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Sagar V. Kamarthi
Northeastern University

Surendra M. Gupta
Northeastern University

Jarupan Lerpong
Northeastern University

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Contact Information

Dr. Surendra M. Gupta, P.E.
Professor of Mechanical and Industrial Engineering and
Director of Laboratory for Responsible Manufacturing
334 SN, Department of MIE
Northeastern University
360 Huntington Avenue
Boston, MA 02115, U.S.A.

(617)-373-4846 ***Phone***
(617)-373-2921 ***Fax***
gupta@neu.edu ***e-mail address***

http://www.coe.neu.edu/~smgupta/ ***Home Page***

Evaluation of Trade-offs in Costs and Environmental Impacts for Returnable Packaging Implementation

Lerpong Jarupan, Sagar V. Kamarthi*, Surendra M. Gupta
Laboratory for Responsible Manufacturing
Dept. of Mechanical, Industrial and Manufacturing Engineering
Northeastern University
360 Huntington Ave.,
Boston, MA 02115 USA

ABSTRACT

The main thrust of returnable packaging these days is to provide logistical services through transportation and distribution of products and be environmentally friendly. Returnable packaging and reverse logistics concepts have converged to mitigate the adverse effect of packaging materials entering the solid waste stream. Returnable packaging must be designed by considering the trade-offs between costs and environmental impact to satisfy manufacturers and environmentalists alike. The cost of returnable packaging entails such items as materials, manufacturing, collection, storage and disposal. Environmental impacts are explicitly linked with solid waste, air pollution, and water pollution. This paper presents a multi-criteria evaluation technique to assist decision-makers for evaluating the trade-offs in costs and environmental impact during the returnable packaging design process. The proposed evaluation technique involves a combination of multiple objective integer linear programming and analytic hierarchy process. A numerical example is used to illustrate the methodology.

Keywords: Returnable Packaging, Costing, Environmental Impact, Multiple Objective Integer Linear Programming (MOILP), Analytic Hierarchy Process (AHP)

1. INTRODUCTION

The escalating need for packaging and the resulting disposal of packaging materials after use are contributing towards the solid waste stream and depleting landfills. It has led the manufacturers to consider reusable and recyclable packaging to minimize the consumption of resources and energy, and to inhibit the process of waste generation. To achieve these goals, the use of reusable packaging and containers are the simplest and most favorable measures that can be implemented by consumers and manufacturers.

In industrial settings, packaging used for handling and transporting large volumes of products are called transport packaging. Examples of transport packaging include pallets, totes, and bulk containers. With the emergence of the reverse logistics awareness, transport packaging has become an important and necessary element of a close-loop distribution network. Not only does transport packaging make the handling of bulk volume easy, it also allows for reusing packaging multiple times. Such transport packagings are referred as "returnables." However, returnable transport packagings are not suitable for every industry. In addition, by putting returnable packaging in practice, companies may entail substantial investment and maintenance expenses [2], [5]. Considering the fact that multi-use packaging, in many cases, would result in cost savings and environmental benefits, it is expected that returnable system for transport packaging will continue to become a viable alternative to one-way packaging. Durability, product protection from damages, and repeated utilization are the important characteristics expected from a well-designed transport packaging. The ergonomic design features such as "stackability" and "collapsibility" allow savings in warehouse space and reduce logistical operation costs of transportation and storage.

*Correspondence: e-mail: sagar@coe.neu.edu; phone: (617)-373-3070

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Designing good returnable packaging is a challenging task. It involves selection of the right packaging materials and the right packaging manufacturing processes. Packaging may be built from completely new and/or recycled materials. For the reasons of strength and durability, transport packaging might be built with thickness twice that of a single-use packaging. However, multi-use packaging can offset the cost with the increased utilization and the reduction of overall material consumption.

Most design evaluations for business-focused manufacturers have not permitted analysis of the combined trade-offs of costs and environmental impacts over the packaging life cycle. The cost of returnable packaging includes such items as materials, manufacturing, collection, storage and disposal. Environmental impacts are explicitly linked with solid waste, air pollution, and water pollution. In this paper, a multi-criteria decision process will be used to assist the decision maker in resolving the trade-offs in costs and environmental impact during the returnable packaging design process. The implementation of returnable packaging design through simple models will allow a reader gain insight into these issues.

