI_{ij}	Recycling revenue index of component j in used product i (index scale $0 =$ lowest, $10 =$ highest).
Root_i	Root node (for example, outer casing) of used product i.
RV_{ij}	Resale value of component j in used product i (\$).
SU_i	Supply of used product i per period (number of products).
$T(\text{Root}_i)$	Time to disassemble Root_i (time units)}.
$T(E_{ik})$	Time to disassemble subassembly k in used product i (time units).
UR_i	Total reuse revenue of used product i per period (\$).
W_{ij}	Weight of component j in used product i (lb).
ΔBZ	Incremental total revenues (between the challenger and the defender).
ΔCZ	Incremental total costs (between the challenger and the defender).

B. Formulation of Fuzzy Cost-Benefit Function

As mentioned earlier, the fuzzy benefit function (*FCB*) of used product i of interest consists of equivalent values (EV) of seven terms (*viz*., total reuse revenue per period (UR_i), total recycle revenue per period (CR_i), total collection cost per period (CC_i), total reprocessing cost per period (RC_i), total disposal cost per period (DC_i), loss-of-sale cost [LC_i), investment cost (IC_i)] as follows:

$$\text{FCB}_i = \frac{\text{EV of } (UR_i + CR_i)}{\text{EV of } (CC_i + RC_i + DC_i + LC_i + IC_i)}. \quad (12)$$

The following subsections explain how the above seven terms are calculated. Some of the terms are modified versions of those by Veerakamolmal and Gupta [23].

1) Total Reuse Revenue Per Period (UR): UR of used product i is influenced by the fuzzy supply of the product per period (SU_i) and the following data of component of type j in the product: the resale value (RV_{ij}), the number of components

(N_{ij}), the fuzzy probability of missing (m_{ij}), and the fuzzy probability of bad quality (broken, worn-out, low-performing, etc) (b_{ij}). This revenue equation can be written as follows:

$$UR_i = \sum_j SU_i \cdot RV_{ij} \cdot N_{ij} \cdot (1 - b_{ij} - m_{ij}). \tag{13}$$

Since SU_i, b_{ij} and m_{ij} are expressed as fuzzy numbers, the resulting UR_i is a fuzzy number too.

2) Total Recycle Revenue Per Period (CR): CR of used product i is calculated by multiplying the component recycling revenue factors by the number of components recycled for materials content, as shown by (14) at the bottom of the page. Note that each component has a percentage of recyclable contents $(RCP_{ij}) \cdot RI_{ij}$ is the recycling revenue index (varying in value from one to ten) representing the degree of benefit generated by the recycling of component of type j (the higher the value of the index, the more profitable it is to recycle the component), W_{ij} is the weight of the component of type j, and *CF* is the recycling revenue factor. Since SU_i, b_{ij}, and m_{ij} are expressed as fuzzy numbers, the resulting CR_i is a fuzzy number too.

3) Total Collection Cost Per Period (CC): CC of used product i is calculated by multiplying the fuzzy supply of used products per period (SU_i) by the cost of collecting one used product from consumers (CO_i)

$$CCi = SU_i \cdot CO_i. \tag{15}$$

Since SU_i is expressed as a fuzzy number, the resulting CC_i is a fuzzy number too.

4) Total Reprocessing Cost Per Period (RC): RC of used product i can be calculated from the disassembly time of the root node (for example, outer casing) of the product ($T(\text{Root}_i)$), the disassembly time of each subassembly in the product ($T(E_{ik})$) and the reprocessing cost per unit time (*CD*) as follows:

$$RC_i = SU_i \cdot \left[T(\text{Root}_i) + \sum_{k=1}^{Mi} T(E_{ik}) \right] \cdot CD. \tag{16}$$

Depending upon the type (vague or objective) of data available of the disassembly times, RC_i is a fuzzy or crisp real number.

5) Total Disposal Cost Per Period (DC): DC of used product i is calculated by multiplying the component disposal cost by the number of component units disposed, as shown in (17) at the bottom of the page. Note that DI_{ij} is the disposal cost index (varying in value from one to ten) representing the degree of nuisance created by the disposal of component of type j (the higher the value of the index, the more nuisance the component creates, and hence it costs more to dispose it of), W_{ij} is the weight of the component of type j, and *DF* is the disposal cost factor. Since SU_i, b_{ij}, and m_{ij} are expressed as fuzzy numbers, the resulting CR_i is a fuzzy number too.

