Integration of Quality Function Deployment and Functional Analysis for Eco-design

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Abstract- This paper proposes an eco-design method to systematically generate design concepts for the reduction of environmental impacts. The method is based on the integration of quality function deployment (QFD) and functional analysis (FA) at the early design stage. While QFD provides a framework to reflect the "voice of environment" in the design planning and evaluations, FA focuses on the functional description of the design to support the generation of design concepts. Particularly, the morphological chart is used to support the synthesis of new design concepts. The integration approach is based on the matrix-based correlation modeling to explicitly capture the links among environmental requirements, engineering metrics, design functions and components. The proposed method consists of four steps. In Step 1, the matrix-based correlation models of the existing design are constructed through QFD and FA. In Step 2, one specific environmental requirement is mapped through the correlation models in order to identify the responsible design functions and components for design generation. Afterwards in Step 3, the identified functions are used to establish the morphological chart to generate possible design solutions (or components) for each function. Then, different design concepts can be synthesized by combining these possible solutions. In Step 4, the generated design concepts can be evaluated via engineering metrics that are relevant to the original environmental requirement. A coffee maker has been selected as an application to demonstrate the proposed 4-step method.

Keywords: design for environment, green quality function deployment, design functions, matrix-based correlation modeling.

1. Introduction

As environment issues become more important in the design practice, this paper focuses on how to analyze and modify existing designs for reducing environmental impacts. In the "quality" culture, design improvement is often driven by customer satisfaction (i.e., voice of customers), and quality function deployment (QFD) has been widely recognized and adopted to reflect customer requirements in the design of the products [1]. In response to the environmental concerns, researchers have extended the practice of QFD to cover the "voice of environment" [2,3,4,5,6,7]. While QFD can be a good tool to reflect the concerns of stakeholders (including customers and environment), further efforts are required to integrate the results of QFD in the design process. Cristofari et al [8] have proposed Green QFD (G-QFD) to consider the environmental issues during the design stage. Afterwards, some methodical extensions have been proposed such as extending G-QFD to QFD II by integrating QFD and life cycle assessment (LCA) to evaluate different product concepts [2,7]. Yet, this paper has two new elements as research contributions. Firstly, this paper proposes the methodical feature of design concept generation using morphological chart. Notably, Sakao [9] has combined TRIZ (theory of

inventive problem solving) with QFD for eco-design. Yet, we argue that morphological chart is a simpler tool (as compared to TRIZ) for engineers. Secondly, this paper proposes the functional analysis of existing designs to explore the opportunities for eco-design improvement. In this case, instead of designing new products, we focus on the modifications of existing designs.

In the next section, we will discuss the approach to integrate QFD and functional analysis (FA) for eco-design. Then, we will propose the methodical procedure along with the coffee maker example to demonstrate the research efforts. Closing remarks will be provided at the end.

2. Integration Approach
2. 1. Background

The basic idea to integrate QFD and functional analysis (FA) for eco-design is to explicitly capture the information of the existing design via correlation models. Here, correlation models essentially capture the linkage information among various design elements. In this work, four specific design elements are identified according to the context of QFD and FA, and they are described as follows.

- Requirements: these include customer and environmental requirements according to the context of QFD. These reflect the ultimate concerns related to the modification of existing designs.
- Metrics: these also correspond to engineering characteristics in QFD, reflecting the actual performance of a design via specific engineering measures (e.g., weight, energy, etc).
- Functions: these describe what the design is expected to perform. They are usually expressed in terms of "verb-object" pairs to describe the desired actions as the functions [10].
- Components: these capture the design parts or solutions to fulfill the functions of the design.

In the practice of QFD, the mapping between requirements and metrics is essential so that the improvement of engineering characteristics (i.e., metrics) can actually enhance the satisfaction of customers. Some QFD experts have also suggested the extension to map between metrics and components (termed as QFD II) to connect the design solutions with the proper engineering measures [9, 11]. In this sense, we suggest that the practice of QFD basically provides the mapping from requirements to metrics to components.

