International Journal of Environmentally Conscious Design & Manufacturing, Vol. 11, No. 1, 2003
Printed in the U.S.A.

INTEGRATION OF GREEN QUALITY FUNCTION DEPLOYMENT AND FUZZY MULTI-ATTRIBUTE UTILITY THEORY-BASED COST ESTIMATION FOR ENVIRONMENTALLY CONSCIOUS PRODUCT DEVELOPMENT

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There are increasing global demands for environmental friendly products. Green Quality Function Deployment – III (GQFD – III) is an innovative tool aiding in the development of environmentally conscious products and processes. An improved version of GQFD – III, Green Quality Function Deployment – IV (GQFD – IV) has been developed in this study. Its improvement over GQFD – III is that the life cycle cost is estimated using the Fuzzy Multi-Attribute Utility Theory (FMAUT) method. FMAUT costing is an excellent cost estimation method at the early design stage in product development. It is more effective than other traditional methods because it does not require detailed data on manufacturing processes of the product and it can handle attributes with uncertainty and incompleteness in nature. In a case study, life cycle costs of coffeemakers were estimated with errors of less than 7% using this new cost estimation model. In GQFD – IV, with the considerations of quality, environment and cost, analytical hierarchy process (AHP) is used for product concept selection and is found to be effective.

INTRODUCTION

Environmentally friendly products have gained more and more interests in recent years because of increasing consumer awareness about environmental issues, along with growing concern for environmental impacts of unrestricted industrial activity. Increasingly stringent environmental regulations, growing costs for waste disposal, and increasing threats of product liability litigation have accentuated the importance of developing environmentally friendly products.

Furthermore, pressures of globalization have ushered in an era of intense competition, where environmentally friendly products can go a long way in helping organizations leverage their competitive advantages. Consequently, manufacturers have to transit to environmentally conscious manufacturing strategy.

Many design tools and methods have been developed to aid in creating environmentally friendly products. "Life Cycle Assessment" (LCA) and "Life Cycle Costing" (LCC) have been developed to improve monitoring and control of industrial operations, which in turn have decreased the negative environmental impacts of routine manufacturing and engineering activities.

LCA is a complex effort consisting of three stages: "inventory analysis," "impact analysis," and "improvement analysis." This approach considers all the material and energy transfers involved in raw material extraction, processing, and manufacture, including the cradle to the grave of a product.

LCC is a methodology used by designers in conjunction with LCA. It takes into account the costs involved in the handling, processing, usage, and so forth, of a product through its life cycle stages. An accurate characterization and quantification of life cycle costs is neither straightforward nor easy. A typical approach is based on the concept of nested costs, in which, life cycle costs are divided into two categories: internal (company) costs and external (social or societal) costs. This is illustrated in Figure 1.

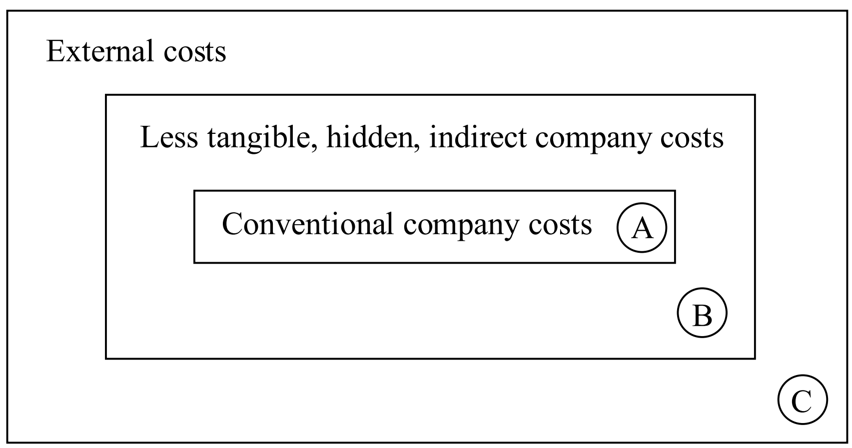

Figure 1. Cost boundaries

Several methods for LCC are contingent valuation, hedonic pricing, and the Revealed Preferences approach. Contingent valuation relies on surveys to estimate what people are willing to pay to prevent environmental degradation or other adverse impacts. Hedonic pricing is an alternative approach that examines and uses market behavior to determine costs associated with the environmental impact in question. The Revealed Preferences approach is an empirical means of establishing customers' willingness to pay without directly engaging in the complex task of identifying and estimating all various physical environmental damages and polling all the affected parties.

A considerable amount of research work has been done in the area of utilizing life cycle methodologies for the design of environmentally conscious products. Berkhout and Howes [1] have described changing patterns and trends in the adoption of life cycle methodologies in European industries. Song and Hyun [2] have conducted a comparison study on different waste management scenarios for PET bottles using Life

Cycle Assessment approach. Through a Life Cycle Assessment study of a rock crusher, Landfield and Karra [3] have shown that the maximum environmental impacts can be attributed to the use phase of the rock crusher. Costic *et al.* [4] have estimated the environmental performance of conventional lead-based solders and their substitutes, using Life Cycle Assessment studies. Donaldson et al. [5] have conducted Life Cycle Assessment studies on a telecommunications semiconductor laser. Hedelmalm [6] compared various interconnection techniques for printed board assemblies using Life Cycle Assessment approach. Pollock [7] has conducted an extensive Life Cycle Assessment analysis for Hewlett – Packard inkjet printer cartridges, which involved over 100 Hewlett Packard employees and many of Hewlett Packard's suppliers. Terho [8] has carried out a Life Cycle Assessment study for telecommunications cables, and included improvement assessment in his study. Van Mier [9] discussed the application of life cycle methods on a 17" Philips brand monitor, demonstrating a strong positive correlation between the economic and environmental aspects of a product.