2. LITERATURE REVIEW

Several studies have attempted to address the issues related to the product and process design with an objective to minimize environmental detriment. Lambert [7] presented a method for solving the general optimal disassembly sequence generation problems using linear programming with environmental constraints. Stuart *et al.* [11] introduced a model called the "emerging product process and consideration of environment (EPPACE)" and used mixed-integer programming (MIP) to evaluate complex cost and environmental tradeoffs over the product life cycle. Lee *et al.* [8] discussed a multi-objective methodology for appropriate end-of-life options for manufactured products subject to the objectives of minimizing environmental impact and deficit. In their work, the optimal disassembly parameters including cost, environmental impact and disassembly time are quantified. Kongar and Gupta [6] presented a multi-criteria optimization model of a disassembly-to-order system for end-of-life products under a variety of physical, financial and environmental constraints. For more information on product recovery from an environmental point of view, see Gungor and Gupta [3].

Clegg *et al.* [1] presented linear programming models of production systems with remanufacturing capability. They examined the environmental impact of both recycling and remanufacturing schemes and totally new products. Their model is used for the purpose of exploring the effects of different cost structures on the long-term viability of remanufacturing operations as well as short-term operations management issues. Hoshino *et al.* [3] presented a goal programming model for two performance measures—total profit and recycling rate—by taking reuse and remanufacturing materials into consideration. Mangun and Thurston [9] developed a model for incorporating long-range planning for component reuse in product portfolio design. With respect to three attributes—cost, reliability, and environmental impact—the decision tradeoff model determines when a product should be taken back and which components should be new, reused, or recycled. Pochampally and Gupta [10] proposed a three-phase approach involving mathematical programming and analytic hierarchy process to completely design a reverse supply chain network while taking uncertainties in supply, quality and reprocessing times of used-products into account.

3. CRITERIA BREAK DOWN FOR RETURNABLE PACKAGING DESIGN

In this study, two related criteria that account for returnable packaging design are considered: *total cost* and *environmental impact*. We assume that the life cycle of returnable packaging involves two phases. During the first phase, all of the packaging material used is completely new. At the end of the first phase, the take-back process of returnable packaging begins. At the beginning of the second phase, if defective components are discovered, the returnable packaging is disassembled and defective components are substituted with reused or new components.

3. 1. Total Cost (TC)

Total cost is broken down into eight elements:

1. **New material cost** ($\mathbf{C}_{NM}$): For the first phase, all packaging components require new packaging materials. However, this cost may also apply to several packaging components in the second phase if defective components are to be replaced.
2. **Manufacturing cost** ($\mathbf{C}_{MF}$): This includes all packaging manufacturing and remanufacturing costs, and may apply to both new and reused packaging components. For the first phase, all components are subjected to this cost.
3. **Assembly cost** ($\mathbf{C}_{AB}$): This cost accounts for new, recycled, and reused packaging components and is a function of the processing time for the assembly.
4. **Recovery (Take-back) cost** ($\mathbf{C}_{RE}$): This cost is incurred for bringing the packaging back to the manufacturing facility, including transportation, handling, and labor costs. Each of the packaging components contributes to this cost.
5. **Disassembly cost** ($\mathbf{C}_{DA}$): This cost is a function of disassembly time to retrieve packaging components for reuse, recycle, or disposal.
6. **Maintenance-for-reuse cost** ($\mathbf{C}_{RU}$): This cost applies only to the components that are reused. It includes costs for cleaning, repairing, and inspection.
7. **Recycle cost** ($\mathbf{C}_{RC}$): This cost applies only to the used components that are to be recycled.
8. **Disposal cost** ($\mathbf{C}_{DS}$): This cost applies only to those packaging components that are to be discarded at the end of each phase.

