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Integrating AHP and DELPHI Methods to Construct A Green Product Assessment Hierarchy for Early Stages of Product Design and Development

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Abstract—From the perspective of reducing the environmental impact, this study applies Analytic Hierarchy Process (AHP) and Delphi Method to construct a product assessment framework for early product planning and development stage to evaluate a product's impact and influence on the environment. This study firstly collects the environmental performance indicators through intensive literature review and employs them as the criteria. Together with Delphi questionnaire, AHP is used to model the hierarchy of the decision problem, which will be basis to develop green product assessment framework in the follow-up research. By completing the study, this well-designed green product assessment framework is intended to provide a systematic, comprehensive, and timely platform to assess the environmental impact of a product. And it aims to reflect the following factors: (1) The green product assessment framework can help design environmentally sound product that take the entire life-cycle into consideration. (2) The green product assessment framework is based on environmental and ecological impact. (3) The green product assessment framework can provide timely assessment results for design improvement.
Keywords —Green Product Assessment, AHP, Delphi Method, Life Cycle Assessment.

1. INTRODUCTION

Ever since the industrial revolution was widely spread out throughout the world in the early 19th century, people fulfill their endless needs and wants via the fast growing industrial development. While enjoying the vast benefits from this major shift, precious and limited resources have been consumed largely and unrestrictly, resulting in gradually damaging and endangering our mere living environment. The recent severe climate change, such as global warming, indicates that the situation have been worsened dramatically. The countermeasures to resolve the critically ecological and environmental impacts are an urgent action that needs to be taken into seriously account.

To address above issues, a systematic approach to help integrate environmental considerations into industrial development is helpful. It should aim at preventing environmental impacts and preserving natural resources without sacrificing economical and industrial development and could serve as an ideal solution to balance between industrial and natural systems. In addition, it should help resolve the environmental concerns by analyzing the entire life span of the industrial operations and studying their interactions with natural systems (Gradel & Allendy, 2003). The life cycle of a product generally starts from the needs or product definitions and it navigates through the design, analysis, manufacturing, assembly, testing, packaging, transportation, usage, and maintenance to the stage of recycling or end-of-life (Billatos & Basaly, 1997; Bras, 1997; Gradel & Allendy, 2003). In other words, this suggests that a successful product design and development needs to consider a more diverse and extensive factors.

However, research shows that more than 70% of the total cost of a product is determined at the early stage of the product design and development (Billatos & Basaly, 1997; Boothroyd, Dewhurst, and Knight, 2002; Dowlatshahi, 1992). This indicates that mistakes or successes in the conceptualization of a product often have the greatest impact throughout the whole product development life cycle. Furthermore, they tend to be amplified over the course of the

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product development. Having a rigorous approach and supporting tools to help analyze designs at early stages can be highly rewarding and be better resolving the ecological and environmental issues.

This research proposed a green product assessment framework with consideration of the ecological and environmental concerns throughout the product's entire life cycle to help assess and identify the potential problems at the early stages of the product design and development. It aimed to prevent the environmental impacts and provide the proper resolutions such that the environmentally conscious product can be reached. To this end, the rest of this paper is structured as follows. The first is a review of the literatures on green design, life cycle analysis and management, Analytic Hierarchy Process (AHP), and Delphi Method. It is followed by describing methodology and procedures for green product assessment construction and questionnaire design. The third is the results and discussion. Finally, conclusions and follow-up research are presented.

2. LITERATURE REVIEW

2.1 Green Design

In Victor Papanek's book, Design for the Real World, he indicated that design is "design for the people's real need" and he also stressed that the design should seriously consider the use of Earth's limited resources and to protect and conserve the natural environment (Papanek, 1969). In other words, when designing product, designer should take the environment conservation as the primary consideration in addition to meeting people's real need.