In the practice of FA, one key procedure is to model the connections between various design functions in terms of material, energy and information flows. In turn, Stone and Wood [10] organized and represented these functions and flows via functional block diagrams. In addition, components are suggested to fulfil the functions, and it is similar to the practice of mapping functional requirements and design parameters in axiomatic design which was developed by Suh [12]. In fact, morphological chart is based on the functional descriptions to combine various components (or solutions) for design concept generation [13]. In this sense, we suggest that the practice of FA basically provides the mapping from functions to components.

Notably, the traditional practice of QFD does not include the information of functions in the methodology. The lack of functional descriptions makes QFD not exactly a proper tool for design concept generation. One deliverable of this paper is to show the integration of QFD and FA to generate new concepts for eco-design. The next sub-section will present the correlation modeling for the integration.

2. 2. Matrix-based Correlation Modeling
2.2.1. Domain of QFD

In the practice of QFD, suppose that engineers have identified k requirements to reflect the needs of customers and the environment. Let $R = \{r_1, r_2, ..., r_i, ..., r_k\}$ be the set of k requirements that cover both the "voice of customers" and the "voice of environment". The ultimate goal of a design is to satisfy these requirements.

To gauge and control the satisfaction of requirements, QFD suggests the mapping from requirements to engineering metrics. Let $M = \{m_1, m_2, ..., m_j, ..., m_l\}$ be the set of l metrics that can be used to measure the engineering properties of a design. Then, a correlation model can be built using matrix representation to reflect the mapping between requirements (i.e., R) and metrics (i.e., M). Let $RM = [rm_{ij}]$ be the correlation matrix between R and M, where rm_{ij} indicates the strength (or relevance) of the jth metric (i.e., m_j) towards the satisfaction of the ith requirement (i.e., r_i). Note that RM is a k-by-l matrix that is equivalent to the relationship matrix in the context of QFD.

Following the practice of QFD II, engineers can be a further mapping from metrics to components. Let $C =$

$\{c_1, c_2, ..., c_j, ..., c_q\}$ be the set of q components, and $MC = [mc_{ij}]$ be the correlation matrix between M and C. In this model, MC is an l-by-q matrix, and mc_{ij} indicates the relevance of the jth component to affect the engineering property measured in the ith metric.

In sum, through the practice of QFD, we are able to obtain two matrix-based correlation models: RM and MC matrices.

2.2.2. Domain of FA

In the practice of FA, one major deliverable is a functional block diagram to describe the connection of different functions of a product. A function can be conceptually viewed as a conversion process among materials, energy and information [10]. For example, suppose that one function is to "heat up water". Then, the inputs of this function is energy and cold water (as one material), and the outputs can be dissipated heat and hot water after the conversion. In this work, let $F = \{f_1, f_2, ..., f_i, ..., f_p\}$ be the set of p functions of a product.

The functional description of a product is one important step towards design creativity and concept generation. For example, the function "heat up water" does not imply how this function can be achieved. By focusing on this functional description, engineers can be unlocked from existing solutions and explore the possible ways to achieve this function (e.g., energy source from fire, electricity or sun). Using a morphological chart, engineers can brainstorm and organize the possible solutions for individual functions, and synthesize some potential design concepts.

As the notion of components captures the design parts or solutions, a correlation model is built to reflect what components are used to satisfy specific functions. Let $FC = [fc_{ij}]$ be the p-by-q correlation matrix between functions (i.e., F) and components (i.e., C), where fc_{ij} indicates the strength (or relevance) of the jth component (i.e., c_j) to satisfy the ith function (i.e., f_i).

In sum, through the practice of FA, we obtain one matrix-based correlation model: FC.

2. 3. Strategy for Eco-design

For eco-design, the basic strategy is to translate the environmental requirements to the functional description of the design. In such a way, we focus on the corresponding functions to generate possible design solutions for improvement. To achieve this, the four-step eco-design process is proposed as follows.

Step 1: Construction of correlation models of the existing design

In the eco-design process, it is assumed that we have the existing design as the reference, for which we want to reduce the environmental impacts. Through the practice of QFD and FA, engineers can analyze the design information and define the lists of requirements (R), metrics (M), components (C) and functions (F). In addition, the correlation matrices are defined via RM, MC and FC.