The total cost (*TC*) expression over the two phases is as follows:

$$TC = \sum_{i=1}^{k} \begin{bmatrix} C_{NM,i} + C_{MF,i} + C_{AB,i} + \\ X_{1i}(w_{DS,i}C_{DS,i} + C_{NM,i} + t_{MF,i}C_{MF,i} + t_{AB,i}C_{AB,i} + w_{RE,i}C_{RE,i} + t_{DA,i}C_{DA,i}) + \\ X_{2i}(t_{AB,i}C_{AB,i} + w_{RE,i}C_{RE,i} + t_{DA,i}C_{DA,i} + t_{RU,i}C_{RU,i}) + \\ X_{3i}(w_{RC,i}C_{RC,i} + t_{MF,i}C_{MF,i} + t_{AB,i}C_{AB,i} + w_{RE,i}C_{RE,i} + t_{DA,i}C_{DA,i}) \end{bmatrix} \quad (1)$$

where i represents a packaging component (i = 1, 2,…, k).
$t_{MF,i}$ represents time to manufacturing and remanufacturing the packaging component i.
$t_{AB,i}$ represents time to assemble the packaging component i.
$t_{DA,i}$ represents time to disassemble the packaging component i.
$t_{RU,i}$ represents time to maintain the packaging component i.
$w_{RE,i}$ represents weight of the packaging component i that requires take-back.
$w_{RC,i}$ represents weight of the packaging component i that requires recycling.
$w_{DS,i}$ represents weight of the packaging component i that requires disposal.
$\boldsymbol{X}$ represents decision variables:
$\boldsymbol{X_{1i}}$ = 1 if packaging component i is new, 0 otherwise,
$\boldsymbol{X_{2i}}$ = 1 if packaging component i is reused, 0 otherwise,
$\boldsymbol{X_{3i}}$ = 1 if packaging component i is recycled, 0 otherwise.

3. 2. Environmental Impacts (EI)

The environmental impact may be measured over three main media.

- *Solid Effluent* (S): It includes components that are disposed after the first phase, as well as any scrap from manufacturing, cleaning, and recycling processes.
- *Air Effluent* (A): It includes air pollution that is generated during the manufacturing processes, the recycling processes and the cleaning processes prior to reuse.
- *Water Effluent* (W): It is generated during the manufacturing processes as well as during the cleaning processes of packaging components prior to reuse.

With regard to the three media described above, the environmental impact may be divided into six elements:

1. $\mathbf{EI}_{MF}$ = Environmental impact from manufacturing and remanufacturing operations.
2. $\mathbf{EI}_{AB}$ = Environmental impact from assembly operations.
3. $\mathbf{EI}_{DA}$ = Environmental impact from disassembly operations which includes the impact of disposal of components if any.

4. $\mathbf{EI}_{RU}$ = Environmental impact from cleaning operations performed on components that are to be reused.
5. $\mathbf{EI}_{RC}$ = Environmental impact from recycling operations conducted on components that are to be recycled.
6. $\mathbf{EI}_{DS}$ = Environmental impact from disposal operations.

Since the above six elements involve three different media, the normalization of values to a uniform scale is required. Thus,

$$EI_{mi} = \frac{A_{\max} - A_{mi}}{A_{\max} - A_{\min}} + \frac{S_{\max} - S_{mi}}{S_{\max} - S_{\min}} + \frac{W_{\max} - W_{mi}}{W_{\max} - W_{\min}} \tag{2}$$

where m represents the six elements of environmental impact (m = 1, 2,…, 6),
i represents a packaging component (i = 1, 2,…, k),
$A_{\max}$ represents maximum allowable concentration of air effluent,
$A_{\min}$ represents minimum allowable concentration of air effluent,
A_{mi} represents measured concentration of air effluent,
$S_{\max}$ represents maximum allowable solid waste level,
$S_{\min}$ represents minimum allowable solid waste level,
S_{mi} represents measured level of solid waste,
$W_{\max}$ represents maximum allowable concentration of water effluent,
$W_{\min}$ represents minimum allowable concentration of water effluent,
W_{mi} represents measured concentration of water effluent.