Despite the barriers and difficulties, ISO 14064 (2006) stresses that product development has to take the environmental impact into account. It also proposes environmental improvement strategies as follows: general considerations, resource conservation, pollution prevention, and design for the environment. Design World (1992) indicated that green design is truly considering product recycling, waste reduction, increased product durability, product design for assembly and disassembly, proper material used, selection of less polluted material, energy conservation, etc. The key thought among of these is 3R principles, which are Reduce, Reuse, and Recycle. The principles are meant to reduce environmental pollution, reduce energy consumption, reuse or recycle components and products. In addition to Green Design, there are other similar terms that are dealing with ecological and environmental conservation, such as, Ecological Design (or Eco-design), Design for Environment (or DFE).

2.2 Life Cycle Analysis and Management

To reduce the environmental impacts, International Organization for Standardization (or ISO) developed environmental management standards – ISO14000 series in 1993, which aim to build up a system to help companies identify and resolve potential problems throughout the entire product life cycle, resulting in reducing the impact on the environment. ISO 14062 (2002) indicated that the environmental impacts were determined by the inputs and outputs of the materials and energy at each phase of the product life cycle. Any changes at each phase potentially affect others of the product life cycle. Typical life cycle starts from production, to transportation, usage, and recycling (Cohan, 1996). When integrating environmental considerations to product design and development, it has to consider the following product-related issues: early integration, product life cycle, multi-functionality, objectives, multi-criteria, and trade-offs (ISO 14062, 2002).

2.3 Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty beginning in 1971, is a structured multi-criteria decision making tool that is employed to reach consensus among groups of recruited experts or decision-makers for dealing with complex decisions. It is used to structure the problem into sub-problems, forming a hierarchy that can be evaluated systematically to achieve better decision-making. The fundamental functions of AHP methodology are structuring complexity, measuring on a ratio scale, and synthesizing (Forman & Gass, 2001), which enable the widely adopted AHP to be utilized in a great variety of applications (Vaidya & Kumar, 2006). The typical ones include: prediction, dynamic priorities, input-output interdependence, resource allocation, planning, conflict resolution, etc. (Saaty, 1980). And there are numerous successful examples by applying AHP in various areas in the world (Forman & Gass, 2001; Vaidya & Kumar, 2006). As AHP is drawing more attention to decision-makers and researchers, Vaidya and Kumar (2006) observed several future applications: widely use for decision making, rising use in the developing countries, more researched used on combining various other techniques with AHP, use of software applications. The generic AHP procedure starts with defining a decision problem and follows by modeling the decision problem into a hierarchy, conducting pair-wise comparisons through a series of judgments to establish priorities and determining the consistency of the judgments (Saaty, 1980; 1999; 2008).

2.4 Delphi Method

Delphi Method, developed by a well-known U.S. think tank – RAND Corporation – in the 1950s after World War II, is a process for reaching consensus among groups of decision-makers or experts on complex issues or problems for making better decisions effectively. Delphi is based on expert assessment and questionnaire anonymously to express panelists' opinions in an iterative feedback process (Linstone and Turroff, 1975; Rowe and Wright, 1999). The collected results are feedback to update the next round questionnaire. The iterative process over a number of rounds is gathered a consensus of opinion among experts in decision-making on issues or future events and can be used for application of prediction or group decision-making. The fundamental characteristics of Delphi questionnaire are (Linstone & Turroff, 1975; Rowe and Wright, 1999):

(1) Anonymity: the viewpoints and judgments expressed by each panelist are anonymously and independently and the appropriate results can be achieved without influences or pressure from other panelists.

(2) Controlled feedback: there is sufficient time for each panelist to think and response to the questionnaire and previous response is allowed and anonymous feedback from other panelists is also provided for reference.

(3) Iteration: experts can iteratively revise their viewpoints and judgments and previous information is also provided as reference for any adjustment.

(4) Quantitative group response: experts' responses are analyzed statistically to determine the consensus and conformity.

3. GREEN PRODUCT ASSESSMENT HIERARCHY CONSTRUCTION

This study is based on application of AHP and Delphi methods to construct the green product assessment framework that can be used to assess the overall environmental performance of a product throughout its entire life cycle. And it aims to help product planners, designers, or engineers to identify potential environmental concerns along with the assessment and to ensure and achieve environmentally sound and sustainable product design and development. To this end, a six-phase study was designed as follows.