Step 2: Mapping of Environmental Requirements to Functions

The request of reducing environmental impacts should be reflected explicitly in the list of requirements (i.e., voice of environment). Through the correlation models, the relevant requirements can be mapped to the corresponding metrics via RM and then to components via MC. At this point, engineers can identify a subset of responsible components that should be modified for eco-design.

Yet, focusing on the responsible components may not be effective for generating new solution concepts since engineers are somewhat locked in the concept of the existing design. Consider the coffee maker example in Section 3. To keep the coffee warm, focusing on the hot plate may lead to the solutions of modifying the warming cycling or the size of the hot plate. If we focus on the function "warm coffee", we can imagine other possible solutions such as using an insulated cup. Thus, the responsible components are further mapped to the functions via FC. The subset of functions that are responsible for eco-design becomes the output of this step.

Step 3: Generation of Design Concepts via Morphological Chart

Given the responsible functions, engineers can initiate the concept generation process using morphological chart. In this chart, engineers are asked to propose various possible solutions to satisfy each of the functions. To synthesize a design concept, one possible solution is picked for each function. For example, suppose that a design consists of two functions: f_1 and f_2, and each function has two possible solutions (or components), symbolically, f_1 with c_{1a} and c_{1b} and f_2 with c_{2a} and c_{2b}. To synthesize a design concept, we need one solution for each function. Thus, there can be four possible design concepts as the outcome: $\{c_{1a}, c_{2a}\}$, $\{c_{1b}, c_{2a}\}$, $\{c_{1a}, c_{2b}\}$ and $\{c_{1b}, c_{2b}\}$.

Notably, the possible number of design concepts can expand rapidly with the number of solutions for each function. In practice, we do not need to investigate all logically possible design concepts. The solution space should be treated as the source of design inspiration, and engineers should exercise their judgments to filter some promising design concepts.

Step 4: Evaluation of Design Concepts

After obtaining several design concepts from the previous step, these concepts can be evaluated via the existing correlation models. Particularly, new design concepts only modify some components in the correlation models. Thus, the new component information can be mapped to the functions and then to metrics and requirements. It is similar to the reverse mapping process in Step 2. Accordingly, engineers can evaluate how the new components can affect the related metrics and the satisfaction of relevant requirements. Based on the metric evaluation, engineers can objectively assess the design concepts towards the satisfaction of requirements. As this paper focuses on the concept generation, the details of the quantitative analysis are skipped.

3. Application
3. 1. Example: Coffee Maker

This section aims to demonstrate the proposed eco-design method using a household coffee maker as an example. Figure 1 shows the parts of the coffee maker after the disassembly. The basic research question is how to systematically redesign this product for reducing environmental impacts. The methodical steps for demonstration are provided in the following sub-sections.

Figure 1. Disassembly of the coffee maker.

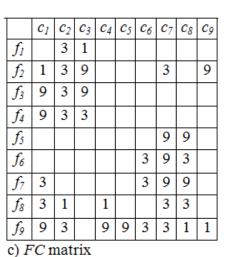### 3. 2. Construction of the Correlation Models (Step 1)

The coffee maker is first analyzed in view of requirements (R), metrics (M), functions (F) and components (C). This information is assumed available since it is an existing design, and the engineers of the company should be able to access such information. In this study, we have defined and shown the lists of requirements, metrics, functions and components in Table 1, which the labels of these design elements are also defined (e.g., r_1, m_1, etc).

Table 1. List of requirements, metric, functions and components.

Requirements (R)	Metrics (M)	Functions (F)	Components (C)
r_1: Safe operation	m_1: Amount of energy	f_1: Receive coffee materials	c_1: Carafe (thermo flask)
r_2: Comfortable to hold	m_2: Thermal distribution	f_2: Mix hot water and powder	c_2: Filter body
r_3: Heat quickly	m_3: Filter efficiency	f_3: Filter out coffee powder	c_3: Temporary filter
r_4: High filtering efficiency	m_4: Lifespan	f_4: Facilitate materials removal	c_4: Top housing
r_5: Load capacity	m_5: Toxicity of materials	f_5: Distribute electricity	c_5: Base housing
r_6: Durable	m_6: Weight	f_6: Heat water	c_6: Heater cover plate
r_7: Low cost	m_7: Types of materials	f_7: Warm brewed coffee	c_7: Heater plate
r_8: Automatic shut off	m_8: Glass volume	f_8: Dissipate heat	c_8: Base (hot plate)
r_9: Less material usage	m_9: Noise and vibration	f_9: Distribute weight	c_9: Water spreader
r_{10}: Less energy consumption	m_{10}: Reheat temperature		
r_{11}: Light weight			
r_{12}: Easy to disassemble			
r_{13}: Reheat option			