6) Loss-of-Sale Cost Per Period (LC): LC of used product i represents the cost of not meeting the demand for reprocessed goods in a timely manner. This occurs because of the unpredictable supply of used products, as consumers do not discard them in a predictable manner. *LC* is difficult to predict and thus is usually guessed by "experts." Due to the involvement of the experts' guesses, LC_i is expressed as a fuzzy number.

7) Investment Cost (IC): IC of used product i is the fixed cost of the recovery facility and the machinery required to reprocess product i. Depending upon the type (vague or objective) of data available of the product and of the region where the recovery facility exists or is planned to be built, IC_i is a fuzzy or crisp real number.

C. Methodology

In order to select the most economical product to reprocess, from a set of candidate used products, we use the following steps.

- Step 1) Eliminate every candidate used product whose *FCB* is less than 1.0.
- Step 2) Assign the candidate used product that has the lowest *IC* as the defender and the product with the next-lowest *IC* as the challenger.
- Step 3) Calculate the ratio of the EV of incremental total revenue ΔBZ (between the challenger and the defender) to the EV of incremental total cost ΔCZ (between the challenger and the defender). If the ratio is less than 1.0, eliminate the challenger. Otherwise, eliminate the defender.
- Step 4) Repeat Steps 2) and 3) until only one used product (which is the most economical one in the set) is left.

D. Numerical Example

We take three different used products (Product-1, Product-2, and Product-3) whose structures are shown in Figs. 3–5, respectively. We assume that the supplies of all these products are per-

$$CR_i = \sum_j \left[SU_i \cdot RI_{ij} \cdot W_{ij} \cdot RCP_{ij} \cdot \{ Nij(1 - m_{ij}) - N_{ij} \cdot (1 - b_{ij} - m_{ij}) \} \right] \cdot CF \tag{14}$$

$$DC_i = \sum_j \left[SU_i \cdot DI_{ij} \cdot W_{ij} \cdot (1 - RCP_{ij}) \cdot \{ N_{ij}(1 - m_{ij}) - N_{ij} \cdot (1 - b_{ij} - m_{ij}) \} \right] \cdot DF. \tag{17}$$

TABLE III
DATA OF USED PRODUCT-1

Component	RV_{1j} ($)	N_{1j}	W_{1j} (lb)	RI_{1j}	RCP_{1j}	DI_{1j}	b_{1j}	m_{1j}
P_{11}	7.0	3	4.5	5	65%	6	(0.1,0.1, 0.2)	(0.3, 0.4, 0.4)
P_{12}	8.0	4	6.5	5	50%	4	(0.5, 0.6, 0.7)	(0.1, 0.2, 0.2)
P_{13}	9.0	2	7.0	3	75%	4	(0.2, 0.3, 0.4)	(0.3, 0.4, 0.4)
P_{14}	6.9	1	2.7	9	35%	5	(0.2, 0.2, 0.3)	(0.1, 0.1, 0.2)
P_{15}	8.4	5	7.5	6	70%	1	(0.1, 0.1, 0.2)	(0.3, 0.4, 0.5)

TABLE IV
DATA OF USED PRODUCT-2

Component	RV_{2j} ($)	N_{2j}	W_{2j} (lb)	RI_{2j}	RCP_{2j}	DI_{2j}	b_{2j}	m_{2j}
P_{21}	1.0	1	3.9	2	40%	3	(0.1, 0.1, 0.2)	(0.0, 0.1, 0.1)
P_{22}	1.5	3	1.5	4	20%	1	(0.1, 0.2, 0.2)	(0.0, 0.0, 0.0)
P_{23}	1.2	7	4.1	1	70%	2	(0.2, 0.3, 0.4)	(0.2, 0.2, 0.3)
P_{24}	2.5	4	3.2	5	90%	4	(0.3, 0.4, 0.5)	(0.1, 0.1, 0.2)
P_{25}	3.1	3	2.0	2	50%	2	(0.3, 0.4, 0.4)	(0.1, 0.1, 0.2)

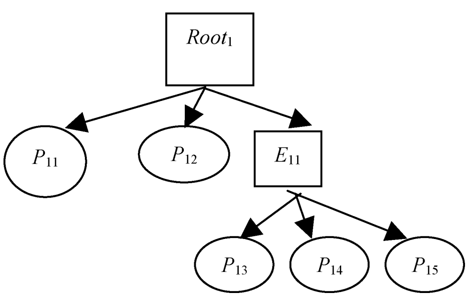

Fig. 3. Structure of used Product-1.