(1) First Phase: Data Collection: Through the intensive literature review, criteria or factors are collected from environmental concerns throughout the entire life cycle that can help form the assessment framework to assess a product's environmental performance in early stages of product design and development. These criteria are environmentally concerned decision problem and its corresponding characteristics and are mainly collected from two sources: international standards (such as, ISO14062 and RoHS) and environmentally conscious research (such as, green design, design for environment, and life cycle analysis).

(2) Second Phase: Initial AHP Hierarchy Construction: tructured into a hierarchical model with multiple levels. The typical levels consist of topmost level (goal or objective of the decision problem), intermediate level (criteria and sub-criteria), and lowest level (decision alternatives or activities) (Saaty, 1980; 2008). This preliminary study is mainly constructed the partial hierarchy that includes decision goal and criteria. Criteria are used to evaluate alternatives to reach the goal. Criteria can further break into sub-criteria for better understanding of the decision problem if necessary. At this phase, the initial hierarchy is constructed.

(3) Third Phase: Questionnaire Design based on Initial AHP Hierarchy: Applying the Delphi method, this phase designs the questionnaire in terms of the hierarchical model from previous phase. The Delphi questionnaire is employed to gather consensus among experts or decision makers in forming the final hierarchy for green product assessment. The questionnaire consists of two sections. The first section briefly presents the objective of the research and introduces the initial AHP hierarchy with supported description for each criterion and sub-criterion, which can provide background information for decision makers to make the decision. The second section provides a number of survey questions which are used to assess the suitability of criteria and sub-criteria. By responding to the questions, decision makers can remove or adjust any unsuitable criterion or sub-criterion and they can also provide any new criterion or sub-criterion if desired. Using a 1-to-9 rating scale (Table 1), the questions are also designed to compare the importance or preference of each criterion over another one with respect to the goal and each sub-criterion over another one under the same criterion. Judgments from the experts will be aggregated and the results will be also used to help construct the secondary hierarchy. A group of experts, recruited by judgment sampling, will participate in this research. The questionnaires are e-mailed to the recruited experts.

Table 1 1-to-9 rating scale (Saaty, 1980; 2008)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated inn practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

(4) Fourth Phase: Secondary AHP Hierarchy Construction: Based on the aggregation of experts' opinions from previous phase, the hierarchical model will be re-adjusted and the secondary hierarchy is constructed.

(5) Fifth Phase: Questionnaire Design based on Secondary AHP Hierarchy: New questionnaire is designed in this phase in terms of secondary AHP hierarchy. The questionnaires are e-mailed to the same group of recruited experts.

(6) Sixth Phase: Final AHP Hierarchy Construction: Final hierarchical model will be constructed based on the aggregated results and opinions from the experts.