The total environmental impact (EI) for returnable packaging over the two phases is as follows:

$$EI = \sum_{i=1}^{k} \left[\begin{array}{l} EI_{MF,i} + EI_{AB,i} + X_{1i}\left((EI_{DS,i} + EI_{MF,i} + EI_{AB,i} + EI_{DA,i})\right) + \\ X_{2i}\left((EI_{AB,i} + EI_{DA,i} + EI_{RU,i})\right) + X_{3i}\left((EI_{RC,i} + EI_{MF,i} + EI_{AB,i} + EI_{DA,i})\right) \end{array} \right] \tag{3}$$

where $\boldsymbol{X}$ represents decision variables, which were described in the previous subsection.

4. EVALUATING THE TRADE-OFFS OF CRITERIA FOR THE PACKAGING DESIGN

Goal programming is one of the most frequently used mathematical tools for solving multi-criteria decision making problems. However a preemptive priority approach as required by goal programming does not allow ways for considering any trade-offs among the different criteria. The objective function in a goal-programming model is replaced by several goals that are to be fulfilled at satisfactory levels. A number of alternative solutions may be undesirable because improvement in one criterion may have to be achieved at the cost of the others. Further, after generating a number of alternative solutions using different priority, the best solution is selected without using a meaningful comparison of the alternatives.

In this paper, we employ a new two-step procedure [13], involving multi-objective integer linear programming (MOILP) and analytic hierarchy process (AHP) [12]. This approach outperforms the goal programming approach by requiring a decision maker to rank order the criteria and to specify the maximum allowable sacrifice level for the top rank criteria. The preferred alternatives are then compared and evaluated using AHP.

Incorporating MOILP into AHP

The procedure involves two stages: (1) the generation of alternative solutions, and (2) the evaluation of alternatives by AHP (see Figure 1). The procedure begins with the process of ranking the criteria in the order of their importance, and specifying their minimal acceptable levels. These levels represent the minimum standards that must be fulfilled by an acceptable solution. The objective function for the top ranking criteria is then optimized. The lower ranking criteria are then successively optimized with a prespecified percentage sacrifice level for the top-ranking criterion. A number of solutions are first generated and later evaluated by AHP.

In the evaluation stage by AHP, the process requires the decision maker to enter relative importance or weights of the criteria, and the relative preference of alternatives within each criterion. These weights and preferences are then integrated to form a composite weight for each alternative and are then used to rank the alternatives.