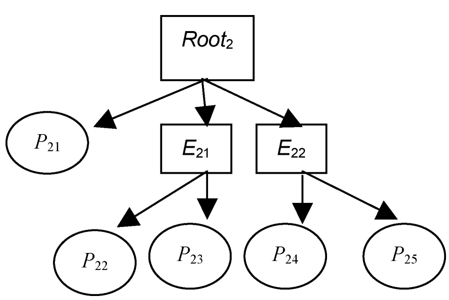

Fig. 4. Structure of used Product-2.

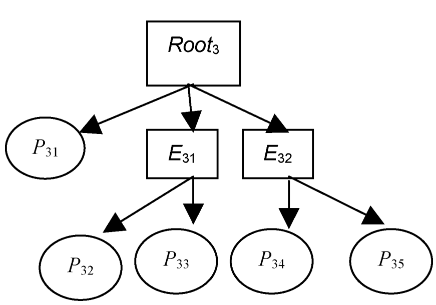

Fig. 5. Structure of used Product-3.

petual. Hence, we take capitalized worth (CW) [21] as the EV. Therefore, *FCB* is the ratio of CW of total revenues to CW of total costs. The data necessary to calculate *FCB* of Product-1, Product-2, and Product-3 are given in Tables III–V, respectively. Also, $T(\text{Root}_1) = 2$ min; $T(\text{Root}_2) = 1.5$ min; $T(\text{Root}_3) = 1.5$ min; $T(E_{11}) = 9$ min; $T(E_{21}) = 7$ min; $T(E_{22}) = 8$ min; $T(E_{31}) = 7$ min; $T(E_{32}) = 8$ min; $SU_1 = (200, 230, 250)$ products per year; $SU_2 = (210, 220, 230)$ products per year; $SU_3 = (600, 650, 700)$ products per year; $CO_1 = \$20$; $CO_2 = \$21$; $CO_3 = \$18$; $IC_1 = \$20000$; $IC_2 = \$25000$; $IC_3 = \$30000$; $LC_1 = \$(300, 500, 700)$ per quarter (three months); $LC_2 = \$(100, 400, 500)$ per quarter (three months); $LC_3 = \$(900, 1000, 1100)$ per quarter (three months); $CF = 0.2$ \$/lb; $DF = 0.1$ \$/lb; $CD = 0.55$ \$/min.

Upon calculating revenues and benefits for each product, we get $\text{FCB}_1 = (0.66, 1.59, 3.11)$, $\text{FCB}_2 = (0.36, 0.59, 0.83)$, and $\text{FCB}_3 = (1.21, 1.89, 3.16)$. Defuzzifying these numbers using (9), we get $\text{FCB}_1 = 1.79$, $\text{FCB}_2 = 0.91$, and $\text{FCB}_3 = 2.09$. Since FCB_2 is less than 1.0, we eliminate it from further analysis.

Now, since IC_1 is less than IC_3, we consider Product-1 the defender and Product-3 the challenger. The defuzzified ratio of CW of ΔBZ to CW of ΔCZ is now calculated and is found to be 2.81, which is greater than 1.0. Hence, we eliminate the defender, i.e., Product-1. Therefore, the remaining product, i.e., Product-3 is the most economical product amongst the three products.

V. PHASE-II (SELECTION OF RECOVERY FACILITIES)

In the second phase of strategic planning, we employ the AHP [17] to identify potential facilities in a set of candidate recovery facilities.

A. Nomenclature

A, *B*, *C*, *D*	Candidate recovery facilities.
FC	Fixed cost of recovery facility.
CS	Customer service at recovery facility.
DT	Average disassembly time of used products.