4. RESULTS & DISCUSSION

The green product assessment construction of this research took the entire product life into consideration in order to effectively evaluate the environmental impacts of a product. Desired criteria were pre-selected based on the product's life cycle (ISO 14062, 2002) and Design for Environment (DFE) principles (Fiksel, 1996; Gradel & Allenby, 2003) from the literature search. These six criteria were material selection, design, manufacturing, distribution, usage, and end-of-life (EOL). Suitable sub-criteria were also determined with respect to each criterion. Materials influence numerous characteristics of a product and play an important role on environmental concerns and considerations. The criteria for ecomaterials properties (Gradel & Allenby, 2003) were then the candidates to be considered as sub-criteria for material selection and they were supply property, recycled supply property, energy property, environmental impact property, legal property, longevity property, and recyclable property. From the literature search, appropriate material selection, effective energy usage, and design for reusability/design for separability should be the key factors to be considered in design stage. Sub-criteria for design were selected from Fiksel's DFE principles (Fiksel, 1996) and they were material substitution, substitution use reduction, energy use reduction, facilitating access to components, simplifying component interfaces, and design for simplicity. Based on Pollution Prevention (P2) initiatives (Fiksel, 1996; Gradel & Allenby, 2003), production reuse, input substitution, and fewer production processes were primary factors to be considered. Sub-criteria for manufacturing were determined as on-site reuse, off-site reuse, alternative technique, alternative energy, alternative materials, low/clean energy consumption, few/clean production consumable, and few generation of waste. Product, packaging, and transportation were considered as three major factors that would influence a product's environmental performance in distribution stage the most. Sub-criteria for distribution were selected from packaging and transportation (Gradel & Allenby, 2003) and they were product's weight, product's volume, packaging size, packaging material, road transport, rail transport, and ocean transport. Solid residue generation during product use, liquid residue generation during product use, gaseous residue generation during product use, and energy consumption during product use are key environmental concerns during usage stage (Gradel & Allenby, 2003). Sub-criteria for usage were mainly based on environmental interactions during product use (Gradel & Allenby, 2003) and they were recyclable waste, waste, liquid residue for causing eutrophication, toxic liquid residue, gaseous residue for causing global warming, gaseous residue for causing acid rain, gaseous residue for causing ozone depletion, and energy consumption during product use. From the literature search, recycle and disposal are two key factors to be considered in end-of-life stage. Sub-criteria for end-of-life were based on WEEE Directives (European Union, 2003b) and US EPA regulations (US EPA, 2010) and they were reuse, service, remanufacture, recycling with disassembly, toxic material, incineration for non- toxic material, and landfill for non- toxic material. The initial hierarchy was structured in terms of the selected criteria and sub-criteria. The complete hierarchy is shown in Table 2.

First round questionnaire was designed based on the initial hierarchy. Partial survey questions are shown in Table 3. Totally there are 16 experts participating in this study. Nine of them are professors from universities, while the rest are professions from industries, organizations, or foundations. All of the sixteen surveys were collected. Statistics results for criteria and sub-criteria are shown in tables 3 and 4, respectively. Among the criteria and sub-criteria, distribution has the lowest mean and three of distribution's corresponding sub-criteria (road transport, rail transport, and ocean transport) have the lowest mean, indicating that distribution is the least important criterion and road transport, rail transport, and ocean transport are the least important sub-criteria. This will be taken into account when restructuring the hierarchical model. The largest standard deviation among all criteria shows that experts' opinions on the criterion – design have the major difference. Design is then the major issue needed to be taken into account for hierarchy revision. In addition, experts' responses to questionnaire, such as questionnaire design and planning, more appropriate criteria and sub-criteria selection and revision, hierarchical model restructuring with more levels to better represent the goal for evaluating the alternatives, are applied to revise the hierarchical model. When considering the criteria for re-organizing and re-structuring the hierarchical model, criterion – design was removed to reflect on experts' opinions and the total desired criteria were reduced to five, which were material selection, manufacturing, distribution, usage, and end-of-life (EOL). The main reason is that this study essentially aims to help designer investigate and assess the overall environmental performance of a product throughout its entire life cycle in the early stages of product design and development. Therefore, design should be placed on the topmost level of the hierarchy to secure the objective. Design for X (DFX) initiatives were then selected to serve as the vital strategy to construct the hierarchical model of the product assessment. DFX is a knowledge-based approach, which takes care of the product development by considering the whole life stages of a product. DFX normally contains a wide range of design guidelines or rules to help address the design issues along the product development processes. The X here represents the new set of desired criteria mentioned above. Final hierarchy construction was applied DFX principles with an emphasis on DFE principles (Fiksel, 1996).

Table 2 Initial hierarchy for green product assessment

Criterion	Sub-Criterion
Material Selection	• Supply property • Recycled supply property • Energy property • Environmental impact property • Legal property • Longevity property • Recyclable property
Design	• Material substitution • Substance use reduction • Energy use reduction • Facilitating access to components • Simplifying component interfaces • Design for simplicity
Manufacturing	• On-site reuse • Off-site reuse • Alternative technique • Alternative energy • Alternative materials • Low/clean energy consumption • Few/clean production consumable • Few generation of waste
Distribution	• Product's weight • Product's volume • Packaging size • Packaging material • Road transport • Rail transport • Ocean transport