Attempts have been made to integrate life cycle methodologies with design tools such as Quality Function Deployment (QFD). Keoleian [10] developed a life cycle design framework that utilizes design checklists to establish product requirements. However, his study has no explicit mechanism to prioritize these requirements and deploy them into the product development process. Hanssen [11] and Forde [12] applied QFD, Life Cycle Assessment and Life Cycle Costing separately for the development of environmentally sound light fittings. However, their method was not systematic in integrating QFD, Life Cycle Assessment and Life Cycle Costing into one efficient tool. Stornebel and Tammler [13] incorporated environmental requirements into traditional QFD matrices. Akao [14] described the applications of QFD techniques in the product development process. Graedel and Allenby [15] developed an environmentally responsible product assessment matrix, which uses checklists to simplify the process of performing Life Cycle Assessment. An innovative design methodology called Green Quality Function Deployment (GQFD) has been developed by Cristofari *et al*. [16]. It integrates QFD and Life Cycle Assessment into a powerful tool that can help design teams document the technical requirements for a product concept while assessing the environmental impacts associated with that concept. Different product alternatives can be assessed based on these requirements thus aiding in the selection of the best product. This tool has been further improved in the Green Quality Function Deployment – II (GQFD – II) methodology developed by Zhang *et al*. [17]. In GQFG – II, Life Cycle Costing is integrated with Life Cycle Assessment and both are incorporated into QFD matrices.

GREEN QUALITY FUNCTION DEPLOYMENT – III

Green Quality Function Deployment – III (GQFD – III) is an innovative design tool for developing environmentally friendly products. An improvement over GQFD – II, GQFD – III integrates QFD matrices with Life Cycle Assessment methods and Life Cycle Costing approach.

As shown in Figure 2, GQFD – III methodology consists of four phases. Phase-I is the "Technical Requirements Identification Phase." The "House of Quality (HOQ) is established in this phase. It enables a design team to capture customer requirements and translate them into technical parameters that a design team can work on. The House of Quality is established for all the product concepts under consideration. There can be several matrices established during this phase, in order to reach a final matrix that consists of technical parameters to a level of detail the design team may deem as necessary.

Phase-II is the "Environmental and Cost Data Establishment Phase." The "Green House" (GH) and the "Cost House" (CH) are established in this phase. The Green House documents the life cycle inventory loads for a product option, and their impacts on the environment. These impacts are expressed in terms of eco-indicator values. The cost house documents the life cycle costs associated with a product concept. The Green House and the Cost House are established for all the product concepts under consideration. The outputs are used as inputs in the subsequent phases.

Phase-III is the "Product Concepts Comparison Phase." The "Concept Comparison Matrix" is established in this phase. In this matrix, all the product options under consideration are documented with their quality, cost and environmental attributes. These data are derived from the House of Quality, the Green House and the Cost House, respectively. The choice for the best product option is made in this phase.

Phase-IV is the "Product/Process Design Phase." QFD techniques are utilized in this phase to develop an optimized manufacturing process for the product concept chosen in Phase-III.