Afterwards, three types of correlation matrices are built. These matrices have three levels of correlation strengths: weak (= 1), medium (= 3) and strong (= 9), and these levels are set based on the traditional practice in QFD. The matrix entries are left blank for the absence of correlation. In addition, for rating the importance of customer requirements, three levels are also selected: very important (= 5), important (= 3) and relatively important (= 1). Figure 2 shows the correlation matrices: RM, MC and FC.

a) RM matrix

	m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}
r_1			3	3		1		1		
r_2					9		3			
r_3	9	9		1		9	3			9
r_4			9	3				3		
r_5				3				9		1
r_6				9			3			
r_7			3	3					3	
r_8	9			3						1
r_9				3	9	9	3			
r_{10}	9	9					9	3		9
r_{11}						9	9	3		
r_{12}				1			1	1		
r_{13}										9

b) MC matrix

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9
m_1	1					3	9	9	
m_2	1					3	9	9	
m_3	9	3	9						
m_4							1		
m_5			1						1
m_6	3	1		3	3	1	1		
m_7	9	1	1	3	3	1	3	3	
m_8	9	3	3	3	3	1	3	1	1
m_9			1				1		1
m_{10}	1					1	9	9	

c) FC matrix

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9
f_1		3	1						
f_2	1	3	9				3		9
f_3	9	3	9						
f_4	9	3	3						
f_5							9	9	
f_6						3	9	3	
f_7	3					3	9	9	
f_8	3	1		1			3	3	
f_9	9	3		9	9	3	3	1	1

Figure 2. Three types of correlation matrices of the coffee maker.

3. 3. Mapping of Environmental Requirements to Functions (Step 2)

Suppose that the incoming environmental requirement is the reduction of energy consumption. From Table 1, it is related to r_{10}, which can be found in the RM matrix. Figure 3 shows the RM matrix with the highlight of r_{10} to track the related metrics, which are m_1, m_2, m_7, m_8 and m_{10}. Here, m_8 is removed from further mapping since it has a relatively weaker correlation to r_{10}. Then, the further mapping is carried out in the MC matrix, and it is highlighted in Figure 4. By checking their correlation strengths, we can observe that c_7 and c_8 are strongly related to these metrics. Thus, c_7 and c_8 are further mapped via the FC matrix, and it is highlighted in Figure 5. Again, by checking the correlation strengths, we identify that f_5, f_6 and f_7 are strongly related to these components, and they become the focus of eco-design.

3. 4. Generation of Design Concepts (Step 3)

The concept generation approach is based on the morphological chart, which is shown in Figure 6 for this application. The first column of the morphological chart lists the functions of the coffee maker. Then, engineers are asked to propose possible solutions for each function. For example, to warm brewed coffee (i.e., f_7), we may use the "hot plate" or the "insulated cup", which are listed as possible conceptual solutions along the row of this function. Then, the engineers can combine various conceptual solutions to come up with different design concepts, which are also shown in Figure 6 for this application.

By focusing on the relevant functions, f_5, f_6 and f_7 identified in the previous step, the engineers need to investigate the opportunities for reducing energy consumption. When considering f_6 (i.e., Heat water), it is noted that there should be some better ways to "insulate the energy flow," which becomes a new function for new design opportunities. This new function is also included in the morphological chart in Figure 6.