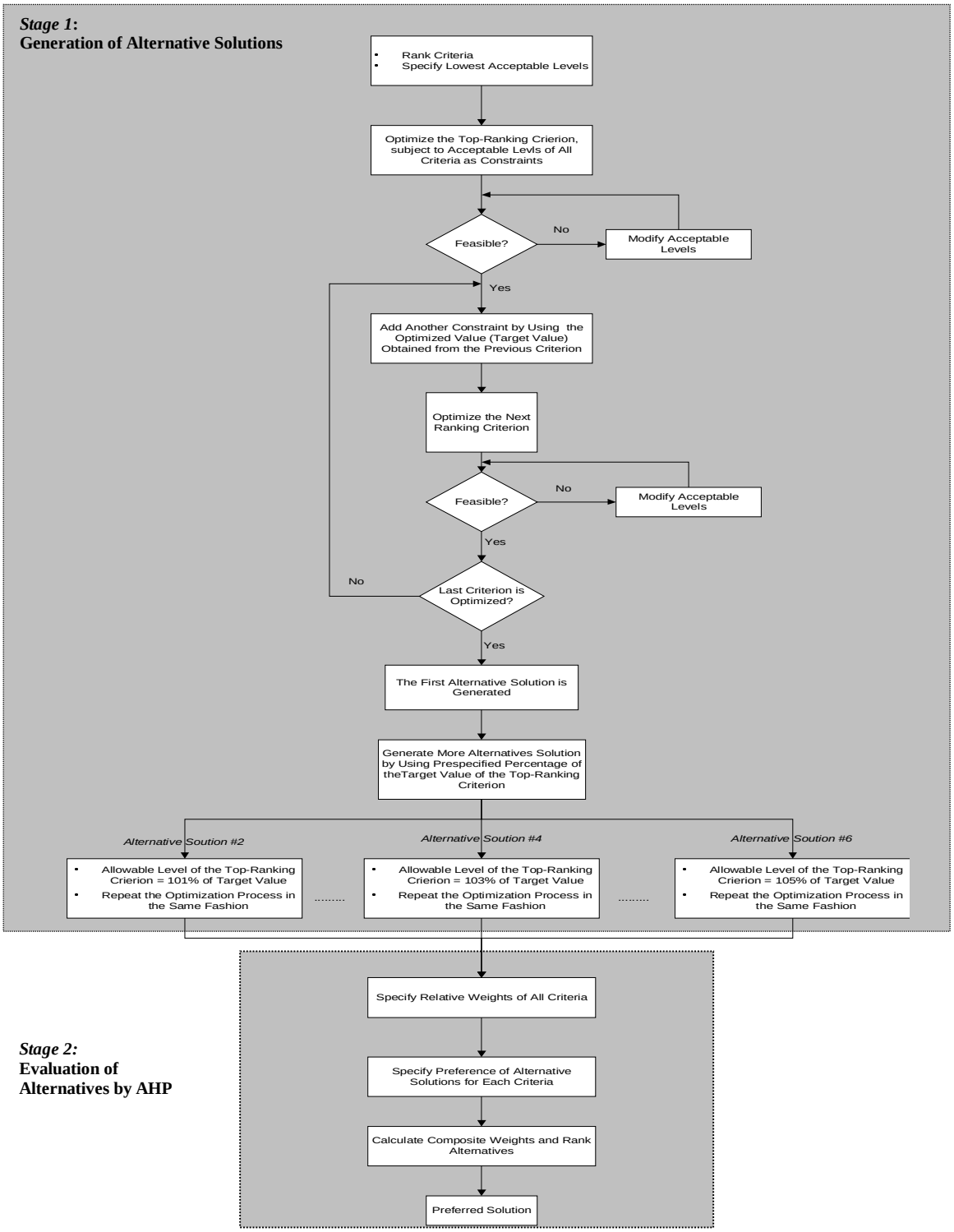

Figure 1. Steps representing the generation and evaluation of alternatives

5. NUMERICAL EXAMPLE

5. 1. Problem Description

A packaging manufacturer wants to design returnable transport packaging for use in the two phases. The transport package comprises of six components. The total cost is the top-ranking criterion. A decision is required for how many new, reused or recycled components to be used to build the transport packaging. The total cost and environmental impact level are not to exceed $500 and 70%, respectively. Other pertinent data is provided in Table 1.

Table 1. Data for the example

Component	Cost Categories							
	C_{NM} ($)	C_{MF} ($/ time)	C_{AB} ($/ time)	C_{RE} ($/ weight)	C_{DA} ($/ time)	C_{RU} ($/ time)	C_{RC} ($/ weight)	C_{DS} ($/ weight)
1	6	4.8	6.6	11	3.6	3	6.6	9.9
2	3.5	6.9	9	8.6	7.6	3	10	3.7
3	12	5.2	10	11	6.9	3	5.6	5.2
4	6	8.1	11	3.4	8.5	3	6.7	4
5	4.1	6.6	3.1	11	9.1	3	5.4	11
6	4.1	8.5	6.9	12	3	3	7.8	8.5

Component	Time and Weight						
	t_{MF} (min)	t_{AB} (min)	w_{RE} (lbs)	t_{DA} (min)	t_{RU} (min)	w_{RC} (lbs)	w_{DS} (lbs)
1	14	6	10	5	10	10	10
2	15	5	8	4	10	8	8
3	13	5	11	4	10	11	11
4	14	6	8	5	10	8	8
5	16	7	11	6	10	11	11
6	16	6	12	5	10	12	12

Component	Environmental Impact Levels (EI)					
	EI_{MF}	EI_{AB}	EI_{DA}	EI_{RU}	EI_{RC}	EI_{DS}
1	2.22	0.4	2.04	2.444	2.638	0.698
2	1.015	2.756	0.47	1.49	2.112	0.266
3	2.04	1.226	0.297	2.249	1.624	1.456
4	2.444	2.098	2.203	1.338	2.879	1.05
5	2.638	2.932	2.76	1.216	0.629	2.373
6	0.698	1.48	0.672	0.31	0.831	0.62