Usage	• Recyclable waste • Waste • Liquid residue for causing eutrophication • Toxic liquid residue • Gaseous residue for causing global warming • Gaseous residue for causing acid rain • Gaseous residue for causing ozone depletion • Energy consumption during product
End-of-Life	• Reuse • Service • Remanufacture • Recycling with disassembly • Toxic material • Incineration for non- toxic material • Landfill for non- toxic material

Table 3 Statistics results for criteria

Criteria	Mean	Std. Dev.
Material Selection	8.50	0.83
Design	6.91	3.03
Manufacturing	7.64	1.05
Distribution	5.07	1.36
Usage	6.71	1.75
End-of-Life	7.86	1.60

Table 4 Statistics results for sub-criteria

Criteria	Sub-criteria	Mean	Std. Dev.
Material selection	Supply property	6.82	1.90
	Recycled supply property	7.80	1.38
	Energy property	6.79	2.13
	Environmental impact property	7.46	1.70
	Legal property	7.86	1.37
	Longevity property	6.36	1.81
	Recyclable property	7.87	1.36
Design	Material substitution	7.87	1.86
	Substance use reduction	7.62	1.56
	Energy use reduction	8.15	1.21
	Facilitating access to components	5.70	2.46
	Simplifying component interfaces	6.50	1.56
	Design for simplicity	6.29	1.86
Manufacturing	On-site reuse	7.47	1.63
	Off-site reuse	6.85	1.56
	Alternative technique	7.00	1.69
	Alternative energy	7.15	1.53
	Alternative materials	7.46	1.61
	Low/clean energy consumption	7.79	1.15
	Few/clean production consumable	7.17	0.93
	Few generation of waste	7.79	1.32
Distribution	Product's weight	6.38	1.79
	Product's volume	6.62	1.74
	Packaging size	6.79	2.11
	Packaging material	7.50	1.77
	Road transport	5.83	2.35
	Rail transport	5.83	1.91
	Ocean transport	5.73	2.54
Usage	Recyclable waste	7.16	2.02

	Waste	7.13	2.24
	Liquid residue for causing eutrophication	6.93	1.64
	Toxic liquid residue	7.79	1.54
	Gaseous residue for causing global warming	8.00	1.58
	Gaseous residue for causing acid rain	7.50	1.55
	Gaseous residue for causing ozone depletion	7.71	1.59
	Energy consumption during product use	8.23	1.39
End-of-Life	Reuse	7.00	2.37
	Service	6.12	1.96
	Remanufacture	6.36	2.20
	Recycling with disassembly	7.00	1.65
	Toxic material	8.08	0.83
	Incineration for non- toxic material	6.38	1.95
	Landfill for non- toxic material	6.54	2.44

To reflect on questionnaire results and experts' opinions, more relevant literatures were searched and the overall sub-criteria were also re-determined with respect to each criterion. Revised sub-criteria for material selection were mainly based on material selection considerations and DFE principles (Fiksel, 1996; Gradel & Allenby, 2003) and RoHS Directives (European Union, 2003a). Revised sub-criteria for production were mainly based on design for manufacturing and assembly/disassembly initiatives (Cerdan, et al, 2009; Dong & Arndt, 2003; Fiksel, 1996; Stoll, 1986). Revised sub-criteria for distribution were mainly based on DFE principles (Fiksel, 1996). Revised sub-criteria for usage were mainly based on environmental interactions during product use (Gradel & Allenby, 2003), energy usage (Fiksel, 1996), and IEEE Standard 1680 – Environmental Performance Criteria (IEEE Standard 1680, 2006). Revised sub-criteria for end-of-life were mainly based on design for closed loop recycling, design for waste minimization initiatives, WEEE Directives (Fiksel, 1996; Muller, et al, 2000; Rose, et al, 2003; European Union, 2003b). The secondary hierarchy was structured in terms of the revised criteria and sub-criteria. The complete revised hierarchy is shown in Table 5. The new questionnaire was also designed to collect the same group of experts' responses and the statistics results are shown in Table 5. Based on the survey results, only minor revision for the hierarchical model was needed. The final hierarchy was then re-constructed (Table 6).