Requirements (R)	Customer Weight	Engineering metrics (M)									
		m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}
r_1	3				3	3		1		1	
r_2	3						9		3		
r_3	5	9	9		1			9	3		9
r_4	3			9	3				3		
r_5	1			3					9		1
r_6	3				9			3			
r_7	3			3	3					3	
r_8	5	9			3						1
r_9	3				3	9	9	3			
r_{10}	5	9	9					9	3		9
r_{11}	3						9	9	3		
r_{12}	5				1		1	1			
r_{13}	3										9
Metric		Kj	k	%	Y	M_g/m^3	K_g	#	Cm^3	Db	k
Row score		135	90	39	88	36	86	143	66	12	123
Relative weight %		16.5	11	4.76	10.75	4.4	10.51	17.48	8	1.46	15

Figure 3. Mapping customer requirements and engineering metrics (RM).

Engineering metrics (M)	Relative weight %	Components (C)								
		c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9
m_1	16.5	1					3	9	9	
m_2	11	1					3	9	9	
m_3	4.76	9	3	9						
m_4	10.8							1		
m_5	4.4			1						1
m_6	10.5	3	1		3	3	1	1		
m_7	17.5	9	1	1	3	3	1	3	3	
m_8	8	9	3	3	3	3	1	3	1	1
m_9	1.46			1				1		1
m_{10}	15	1					1	9	9	
Row score		346	66.3	90	108	108	51	482	443	13.9
Relative weight %		20.3	3.87	5.3	6.32	6.32	2.98	28.2	25.9	0.81

Figure 4. Mapping engineering metrics and components (MC).

Components (C)	Relative weight %	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9
					Functions (F)					
c_1	20.3		1	9	9			3	3	9
c_2	3.87	3	3	3	3				1	3
c_3	5.27	1	9	9	3					
c_4	6.32								1	9
c_5	6.32									9
c_6	2.98						3	3		3
c_7	28.2		3			9	9	9	3	3
c_8	25.9					9	3	9	3	1
c_9	0.81		9							1
Row score		16.9	171	241	210	487	340	557	233	428
Relative weight %		0.62	6.37	9	7.81	18.1	12.7	20.7	8.69	15.9

Figure 5. Mapping components and functions (FC).

Functions	Possible conceptual solutions			Impact consequence (positive/negative)
f_1: Receive coffee material	Automatic receive	Manual Receive		More energy needed
f_2: Mix hot water and powder	Filter	Osmosis		Time increases then energy increases
f_3: Filter out coffee powder	Paper filter	Steel mesh filter	Plastic filter	High impact/less impact
f_5: Distribute electricity	Cord			Electrical shock (Insulation required)
f_6: Heat water	Submersible element	Large heating plate		More energy consumption
f_7: Warm brewed coffee	Hot plate	Insulated cup		Energy consumption/kept
f_8: Dissipate heat	Temp insulation	Seal covers		Energy kept
f_9: Distribute weight	Minimize heavy material	Disassemble parts (carafe)		Solid waste impact
Insulate energy flow	Rubber O-ring	Screws	Grommet sealing	Less energy leakage

Design Concept 3   Design Concept 1   Design Concept 2

Figure 6. Morphological chart for concept generation.

3. 5. Evaluation of Design Concepts (Step 4)

By checking Step 2 and Figure 4, we have identified that the metrics m_1, m_2, m_7 and m_{10} are relevant to this eco-design. Thus, we evaluate the proposed design concepts with these metrics with the 5-point scale to indicate the environment impact. Specifically, the 5-point scale ranges from zero (very low impact) to four (very high impact). After the evaluations of each design concept, the grade points are summed with consideration of the metrics relative weight to yield the overall assessment. Below is an example of how to calculate the total score of the environmental impacts of design concept 1:

The total score =
$3 * 0.165 + 3 * 0.11 + 4 * 0.1748 + 3 * 0.15 = 1.97$

The evaluation results are provided in Table 2. The discussion for each design is provided as follows.