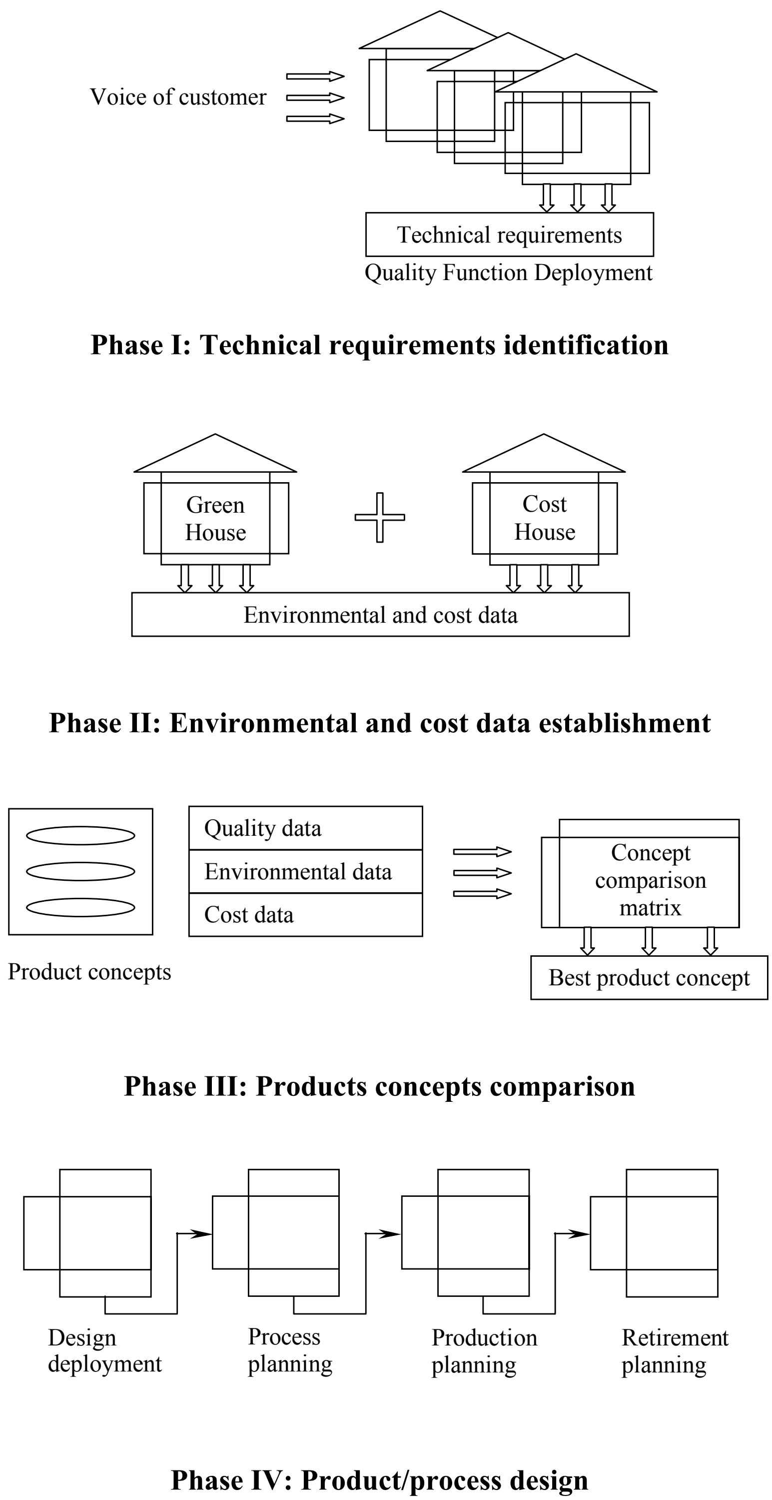

Figure 2. Green Quality Function Deployment – III

Despite the several advantages GQFD – III affords over conventional design approaches, much work needs to be done in the area of developing models that can help in the better quantification hidden and indirect life cycle costs.

The structure of the Cost House is as shown in Figure 3. In the Cost House, room 1 indicates the cost items for different life cycle stages. These include material costs, processing costs, disposal costs, transportation costs, and so forth. Room 2 shows the factors that are affected by cost reduction. These could be quality, environmental performance, functionality, and so forth. Room 3 is the "Cost Impacts Relationship Matrix." Room 4 indicates the priorities of cost items that need to be reduced. Room 5 is the "Correlation Matrix," which indicates the correlations between the cost items listed in room 1. Room 6 is optional and documents the target costs that a design team may wish to achieve.

In the current Cost House establishment, cost items including material costs, processing costs, disposal costs, transportation costs, and so forth are considered. Actual cost values are used to establish the Cost House. However, these cost values are usually difficult to estimate in early design phases. Cost contributions of the factors are fuzzy and vague. In this study, the concept of GQFD – IV is presented. Its improvement over GQFD – III lies in the establishment of the Cost House. A new cost estimation method based on fuzzy multi attribute utility theory is developed.

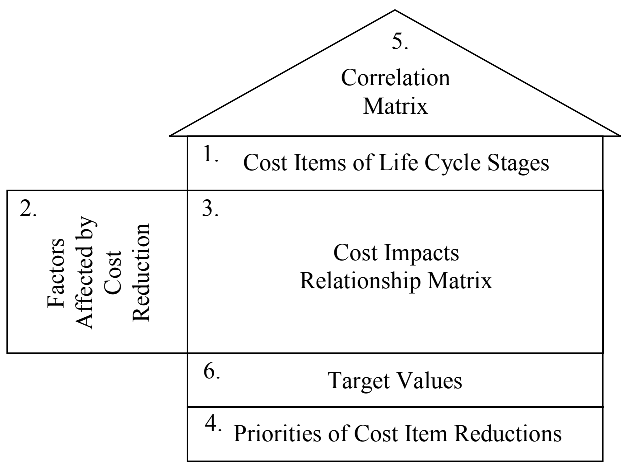

Figure 3. Cost House

FUZZY MULTI-ATTRIBUTE UTILITY COST ESTIMATION

Multi-Attribute Utility Theory (MAUT)

Product cost is determined by a number of attributes (or cost drivers). Each attribute can be set to several levels. These feature levels depend on the nature of design. In this study, eight attributes are chosen. For each attribute, a higher level has more contribution to product cost than a lower level, provided that all other attributes are fixed. Different levels have different influence on the cost. MAUT assigns a utility value to each level, which reflects its influence extent on the cost. The higher the level, the larger the utility value. Experts assign the utility value for each level based on their experience. By means of the utility theory, expert's preference on the influence of feature levels on product cost is expressed in a simple mathematical form.

With the utility values of each attribute, attributes can be compared and integrated. Therefore, a general utility value, called cost index, can be obtained by combining utility values of all attributes. The cost index has a direct relationship with the real cost.

MAUT-based cost estimation begins with defining attributes, which are variables that affect life cycle cost of products. Based on experts' experience, eight variables are chosen for a general-purpose analysis. They are:

- Complexity (9 levels)
- Quality (4 levels)
- Material in manufacture (4 levels)
- Size (5 levels)
- Material in use (3 levels)
- Energy consumption in use (3 levels)
- Material in disposal (3 levels)
- Labor used in disposal (3 levels)

After the attributes are defined, levels for each attribute need to be determined. The number of levels may vary from one attribute to another. The definition of the feature levels for each attribute and their corresponding utility values are given by experts.

The next step is to assign utility values to the defined feature levels. Experts do not assign the utility value for each level directly. The value of the lowest level for each attribute, given by experts, always equals to 1, i.e., $u_{i1k} = 1$ always holds true. The values for other levels are established according to cost magnitudes compared to that of the lowest level. u_{ijk} denotes the cost value defined for level j of attribute i by kth expert. m is the number of attributes; n_m is the number of levels for attribute m; l is the number of experts.

Cost values are converted into utility values by dividing the cost values of the highest level for each attribute. That is

$$U_{ijk} = u_{ijk} / u_{in_ik} \tag{1}$$

After this transformation, utility values are between 0 and 1. The characteristic of utility values makes it easier for later combination of utility values for individual attributes. The combined general utility values for all attributes can be considered as the cost index.

The importance of each attribute is not equal. A weight, which indicates the influence of each attribute on the cost, is given to each attribute in the cost model.