TABLE V
DATA OF USED PRODUCT-3

Component	RV_{3j} (\$)	N_{3j}	W_{3j} (lb)	RI_{3j}	RCP_{3j}	DI_{3j}	b_{3j}	m_{3j}
P_{31}	9.0	2	4.0	9	30%	4	(0.2, 0.3, 0.4)	(0.1, 0.2, 0.3)
P_{32}	8.0	5	5.0	7	60%	3	(0.1, 0.2, 0.2)	(0.1, 0.2, 0.2)
P_{33}	9.0	3	2.0	8	70%	1	(0.3, 0.4, 0.4)	(0.1, 0.2, 0.2)
P_{34}	7.0	2	6.0	9	25%	3	(0.2, 0.3, 0.3)	(0.3, 0.3, 0.4)
P_{35}	7.0	1	5.2	6	50%	2	(0.3, 0.3, 0.4)	(0.1, 0.1, 0.2)

QI Quality of used products.

QO Quality of reprocessed goods.

SU Supply of used products.

TP Throughput at recovery facility.

B. Selection of Potential Recovery Facilities Using AHP

Here, the first level in the hierarchy contains our primary objective, i.e., selecting potential facilities from a set of candidate recovery facilities. The last level in the hierarchy contains the candidate recovery facilities. The level in the middle contains criteria that must somehow be useful in comparing the candidate recovery facilities. For example, fixed cost and average skill level of the employees are criteria that can compare the candidate facilities. Though the criteria to be considered in a reverse supply chain seem to be similar to those considered in a forward supply chain [22], there are three special factors in a reverse supply chain, which need to be incorporated in AHP in such a way that the hierarchy levels are not disturbed. The following are those special factors: average quality of used products, average supply of used products, average disassembly time of used products.

- *Average quality of used products*: Unlike in a forward supply chain, components of incoming goods (used products) of even the same type in a recovery facility are likely to be of varied quality (worn-out, low-performing, etc). Though the average quality of reprocessed goods (*QO*) is a criterion that can compare two or more candidate facilities, it is not justified to use *QO* as an independent criterion for comparison because *QO* depends on average quality of incoming products (*QI*). However, *QI* must not be taken as an independent criterion too because it cannot compare the candidate facilities. So, the idea is to take the difference between *QO* and *QI* as a criterion in the hierarchy.
- *Average supply of used products*: The only driver to design a forward supply chain network is the demand for new products, and so if there is low demand for new products, there is practically no forward supply chain. However, this may not be an option in many RSCNs, as reverse supply chain must be administered regardless of the levels of supply or demand due to the possible drivers like environmental regulations and asset recovery. In supply-driven cases like these, it is unfair to judge a recovery facility without considering the supply of used products (*SU*) in the hierarchy. Though throughput (*TP*) is a criterion that can compare two or more candidate recovery facilities, it is not justified to use *TP* as an independent criterion because *TP* depends on *SU*. However, *SU* must not be taken as an independent criterion too because it cannot compare the candidate facilities. Furthermore, a low *SU* might lead to a low *TP* and a high *SU* might lead to a high *TP*. So, the idea is to take (*TP*)/(*SU*) as a criterion in the hierarchy. Thus, we compensate for the effect of a low *TP* by dividing *TP* with a possibly low *SU*, in order not to underestimate the facility under consideration. Similarly, we dampen the effect of a high *TP* by dividing *TP* with a possibly high *SU*, in order not to overestimate the facility under consideration.

  Note that if used product i is chosen in Phase-I, *SU* in this phase (Phase-II) is the same as SU_i in Phase-I.
- *Average disassembly time of used products*: Average disassembly time (*DT*) is not exactly the inverse of *TP* because *TP* takes into account the whole reprocessing (disassembly plus recovery) time. Unlike in a forward supply chain, components of incoming goods (used products) in a recovery facility are likely to be deformed and/or broken and/or different in number even for the same type of products. Hence, incoming products of the same type might have different reprocessing times, unlike in a forward supply chain where manufacturing time and assembly time are predetermined and equal for products of the same type. Since *TP* of a recovery facility depends upon the *DT*, it is unfair to not consider *DT* in the hierarchy. However, *DT* must not be taken as an independent criterion because it cannot compare the candidate facilities. Furthermore, a high *DT* might lead to a low *TP* and a low *DT* might lead to a high *TP*. So, the idea is to take (*TP*)(*DT*) as a criterion in the hierarchy. Thus, we compensate for the effect of a low *TP* by multiplying *TP* with a possibly high *DT*, in order not to underestimate the facility under consideration. Similarly, we dampen the effect of a high *TP* by multiplying *TP* with a possibly low *DT*, in order not to overestimate the facility under consideration.