- **Concept 1**. Since the design includes large heating plate and hot plate, the expected energy consumption is high. Also, as the focus is to insulate the temperature by using O-ring components, the score which has been given to the amount of energy is high (3). In view of the types of the materials, since it frequently uses consumed papers, the environmental impact has been evaluated as "very high" (4). The reheat option is considered when we have the hot plate option and the type of material usage. Hot plate is available and the suggested material is aluminum. Thus, the score which has been given is high (3).
- **Concept 2**. For the amount of energy, there is no hot plate for warming brew coffee (f_7). Thus, the score which has been given for the amount of energy is medium (2). Also, since there is no reheat option, the score is very low (0) (no hot plate).
- **Concept 3**. For the types of materials, there is no temporary filter. Instead, it has a permanent plastic filter. In terms of the amount of energy and thermal distribution, the scores are as same as Concept 1, and the given scores are high (3). In addition, the evaluation of types of materials is medium (2) because there is no paper filter.

After the discussion and the overall assessment, we consider that Concept 2 is the promising design for reducing environmental impacts.

Table 2. Evaluation of design concepts.

	m_1: Amount of energy	m_2: Thermal distribution	m_7: Types of materials	m_{10}: Reheat temperature	Total score
Concept 1	3 (high)	3 (high)	4 (very high)	3 (high)	1.97
Concept 2	2 (medium)	2 (medium)	4 (very high)	0 (very low)	1.25
Concept 3	3 (high)	3 (high)	2 (medium)	3 (high)	1.62
Metrics relative weight %	16.5	11	17.48	15	

4. Conclusion

This paper has proposed the eco-design method that supports the generation of design concepts for reducing environmental impacts. The key technique of the proposed method is to integrate the functional descriptions of a product in the framework of QFD for eco-design. The integration is done based on the unified correlation models represented in a matrix format. The proposed method has been demonstrated through an example of a coffee maker. In the future work, we consider the QFD practice has a solid ground for design planning and the FA practice for conceptual design. Yet, certain features of these practices have not been incorporated in our current method such as benchmarking and tradeoff analysis. The proposed method provides a solid framework for the extension to include more features for the eco-design method.

References
[1] Y. Akao "Quality Function Deployment: Integrating Customer Requirements into Product Design", New York, Productivity Press, 1990, pp. 392.
[2] Y. Zhang "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, 1999, pp. 1075-1091.
[3] H. Kaebernick, S. Kara, M. Sun "Sustainable Product Development and Manufacturing by Considering Environmental Requirements", Robotics and Computer Integrated Manufacturing, Vol. 19, 2003, pp. 461-468.
[4] C. Kuo, H. Wub, I. Shieh "Integration of Environmental Considerations in Quality Function Deployment by Using Fuzzy Logic", Expert Systems with Applications, Vol. 36, 2009, pp. 7148-7156.
[5] S. Devanathan, D. Ramanujan, W. Bernstein, F. Zhao, K. Ramani "Integration of Sustainability into Early Design through the Function Impact Matrix", ASME Journal of Mechanical Design, Vol. 132, 2010, P. 081004-1.
[6] K. Masui, T. Sakao, M. Kobayashi, A. Inaba "Applying Quality Function Deployment to Environmentally Conscious Design", International Journal of Quality & Reliability Management, Vol. 20, 2003, pp. 90-106.
[7] G. Rathod, S. Vinodh, U. Madhyasta "Integration of ECQFD and LCA for Enabling Sustainable Product Design in an Electric Vehicle Manufacturing

Organisation", International Journal of Sustainable Engineering, Vol. 4, 2009, pp. 202-214.

[8] M. Cristofari, A. Deshmukh, B. Wang "Green Quality Function Deployment", Proceedings of the 4th International Conference on Environmentally Conscious Design and Manufacturing, July 23-25, Cleveland, Ohio, 1996, pp. 297-304.

[9] T. Sakao "A QFD-Centred Design Methodology for Environmentally Conscious Product Design", International Journal of Production Research, Vol. 45, 2007, pp. 4143-4162.

[10] R. Stone, K. Wood "Development of a Functional Basis for Design", ASME Journal of Mechanical Design, Vol. 122, 2000, pp. 359-370.

[11] J.R. Hauser, D. Clausing "The House of Quality", Harvard Business Review, Vol. 66, 1988, pp. 63- 73.

[12] N.P. Suh "Axiomatic Design: Advances and Applications", Oxford University Press, New York, 2001.

[13] K. Otto, K. Wood "Product Design: Techniques in Reverse Engineering and New Product Development", Prentice Hall, New Jersey, 2001.