In order to compare design alternatives, multi attribute decision-making should integrate the utility values for each attribute into one general utility value – cost index. Without fuzziness, comparison and integration of the utility value for each attribute can be easily done with Multiplicative Utility Model [18].

$$U(X) = \frac{\prod_{i=1}^{m}\left[W \cdot w_i \cdot U_i(x_i) + 1\right] - 1}{W} \tag{2}$$

$$1 + W = \prod_{i=1}^{m}(1 + W \cdot w_i) \tag{3}$$

where

$U(X)$	general utility value, cost index;
W	scaling factor;
w_i	weight for attribute i;
m	number of attributes;
$U_i(x_i)$	utility value of attribute i at level x_i;
X	Vector $X = (x_1, x_2, x_3, \ldots, x_i, \ldots x_m)$; and
x_i	specific feature level for attribute i.

$U(X)$ is a function of vector X. It means that $U(X)$ depends on the feature level of each attribute.

Fuzzy Multi-Attribute Utility Theory (FMAUT)

In FMAUT, w_i and $U_i(x_i)$ are fuzzy and are expressed by membership functions instead of real numbers. Thus, the result $U(X)$ is fuzzy and is expressed by membership functions of cost index instead of a general utility value [19].

Membership Function for Attributes

Experts have different opinions about utility values. Also utility values are vague and fuzzy. Therefore, a membership function for each level of an attribute should be constructed to reflect expert opinions about the utility values. For a triangular membership function, the minimum and maximum utility values for each level given by the experts form the two bottom points, and the average of the utility values form the top point. The following operations should be done for each level of an attribute.

$$\begin{cases} TL_{ij} = \min(U_{ijk}) \\ TM_{ij} = \sum_{i=1}^{l} U_{ijk} \Big/ l \\ TU_{ij} = \max(U_{ijk}) \end{cases} \tag{4}$$

where

TL_{ij} the lowest utility value of the membership function for level j of attribute i;
TM_{ij} the utility value of the membership function with membership grade equal to 1;
TU_{ij} the highest utility value of the membership function for level j of attribute i;

The membership grades for utility values TL_{ij} and TU_{ij} are 0; the membership grade for utility value TM_{ij} equals to 1. This is based on the assumption that among the utility values given by the experts, the average of the values is more likely to denote the feature level than the minimum value or maximum value.

Membership functions for all feature levels of all attributes, based on experts' experience, are stored in the model. For a specific design, if users have identified the design to be a feature level for an attribute, the corresponding membership functions can be retrieved. A membership function is established for each attribute. Eight attributes have eight membership functions. These membership functions are combined together to make a membership function of the cost index.

Although all attributes are quite different, they can be compared according to their contributions to the final cost. Utility theory makes it possible for all attributes to be expressed by comparable utility values. Therefore, they can be combined into one general utility value — cost index.

Membership Functions for Weights

Similar to the utility values of feature levels, weights can be expressed in the form of membership function because of their fuzziness. Experts give the weights (w_{i1}, w_{i2}, …, w_{il}) for attribute i, membership function of weight for attribute k can be constructed as follows

$$\begin{cases} WL_i = \min(w_{ik}) \\ WM_i = \sum_{k=1}^{l} w_{ik} \Big/ l \\ WH_i = \max(w_{ik}) \end{cases} \tag{5}$$

WL_i, WH_i are the two bottom points of the membership function with a membership grade equal to 0 and WM_i is the top point of membership function with membership grade equal to 1.

Membership Function for Cost Index

The result $U(X)$ is fuzzy and is expressed by the membership function of the cost index instead of a general utility value as

$$\mu(U(X)) = \frac{\prod_{i=1}^{m} \left[W \cdot \mu(w_i) \cdot \mu(U_i(x_i)) + 1\right] - 1}{W} \tag{6}$$

$$1 + W = \prod_{i=1}^{m} (1 + W \cdot w_i^{\max}) \tag{7}$$

where

$\mu(U(X))$	membership function of cost index;
$\mu(w_i)$	membership function of weight for attribute i;
$\mu(U_i(x_i))$	membership function of utility value for attribute i; and
w_i^{max}	max weight value among five weights given by experts for attribute i.

Defuzzication

The membership function of the cost index describes the relationship between the membership grade and general utility value (cost index). In order to obtain the quantitative cost index, the cost index membership function needs to be defuzzified. Two defuzzification methods are commonly used: Center of Area (COA) Method and Center of Maximum (COM) Method [20].

In the COA method, the center of the membership function is considered to be the expected cost index. For a triangle membership function, it is the centroid of the triangle. In the COM method, the average of the minimum utility value and the maximum utility value is considered to be the expected cost index. Usually, the results of the two methods are very close.

Regression Model

A regression model is established for cost estimation with historical data. Cost indices can be converted into cost values with this regression model. Cost value is assumed in an exponential relationship with the cost index. The regression model can be expressed as

$$Cost = ae^{b(index)} \tag{8}$$

The linear form is

$$\ln(Cost) = \ln a + b(index) \tag{9}$$

where a and b are the parameters in the regression model.

The complete FMAUT cost estimation process is shown in Figure 4.