The intangible criterion that we consider in our approach is customer service (*CS*). *CS* basically gives an idea about how well a recovery facility is utilizing the incentives provided by the government, by what extent it is meeting the environmental regulations, what kind of incentives it is giving the collection centers supplying the used products, and what kind of incentives it is giving the customers buying the reprocessed goods. We are using the term “customer service” here because in our opinion, any beneficiary is a customer, be it the government or the collection center or the actual customer buying the reprocessed goods. In addition to the above criteria, we consider the

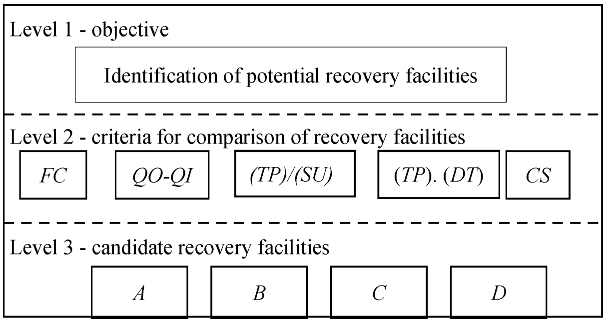

Fig. 6. Three-level hierarchy.

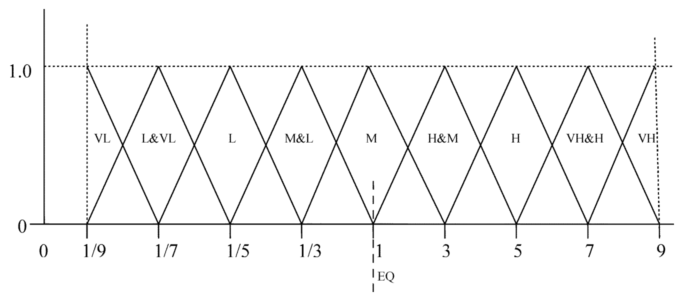

Fig. 7. TFNs for linguistic pair-wise judgments.

TABLE VI
CONVERSION OF LINGUISTIC PAIR-WISE JUDGMENTS INTO TFNs

Linguistic judgment	TFN
Very High (VH)	(7, 9, 9)
Between Very High and High (VH&H)	(5, 7, 9)
High (H)	(3, 5, 7)
Between High and Medium (H&M)	(1, 3, 5)
Medium, Almost Equally (M)	(1/3, 1, 3)
Exactly Equal (EQ)	(1, 1, 1)
Between Medium and Low (M&L)	(1/5, 1/3, 1)
Low (L)	(1/7, 1/5, 1/3)
Between Low and Very Low (L&VL)	(1/9 1/7, 1/5)
Very Low (VL)	(1/9, 1/9, 1/7)

fixed cost of the facility (*FC*) too in the hierarchy. Fig. 6 illustrates the three-level hierarchy in our approach to implement AHP for identifying potential recovery facilities.

Since it is generally not easy to come up with numerical pair-wise judgments in the implementation of AHP and especially so in the case of a reverse supply chain that faces many uncertainties, we use the fuzzy set theory (for conducting pair-wise judgments) in this phase too. The next subsection (*Illustrative Example*) makes this clearer.

C. Illustrative Example

Table VI and Fig. 7 [15] show the linguistic values which we use (after first converting them into TFNs and then defuzzifying the respective TFNs) in our example for conducting pair-wise judgments in the implementation of the AHP. Table VII shows comparative importance values given to the criteria in the second level of hierarchy in this example. It also gives the normalized eigenvector of the comparative importance value matrix. This vector represents the relative weights given by the decision maker to the independent criteria.