Table 5 Secondary hierarchy for green product assessment and statistics results

Criterion	Sub-Criterion	Sub-Criterion	Mean	Std. Dev.
Material Selection	Reduction of Environmental impact	Low Energy Consumption Materials	7.69	0.95
		Material Contaminants Prevention	7.55	0.82
		Non-Toxic / Hazardous Substances	8.15	0.90
	Material Simplification	Supply Property	6.69	1.49
		Fewer Types of Materials	6.92	1.26
		Similar or Compatible Materials	6.62	1.71
	Material Recovery	Recyclable Materials	7.31	1.25
		Recycled / Renewable Materials	7.25	1.66
Production	Green Manufacturing	Modular Design	7.00	1.00
		Remanufactured / Reusable Components	6.77	1.24
		Simple Appearance Design	6.00	1.25
	Simplification of Assembly Process	Easy Assembly	7.54	0.78
		Simplification of Component Interfaces	7.00	1.35
		Simplicity	7.00	1.35
Distribution	Weight and Volume	Packaging Weight Reduction	7.00	1.68
		Packaging Volume Reduction	7.08	1.04
	Packaging Size and Material	Packaging Size Reduction	7.62	1.33
		Fewer Types of Packaging Material	7.38	0.87
		Packaging Recovery	7.85	0.80
Usage	Energy Consumption	Effective Energy Consumption	8.23	0.60
		Renewable Energy	7.67	1.15
	Waste Reduction	Solid residue generation during product use	6.36	1.57
		Liquid residue generation during product use	6.50	1.65
		Gaseous residue generation during product use	6.60	1.71
End-of-Life	Recycling / Closed-loop	Reuse	7.46	0.78

	Recycling	Service	7.36	0.50
		Remanufacture	7.08	0.86
		Recycling without Disassembly	7.58	0.90
		Recycling with Disassembly	7.42	1.38
	Disposal / Disposal Reduction	Product Biodegradability	7.50	0.80
		Waste Disposability	7.31	1.25
		Waste Incineration	6.25	2.18

5. CONCLUSIONS

Through a series of Delphi questionnaire, the green assessment hierarchical model introduced here is mainly based on product's life cycle, applicable international environmental regulations, and environmentally related research. The following task of this research is to complete the AHP hierarchy construction via pair-wise comparisons through a series of judgments to establish priorities and determination of the consistency of the judgments. And together with following Delphi questionnaire, the overall environmentally conscious product assessment framework can be developed in the end. Application of this assessment hierarchy in the early stages of design and development processes can help to exam and identify potential environmental issues for product improvement in a timely manner. Considering all aspects of a product life cycle, this assessment hierarchy can also serve as an effective means to develop the environmentally sound solutions to achieve the sustainable product design that is attaining and maintaining regulatory compliance.

Table 6. Final hierarchy for green product assessment

Criterion	Sub-Criterion	Sub-Criterion
Material Selection	Reduction of Environmental impact	• Low Energy Consumption Materials • Material Contaminants Prevention • Non-Toxic / Hazardous Substances
	Material Simplification	• Fewer Types of Materials • Similar or Compatible Materials
	Material Recovery	• Recyclable Materials • Recycled / Renewable Materials
Production	Green Manufacturing	• Modular Design • Remanufactured / Reusable Components • Simple Exterior Design
	Simplification of Assembly Process	• Easy Assembly • Simplification of Component Interfaces • Simplicity
Distribution	Weight and Volume	• Packaging Weight Reduction • Packaging Volume Reduction
	Packaging Size and Material	• Packaging Size Reduction • Fewer Types of Packaging Material • Packaging Recovery
Usage	Energy Consumption	• Effective Energy Consumption • Multifunctional Product • Renewable Energy
	Waste Reduction	• Solid residue generation during product use • Liquid residue generation during product use • Gaseous residue generation during product use
End-of-Life	Recycling / Closed-loop Recycling	• Material Marking • Recovery and Ruse • Service • Remanufacture • Recycling without Disassembly • Recycling with Disassembly

	Disposal / Disposal Reduction	• Product Biodegradability • Waste Disposability • Waste Incineration

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