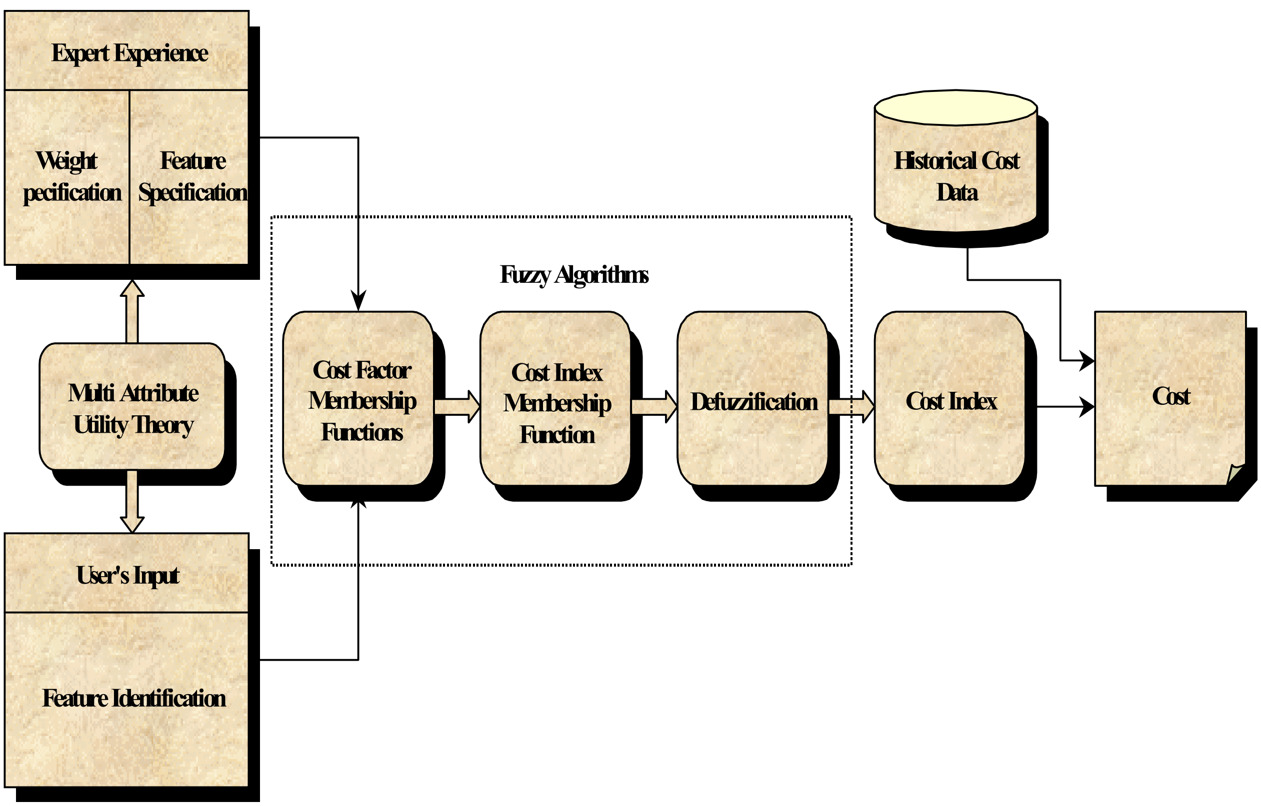

Figure 4. FMAUT cost estimation

FMAUT Cost Estimation Case Study – Coffeemaker

The following sections describe a case study of estimating the life cycle costs of coffeemakers with the FMAUT for GQFD-IV implementations. Attributes and feature levels for the life cycle cost estimation of the coffeemakers are shown in Table 1.

Levels	Attributes							
	Manufacture				Use		Disposal	
	Complexity	**Quality**	**Material**	**Size (cups)**	**Material**	**Energy**	**Material**	**Labor**
1	Extremely simple	Economical	Low-grade plastic	4 and under	Small amount	Low	Small amount	Low
2	Simple	Medium	General purpose plastic	5 – 8	Moderate amount	Middle	Moderate amount	Middle
3	Somewhat simple	High	Plastic & special materials	9 – 10	Large amount	High	Large amount	High
4	Simple to Medium	Special purpose	Stainless steel & special materials	11 – 12				
5	Medium			13 and up				
6	Medium to complex							
7	Somewhat complex							
8	Complex							
9	Extremely complex							

Table 1. Attributes and feature levels for life cycle cost estimation of coffeemakers

Since the structures of most coffeemakers are similar, it can be assumed that a coffeemaker's complexity is determined by the number of features it possesses. Features that coffeemakers commonly have, for example, cord storage, swing out basket, etc. are neglected. Other features, such as programming capability, reflect the technical development in coffeemaker design. In other words, the more technical content in a coffeemaker, the higher the complexity is. The quality of a coffeemaker is determined by its life and reliability. The longer it is, the higher its quality will be. The length of the warranty (years) from the manufacturer is an indicator of the coffeemaker’s quality. Levels for material can be determined from materials used in the production of a coffeemaker. Most common materials include low-graded plastic, general purpose plastic, glass, stainless steel, and other special materials. Levels for size are simply determined from the number of cups a coffeemaker serves.

In the usage stage, material and energy are selected as the attributes. Cost in material is mainly related to paper filters. Some coffeemakers utilize a permanent filter. The cost in material is low. Energy levels are determined by the electricity a coffeemaker consumes, based on the assumption that the same amount of coffee is served every day.

In the disposal stage, material and labor are selected as two attributes. Material levels are determined by the amount of materials being disposed, including paper filters and structural materials, such as glass, plastic, etc. Labor levels are determined by labor used in disposal.

As an example, life cycle costs of two coffeemakers are estimated using the proposed method. The first coffeemaker being analyzed is a programmable thermal carafe black coffeemaker. Its features include:

- Fully programmable 24-hour clock;
- Patented brew-through and pour-through lid that keeps air out and coffee fresh;
- 8-cup thermal carafe that keeps coffee hot for up to 8 hour;
- Brew Pause™ that lets you enjoy a cup before brewing is finished;
- Automatic shutoff with a beep when brewing is done;
- Water-level indicator.

Attribute	Level
Complexity	6
Quality	3
Material in manufacture	3
Size	2
Material in use	2
Energy consumption in use	2
Material in disposal	2
Labor used in disposal	2

Table 2. Feature levels of Coffeemaker 1

This coffeemaker is considered having a complexity level of 6. It has a three-year manufacturer's warranty, thus its quality level is 3. All the feature levels are shown in Table 2.