TABLE VII
COMPARATIVE IMPORTANCE VALUES AT SECOND LEVEL

	FC	***IQ***	**(*TP*)/(*SU*)**	**(*TP*)(*DT*)**	***CS***	**Norm. eigen vector**
FC	EQ	L	H&M	H	H	0.27
IQ	1/L	EQ	VH&H	H&M	H	0.48
(*TP*)/(*SU*)	1/H&M	1/VH&H	EQ	EQ	EQ	0.07
(*TP*)(*DT*)	1/H	1/H&M	1/EQ	EQ	H&M	0.12
CS	1/H	1/H	1/EQ	1/H&M	EQ	0.06

TABLE VIII
COMPARATIVE IMPORTANCE VALUES OF RECOVERY FACILITIES WITH RESPECT TO FC

FC					
	A	***B***	***C***	***D***	**Norm. eigen vector**
A	EQ	VH&H	H	VH	0.69
B	1/VH&H	EQ	EQ	EQ	0.10
C	1/H	EQ	EQ	EQ	0.11
D	1/VH	EQ	EQ	EQ	0.10

TABLE IX
COMPARATIVE IMPORTANCE VALUES OF RECOVERY FACILITIES WITH RESPECT TO (*QO-QI*)

QO-QI					
	A	***B***	***C***	***D***	**Norm. eigen vector**
A	EQ	EQ	VH&H	EQ	0.31
B	EQ	EQ	VH	EQ	0.32
C	1/VH&H	1/VH	EQ	VL	0.04
D	1/EQ	1/EQ	1/VL	EQ	0.33

TABLE X
COMPARATIVE IMPORTANCE VALUES OF RECOVERY FACILITIES WITH RESPECT TO (*TP*)/(*SU*)

(*TP*)/(*SU*)					
	A	***B***	***C***	***D***	**Norm. eigen vector**
A	EQ	EQ	EQ	H&M	0.28
B	EQ	EQ	EQ	VH	0.35
C	EQ	EQ	EQ	H	0.31
D	1/H&M	1/VH	1/H	EQ	0.06

Tables VIII–XII show comparative importance values of the decision alternatives, *viz*., recovery facilities *A*, *B*, *C*, and *D* with respect to the criteria *viz*., *FC*, (*QO-QI*), (*TP*)/(*SU*), (*TP*)(*DT*), and *CS*, respectively. They also show the normalized eigenvectors of the respective comparative importance value matrices.

Each of the matrices in Tables VII–XII has a CRatio whose value is less than or equal to 0.1. Table XIII shows the aggregate matrix of rankings of recovery facilities with respect to each criterion in the second level of hierarchy. This matrix is the aggregate of the eigenvectors obtained in Tables VIII–XII.

Multiplying the matrix in Table XIII with the normalized eigenvector obtained in Table VII, we get the following normalized ranks for the facilities: $\mathrm{Rank}_{\mathrm{A}} = 0.43$; $\mathrm{Rank}_{\mathrm{B}} = 0.26$; $\mathrm{Rank}_{C} = 0.09$; $\mathrm{Rank}_{D} = 0.22$. If the decision maker (i.e., a practitioner who is interested in pursuing the business of recovering components and materials from used electronic products)

TABLE XI
COMPARATIVE IMPORTANCE VALUES OF RECOVERY FACILITIES WITH RESPECT TO (*TP*)(*DT*)

(*TP*)(*DT*)					
	A	***B***	***C***	***D***	**Norm. eigen vector**
A	EQ	M	H&M	VH&H	0.43
B	1/M	EQ	VH	H	0.42
C	1/H&M	1/VH	EQ	EQ	0.08
D	1/VH&H	1/H	EQ	EQ	0.07

TABLE XII
COMPARATIVE IMPORTANCE VALUES OF RECOVERY FACILITIES WITH RESPECT TO CS

CS					
	A	***B***	***C***	***D***	**Norm. eigen vector**
A	EQ	VH&H	H	EQ	0.45
B	1/VH&H	EQ	L	VL	0.04
C	1/H	1/L	EQ	EQ	0.19
D	EQ	1/VL	EQ	EQ	0.32

TABLE XIII
AGGREGATE OF RANKINGS OF RECOVERY FACILITIES WITH RESPECT TO EACH CRITERION

	A	***B***	***C***	***D***
FC	0.69	0.10	0.11	0.10
IQ	0.31	0.32	0.04	0.33
(*TP*)/(*SU*)	0.28	0.35	0.31	0.06
(*TP*)(*DT*)	0.43	0.42	0.08	0.07
CS	0.45	0.04	0.19	0.32

wishes to choose only those recovery facilities whose ranks are at least 0.25 as the potential recovery facilities, he will choose recovery facilities *A* and *B*. Note that the ranks of the four candidate facilities are relative, and the cutoff limit of 0.25 here is arbitrary (the objective is to select the best ones from the candidate recovery facilities).