By following Section 3, a multi-objective integer linear programming model is constructed as follows.

$$Minimize \quad TC = \sum_{i=1}^{6} \begin{bmatrix} C_{NM,i} + C_{MF,i} + C_{AB,i} + \\ X_{1i}(w_{DS,i}C_{DS,i} + C_{NM,i} + t_{MF,i}C_{MF,i} + t_{AB,i}C_{AB,i} + w_{RE,i}C_{RE,i} + t_{DA,i}C_{DA,i}) + \\ X_{2i}(t_{AB,i}C_{AB,i} + w_{RE,i}C_{RE,i} + t_{DA,i}C_{DA,i} + t_{RU,i}C_{RU,i}) + \\ X_{3i}(w_{RC,i}C_{RC,i} + t_{MF,i}C_{MF,i} + t_{AB,i}C_{AB,i} + w_{RE,i}C_{RE,i} + t_{DA,i}C_{DA,i}) \end{bmatrix} \quad (4)$$

$$Minimize\ EI = \sum_{i=1}^{6} \begin{bmatrix} EI_{MF,i} + EI_{AB,i} + X_{1i}\left((EI_{DS,i} + EI_{MF,i} + EI_{AB,i} + EI_{DA,i})\right) + \\ X_{2i}\left((EI_{AB,i} + EI_{DA,i} + EI_{RU,i})\right) + X_{3i}\left((EI_{RC,i} + EI_{MF,i} + EI_{AB,i} + EI_{DA,i})\right) \end{bmatrix} \quad (5)$$

Subject to

$$\sum_{i=1}^{6} (X_{1i} + X_{2i} + X_{3i}) = 6 \quad (6)$$

$$\sum_{j=1}^{3} (X_{ji}) = 1, \text{ for each } i;\ i \in \{1, 2, ..., 6\} \quad (7)$$

$$TC \leq 500 \quad (8)$$

$$EI \leq 70 \quad (9)$$

$$X_{1i}, X_{2i}, X_{3i} = \{0,1\} \text{ for all } i$$

5. 2. Solution Methodology

Stage 1: *Generation of Alternatives*

Step 1.1. Rank the two criteria and specify their lowest allowable levels as follows: Total cost (TC) is the most important criterion and must not exceed $500. The environmental impact (EI) is the next ranking criterion and must not exceed the level of 70%.

Step 1.2. Optimize the most important criterion, TC, subject to the allowable levels of both criteria. The solution to this optimization problem and the objective function value obtained in this example is $387.80, which will be regarded as the target cost.

Step 1.3. Generate the first alternative solution by introducing TC ≤ 387.80 as an additional constraint, and then minimizing the next ranking criteria, EI. The optimization gives EI = 48.9, TC = 387.80. The feasible solution is (X21, X22, X23, X24, X25, X26) = (1, 1, 1, 1, 1, 1).

Step 1.4. Generate the second alternative solution by relaxing TC to 391.68 (101% of 387.8). Add TC ≤ 391.8 as a constraint. Minimize the TC as the top-ranking criterion. The new optimized TC is 389.40. Add TC ≤ 389.40 as another constraint and optimize the next-ranking criterion, EI. The optimization gives EI = 46.5, TC = 388.30. The feasible solution is (X11, X32, X33, X24, X15, X26) = (1, 1, 1, 1, 1, 1).

Step 1.5. Generate four more alternatives with allowable cost 102%, 103%, 104%, and 105% of 387.80 just as in Step 1.4. The final results are shown in Table 2.

Stage 2: *Evaluation of the Alternative Solutions*

Step 2.1. Specify the relative weights of TC and EI to be 0.7, and 0.3, respectively.

Step 2.2. Assign the relative preferences of the six alternatives for each criterion. In AHP, the alternatives must be compared pair wise over each criterion on a scale of 1 to 9, where 1 represents equally preferred and 9 represents extremely preferred (see Table 3).

Step 2.3. Develop the composite weights and rank alternatives. Finally, the best alternative is obtained (see Figure 2). Obviously, the best solution is the first alternative.