After feature identification, corresponding membership functions are retrieved from the database that has been constructed from expert experience. For example, the membership function of complexity at level 6 is shown in Figure 5.

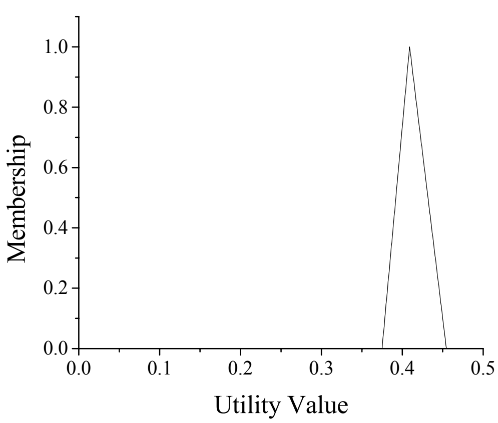

Figure 5. Membership function of complexity at level 6

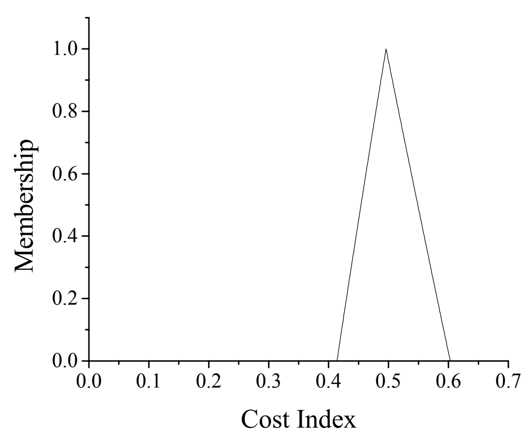

Figure 6. Membership function of cost index

After the membership functions of all the attributes are retrieved, membership function of cost index is calculated according to equations (6) and (7). The membership function of cost index for Coffeemaker 1 is shown in Figure 6.

An expected cost index is obtained through defuzzification. The cost index value is 0.4958.

Index	Cost
0.29575	32.3
0.30205	36.5
0.34465	51
0.4878	57
0.5238	69
0.94155	211.5

Table 3. Historical data

A regression model is formed with historical data, which is shown in Table 3. The fitted model is

$$Cost = 17.4324e^{2.8280index} \tag{10}$$

Regression curve is shown in Figure 7. Map the cost index into the regression model. The cost of Coffeemaker 1 is 70.84 dollars. The cost provided by manufacturer is 75.5 dollars. The relative error is less than 7%.

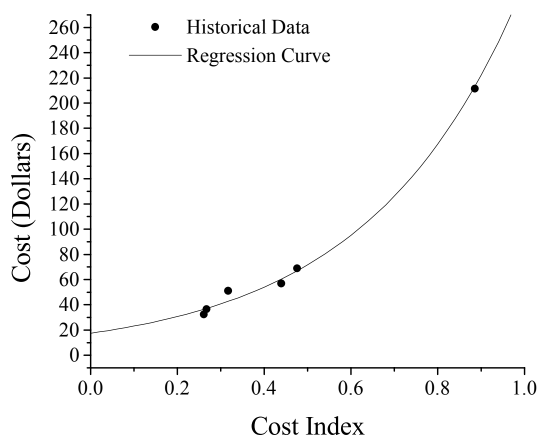

Figure 7. Regression curve

For the purpose of comparison, another coffeemaker – Coffeemaker 2 is analyzed. Its features include:

- Programmable logic clock/timer;
- 2-hour automatic shutoff;
- Pause 'n serve;
- Lift-up lid and filter basket;
- Nonstick warming plate.

This coffeemaker is considered having a complexity level of 5. It has a one-year manufacturer's warranty, thus its quality level is 1. All the feature levels are shown in Table 4.

Attribute	Level
Complexity	5
Quality	1
Material in manufacture	3
Size	4
Material in use	2
Energy consumption in use	2
Material in disposal	2
Labor used in disposal	2

Table 4. Feature levels of Coffeemaker 2

The cost index and cost are 0.3619 and 48.51 dollars, respectively. Cost estimation for Coffeemaker 1 and Coffeemaker 2 are summarized in Table 5.

	Cost index	Estimated cost	Actual cost	Relative error
Coffeemaker 1	0.4958	70.84	75.50	6.17%
Coffeemaker 2	0.3619	48.51	51.50	5.81%

Table 5. Summary of the life cycle cost estimation for coffeemakers

From these two examples it shows that with FMAUT method, life cycle cost can be estimated satisfactorily with errors within 7%, compared to the actual costs.

PRODUCT CONCEPT COMPARISON AND OPTIMAL DESIGN

In order to find the optimal design, the Concept Comparison Matrix (Figure 8) is established. The Concept Comparison Matrix documents the quality, cost and environmental data associated with each product option. This matrix is divided into three rooms: the "Quality Room," the "Environment Room," and the "Cost Room." The upper part of the Quality Room has the customer requirements along with their respective importance ratings. In this case of Coffeemaker 1, only the three most important requirements have been listed.