VI. PHASE-III (MINIMIZATION OF OVERALL COST ACROSS RSCN)

In this phase, we focus on the transfer of used products between the collection centers and the recovery facilities, and of the reprocessed (remanufactured) products between the recovery facilities and the demand centers. A notable point here is that since supply rate of a given used product is often an imprecise number, we take a TFN for the same.

A. Nomenclature for the Transshipment Model

a_1 Space occupied by one unit of remanufactured product (square units/product).

a_2 Space occupied by one unit of used product (square units/product).

CAP_v Capacity of recovery facility v to remanufacture products (products).

C_u Cost per product retrieved at collection center u ($/product).

d_w Demand of remanufactured products at demand center w.

I_{uv} Decision variable representing the number of products to be transported from collection center u to recovery facility v.

O_{vw} Decision variable representing the number of products to be transported from recovery facility v to demand center w.

R_v Cost of remanufacturing per product at recovery facility v ($/product).

S_{1v} Storage capacity of recovery facility v for remanufactured products (square units).

S_{2v} Storage capacity of recovery facility v for used products (square units).

S_u Storage capacity of collection center u for used products (square units).

SUP_u Supply at collection center u (products).

TI_{uv} Cost of transporting one product from collection center u to recovery facility v ($/product).

TO_{vw} Cost of transporting one product from recovery facility v to demand facility w ($/product).

u Collection center.

v Recovery facility.

w Demand center.

Y_v Binary variable (0/1) for selection of recovery facility v.

B. Transshipment Model Formulation

The following is the single-period and single-product transshipment model formulation that is implemented to achieve minimum overall cost, i.e., sum of the costs of retrieval, inventory, remanufacturing, and transportation of products (used and remanufactured) across the supply chain (in the formulation, we assume that the inventory cost of a used product is 25% of its retrieval cost C_u and that of a remanufactured product is 25% of its remanufacturing cost R_v).

Minimize

$$\sum_u \sum_v C_u I_{uv} + \qquad \text{Retrieval costs.}$$

$$\sum_u\sum_v TI_{uv}I_{uv} + \sum_u\sum_v TO_{vw}O_{vw} +$$
Transportation costs.
$$\sum_v\sum_w R_vO_{vw} +$$
Remanufacturing costs.
$$\sum_u\sum_v\left(\frac{C_u}{4}\right)\cdot I_{uv} + \sum_v\sum_w\left(\frac{R_v}{4}\right)\cdot O_{vw};$$
Inventory costs. (18)

Subject to

$$\sum_v O_{vw} = dw; \forall w$$
Demand at each demand center must be met. (19)

$$\sum_u I_{uv} \geq \sum_w O_{vw}; \forall v$$
Total output of each recovery facility is at most its total input. (20)

$$\sum_w a_1\cdot O_{vw} \leq S_{1v}\cdot Y_v; \forall v$$
Total space occupied by remanufactured products at each recovery.
facility is at most its capacity for remanufactured products. (21)

$$\sum_v a_2\cdot I_{uv} \leq S_u; \forall u$$
Total space occupied by used products at each collection center is at most its capacity. (22)

$$\sum_u a_2\cdot I_{uv} \leq S_{2v}\cdot Y_v; \forall v$$
Total space occupied by used products at each recovery facility is at most its capacity for used products. (23)

$$I_{uv} \geq 0; \forall u, v$$
Quantities of transported products are nonnegative numbers. (24)

$$O_{vw} \geq 0; \forall v, w$$
Total output of each recovery facility is at most its capacity to remanufacture. (25)

$$\sum_w O_{vw} \leq \mathrm{CAP}_v; \forall v \quad (26)$$

$$\sum_v I_{uv} \leq \mathrm{SUP}_u; \forall u$$
Total quantity of used products supplied to recovery facilities by each collection center is at most the supply to that collection center. (27)

Note that a_1 and a_2 are considered possibly different. The reason is that a component from a used product of one model may be used in a remanufactured product of a different model that may occupy a different amount of space.

Also, the model assumes that there is always enough supply of the used products to satisfy the demand for the remanufactured products and that enough storage space (for used and remanufactured products) is always available at the recovery facilities. Moreover, inventory costs at the collection centers and demand centers are not considered in the model (for example, if the supply of used products is higher than the demand for remanufactured products, the collection centers are deemed to incur inventory costs). However, the model may be revised accordingly, in response to revision of existing constraints or addition of new constraints. In their future research, the authors plan to extend the model to incorporate multiple periods and multiple products (used and remanufactured).