Table 2. Alternative solutions

Specify TC ≤ 500, EI ≤ 70;Target cost = $387.8

Alternative	Allowable TC ($)	Actual TC ($)	EI	Number of Packaging Parts		
				New	Reused	Recycled
1	387.8	387.8	48.9	**0**	**6**	**0**
2	391.68	391.68	47.5	**2**	**2**	**2**
3	395.56	393.24	44.7	**1**	**4**	**1**
4	399.43	399.43	43.9	**0**	**4**	**2**
5	403.31	403.31	44.2	**0**	**3**	**3**
6	407.19	407.19	45.6	**1**	**3**	**2**

Table 3. Relative preference for *TC* & *EI*

	Alternative					
	1	2	3	4	5	6
TC ($)	387.8	391.68	395.56	399.43	403.31	407.19
Relative Preference	**6**	**5**	**4**	**3**	**2**	**1**
EI	48.9	47.5	44.7	43.9	42.2	45.6
Relative Preference	**7**	**6**	**3**	**2**	**1**	**4**

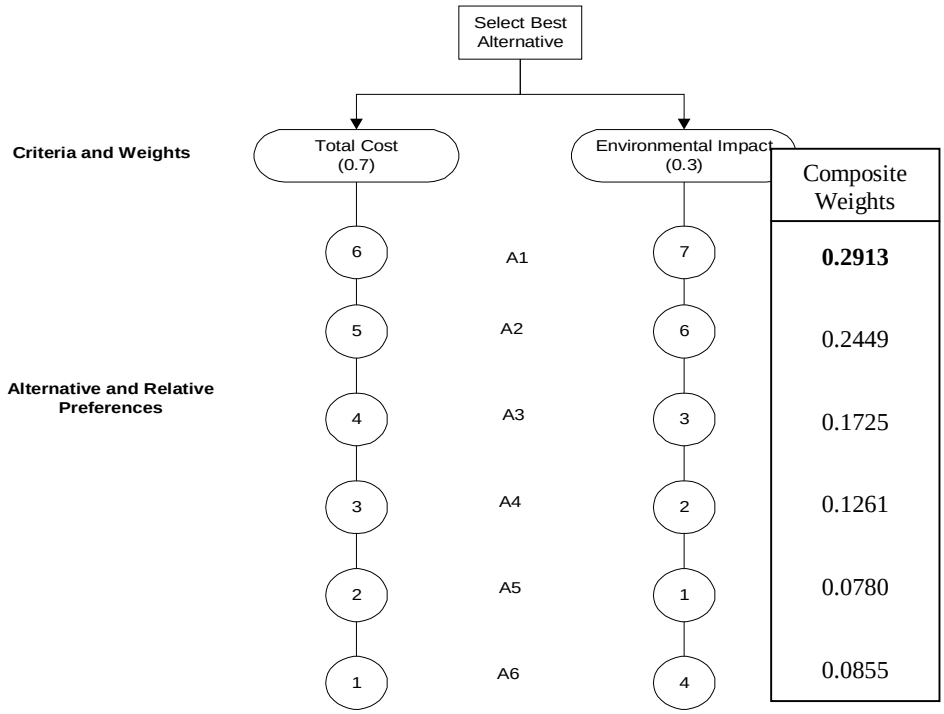

Figure 2. Composite weights and evaluation of alternatives

7. CONCLUSIONS

In this paper, a two-step approach, involving a multiple objective integer linear programming (MOILP) and the analytic hierarchy process (AHP) was utilized to evaluate trade-offs among criteria of a multi-criteria decision making problem for returnable packaging design. Total cost and environmental impacts were used as the two criteria. Total cost included the costs of materials, manufacturing, collection, and disposal. Environmental impacts were encountered from the operations of manufacturing, assembly, disassembly, and recycling. The approach used in this paper consisted of two stages. Stage 1 generated the alternative solutions for the multi-objective integer linear programming model. Stage 2 evaluated those alternatives by using AHP in order to obtain the most preferred solution that determined which packaging components need to be new, reused, or recycled. The methodology was illustrated with the help of a numerical example.

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