	Quality Data ↑			Quality Points	Environmental Data ↓			Total Eco-points	Cost Data ↑
	Importance Ratings				Life Cycle Stages				
	3	4	5						
Requirements / Product Concepts	High temp. Retention	Light Weight	Non-messy Operation		Manufacture	Use	Disposal		Life Cycle Cost
Coffeemaker 1	10	9	9	111	722	3902	20	4644	70.84
Coffeemaker 2	6	6	8	82	511	3073	11	3595	48.51
Coffeemaker 3	6	7	6	76	589	3762	13	4364	35.65

Figure 8. The Concept Comparison House

After a detailed technical ana1ysis of each product option, a design team is required to indicate the extent to which each product will satisfy each of the customer requirements. This is done using numbers in the range of one to ten. A higher number indicates a better degree of achievement. For example, Coffeemaker l has the values of six, nine and ten for the customer requirements of High Temperature Retention, Light Weight and Non-messy operation, respectively. This is done for all the coffeemakers. The total Quality Points for each coffeemaker are calculated by multiplying the importance ratings for each customer requirement by the corresponding quality points. The Environmental Data Room documents the Eco-indicator values associated with each life cycle stage, for each product option. These values are obtained from the Green House, which is established for each coffeemaker. The Cost Data Room documents the life cycle costs for each product option. These values are obtained from the Cost House obtained with the FMAUT cost estimation method. The data in the Concept Comparison Matrix clearly shows the quality, cost and environmental attributes of all the products under considerations.

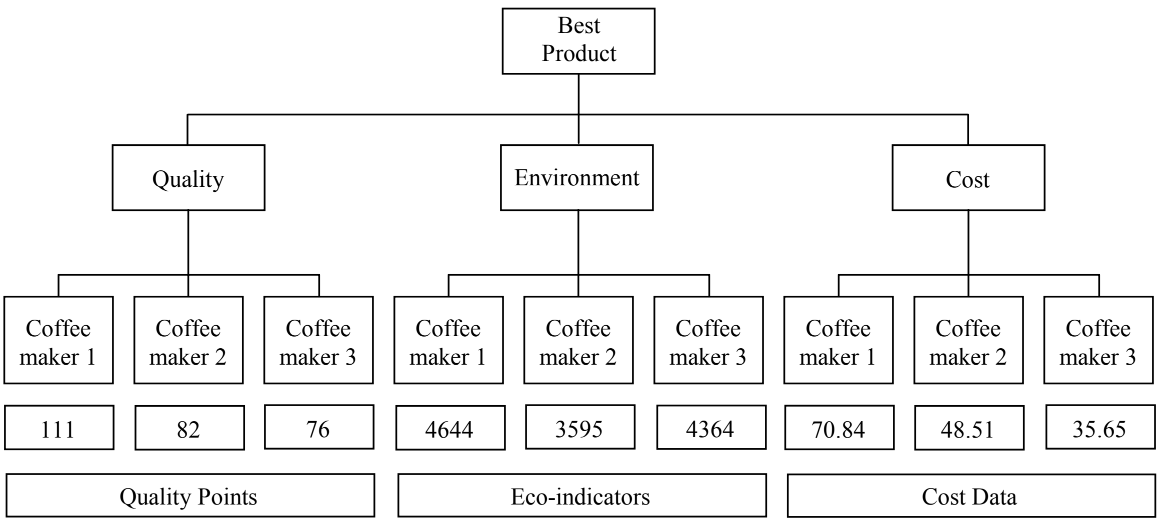

Figure 9. Decision hierarchy for the best product concept

In order to compare the products in terms of their environmental, quality and cost attributes, pair-wise comparisons are carried out for each of the products. The contents of the Concept Comparison Matrix may be used for this purpose. In order to select the best product concept, the Analytical Hierarchy Process (AHP) may be used. The decision hierarchy is shown in Figure 9. The comparison between the product designs is done using a scale from one to nine, and has been described in Table 6. For comparing coffeemakers in terms of quality attributes, the Quality Points documented in the Quality Room may be used. For environmental and cost comparisons, data in the Green Room and the Cost Room may be used, respectively.

Importance Rating	Preference Description
1	Equally preferred
2	Equally to moderately preferred
3	Moderately preferred
4	Moderately to strongly preferred
5	Strongly preferred
6	Strongly to very strongly preferred
7	Very strongly preferred
8	Very to extremely strongly preferred
9	Extremely preferred

Using AHP, quality priorities are indicated in Table 7. Coffeemaker 1 is moderately to strongly preferred to Coffeemaker 2 and strongly to very strongly preferred to coffeemaker 3. Coffeemaker 2 is moderately to strongly preferred to coffeemaker 3. The diagonal elements are always one and the remaining values are reciprocal values depending on previous assignments. The priorities are found after normalization to the table values, which is dividing each element in each column by the sum of that corresponding column. The results and final priorities are shown in Table 8. Using a similar approach, environmental priorities and cost priorities are shown in Tables 9 – 12.

Quality	Coffeemaker 1	Coffeemaker 2	Coffeemaker 3
Coffeemaker 1	1.00	4.00	6.00
Coffeemaker 2	0.25	1.00	4.00
Coffeemaker 3	0.17	0.25	1.00
Sum	1.42	5.25	11.00

Table 7. Comparisons of quality attributes

Quality	Priorities
Coffeemaker 1	0.6711
Coffeemaker 2	0.2435
Coffeemaker 3	0.0854

Table 8. Quality priorities

Environment	Coffeemaker 1	Coffeemaker 2	Coffeemaker 3
Coffeemaker 1	1.00	0.25	0.33
Coffeemaker 2	4.00	1.00	2.00
Coffeemaker 3	3.00	0.50	1.00

Table 9. Comparison of environmental attributes

Environment	Priorities
Coffeemaker 1	0.1226
Coffeemaker 2	0.5571
Coffeemaker 3	0.3202

Table 10. Comparisons of environmental attributes

Cost	Coffeemaker 1	Coffeemaker 2	Coffeemaker 3
Coffeemaker 1	1.00	0.25	0.14
Coffeemaker 2	4.00	1.00	0.25
Coffeemaker 3	7.00	4.00	1.00

Table 11. Comparisons of cost attributes

Cost	Priorities
Coffeemaker 1	0.0778
Coffeemaker 2	0.2344
Coffeemaker 3	0.6877

Table 12. Cost priorities

A similar procedure is adopted for calculating the weights for environmental, quality and cost requirements. In this case, environmental and quality requirements are given an equal preference. The environmental requirements are given a moderately higher preference over cost requirements, while quality requirements are given a higher preference over cost requirements. Details are shown in Table 13.