C. Numerical Example

Besides three collection centers and three demand centers, we consider the product type (i.e., Product-3) chosen in Phase-I and the two potential recovery facilities (*viz.*, A and B) chosen in Phase-II.

The supply of Product-3 is a TFN, (600, 650, 700) per period. The defuzzified supply is 633.33 per period. Assuming equal supply rate at all the three collection centers, we get $\mathrm{SUP}_1 = \mathrm{SUP}_2 = \mathrm{SUP}_3 = 211.11$. The other data necessary for implementation of the linear programming model are as follows: $C_1 = 29$; $C_2 = 25$; $C_3 = 37$; $TI_{1\mathrm{A}} = 3$; $TI_{2\mathrm{A}} = 4$; $TI_{3\mathrm{A}} = 5.3$; $TI_{1\mathrm{B}} = 3.2$; $TI_{2\mathrm{B}} = 1.4$; $TI_{3\mathrm{B}} = 6.7$; $TO_{\mathrm{A}1} = 2.6$; $TO_{\mathrm{B}1} = 3.2$; $TO_{\mathrm{A}2} = 3.4$; $TO_{\mathrm{B}2} = 2.5$; $TO_{\mathrm{B}3} = 1.6$; $TO_{\mathrm{B}3} = 2.1$; $R_{\mathrm{A}} = 4$; $R_{\mathrm{B}} = 4.3$; $d_1 = 100$; $d_2 = 200$; $d_3 = 150$; $a_1 = a_2 = 0.5$; $S_{1\mathrm{A}} = 550$; $S_{1\mathrm{B}} = 550$; $S_{2\mathrm{A}} = 550$; $S_{2\mathrm{B}} = 550$; $S_1 = 550$; $S_2 = 550$; $S_3 = 550$; $\mathrm{CAP}_{\mathrm{A}} = 300$; $\mathrm{CAP}_{\mathrm{B}} = 250$.

Upon application of the above data to the transshipment model—using LINGO (v4), we get the following optimal solution:

$I_{1\mathrm{A}} = 211$, i.e., 211 products are to be transported from collection center 1 to recovery facility A;
$I_{1\mathrm{B}} = 0$, i.e., no products are to be transported from collection center 1 to recovery facility B;
$I_{2\mathrm{A}} = 0$, i.e., no products are to be transported from collection center 2 to recovery facility A;
$I_{2\mathrm{B}} = 211$, i.e., 211 products are to be transported from collection center 2 to recovery facility B;
$I_{3\mathrm{A}} = 28$, i.e., 28 products are to be transported from collection center 3 to recovery facility A;
$I_{3\mathrm{B}} = 0$, i.e., no products are to be transported from collection center 3 to recovery facility B;
$O_{\mathrm{A}1} = 100$, i.e., 100 products are to be transported from recovery facility A to demand center 1;
$O_{\mathrm{A}2} = 0$, i.e., no products are to be transported from recovery facility A to demand center 2;
$O_{\mathrm{A}3} = 139$, i.e., 139 products are to be transported from recovery facility A to demand center 3;
$O_{\mathrm{B}1} = 0$, i.e., no products are to be transported from recovery facility B to demand center 1;

$O_{B2} = 200$, i.e., 200 products are to be transported from recovery facility B to demand center 2;
$O_{B3} = 11$, i.e., 11 products are to be transported from recovery facility B to demand center 3.

VII. Conclusion

We proposed a three-phase fuzzy logic approach in our methodology to effectively design a reverse supply chain network. Phase I selected the most economical product to reprocess from a set of different used products using a fuzzy benefit function. Phase II employed the AHP and the fuzzy set theory to identify potential facilities in a set of candidate recovery facilities operating in the region where the reverse supply chain network is to be designed. Finally, phase III solved a single-period and single-product discrete location model to minimize overall cost across the reverse supply chain network.

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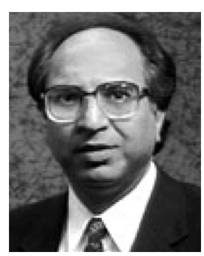

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