	Quality	Environment	Cost	Weights
Quality	1.00	1.00	2.00	0.3873
Environment	1.00	1.00	3.00	0.4429
Cost	0.50	0.33	1.00	0.1698

Table 13. Calculation of weights for environmental, quality and cost requirements

Final scores of product concepts can be calculated as shown in Table 14.

	Score
Coffeemaker 1	0.3274
Coffeemaker 2	0.3809
Coffeemaker 3	0.2917

Table 14. Final scores for product designs

From Table 14, it can be concluded that Coffeemaker 2 is the optimal design.

CONCLUSIONS

In this study, Green Quality Function Deployment – IV (GQFD – IV) has been developed. Its improvement over GQFD – III is that life cycle cost estimation model based on Fuzzy Multi-Attribute Utility Theory is established and applied to Green Quality Function Deployment. FMAUT costing enables accurate cost estimation at early design stages in product development. It is more effective than other traditional methods because it does not require detailed manufacturing process information and it can handle attributes with uncertainty and incompleteness in nature. Because of the fuzzy operations of a number of experts' experiences and opinions, the subjectivity is reduced in assessing product life cycle costs.

In the case study illustrated in the paper, the life cycle costs of two coffeemakers are estimated with errors of less than 7% using this new cost estimation model. Analytical hierarchy process was used for the best product concept selection and was found to be effective.

REFERENCES

1. Berkhout, F., and Howes, R., "The Adoption of Life Cycle Approaches by Industry: Patterns and Impacts," *Resources, Conservation and Recycling*, Vol. 20, No. 2, pp. 71-94, 1997
2. Song, H., and Hyun, J., "A Study on the Comparison of the Various Waste Management Scenarios for PET Bottles Using the Life Cycle Assessment (LCA) Methodology," *Resources, Conservation and Recycling*, Vol. 27, No. 3, pp. 267-284, 1999
3. Landfield, A., and Karra, V., "Life Cycle Assessment of a Rock Crusher," *Resources, Conservation and Recycling*, Vol. 28, No. 3-4, pp. 207-217, 2000
4. Costic, M., Sullivan, J., *et al*. "LCI for Automotive Electronic Systems: Substitution Assessment of Ag-Sn for Pb-Sn Solder at Ford Motor Company," *Proceeding of IEEE International Symposium on Electronics and the Environment*, 1996
5. Donaldson, J., Francis, D., et al. "The Life Cycle Assessment of a Telecommunications Semiconductor Laser," *Engineering Science and Education Journal*, 1996
6. Hedemalm, P., and Segerberg, T., "Comparative Life Cycle Assessment of Modern Inter-Connection Techniques for Printed Board Assemblies," *Japan IEMT Symposium Proceedings of the IEEE/CMPT International Electronic Manufacturing Technology (IEMT) Symposium*, 1995
7. Pollock, D., and Coulon, R., "Life Cycle Assessment of a Inkjet Print Cartridge," *Proceeding of IEEE International Symposium on Electronics and the Environment*, 1996
8. Terho, M., "LCA for Telecommunications Cable," *Proceeding of IEEE International Symposium on Electronics and the Environment*, 1996
9. Van Mier, G., Sterke, C., and Steve, A., "Life Cycle Cost Calculations and Green Design Options. Computers as an Example," *Proceeding of IEEE International Symposium on Electronics and the Environment*, 1996
10. Keolian, G., "Life Cycle Design," *Environmental Life Cycle Assessment*, Edited by M. Curran, McGraw Hill, 1996
11. Hannsen, O., Rydberg, T., and Rønning, A., "Integrated Life Cycle Assessment in Product Development and Management," *Environmental Life Cycle Assessment*, Edited by M. Curran, McGraw Hill, 1996

12. Førde, J., Rekdal, E., et al. "Environmentally Sound Product Development of Light Fittings," *Case Project Report from the NEP Project at Glamox AS in Molde*, *Norway*, 1995
13. Stornebel, K., and Tammler, U., "Quality Function Deployment," *Umwelt Wirschafts Forum*, 1995
14. Akao, Y., Quality Function Deployment, Integrating Customer Requirements into Product Design, Cambridge Productivity Press, 1990
15. Graedel, T. E., and Allenby, B. R., Design for Environment, Prentice Hall, 1996
16. Cristofari, M., Deshmukh, A., and Wang, B., "Green Quality Function Deployment," Proceedings of the 4th International Conference on Environmentally Conscious Design and Manufacturing, 1996
17. Zhang, Y., Wang, H.-P., and Zhang, C., "Green QFD – II, A Life Cycle Approach for Environmentally Conscious Manufacturing by Integrating LCA and LCC into QFD Matrices," International Journal of Production Research, Vol. 37, No. 5, pp. 1075-1091, 1999
18. Keeney R. L., and Raiffa, H. Decision with Multiple Objectives: Preferences and Value Tradeoffs, John Wiley & Sons, Inc., New York, 1996
19. Ting, P.-K., Zhang, C., Wang, B., Deshmukh, A., and DuBrosky, B., "Product and Process Cost Estimation with Fuzzy Multi-Attribute Utility Theory," *Engineering Economist*, Vol. 44, No. 4, pp. 303-331, 1999
20. Hellendoorn, H., and Thomas, C., "Defuzzification in Fuzzy Controllers," *Journal of Intelligent & Fuzzy Systems*, Vol. 1, No. 2, pp. 109-123, 1993