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A framework for the integration of environmental and business aspects toward sustainable product development

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Growing environmental concerns, coupled with public pressure and stricter regulations, are fundamentally impacting the way companies design and launch new products across the world. Companies are recognising that implementing design for environment (DfE) in their product development process provides opportunities both for improving environmental aspects of a product and for enhancing the product competitiveness. Therefore, integrating environmental and business aspects for decision-making during DfE consideration are crucial in the product design process. The environmental aspect of the product is captured by the lifecycle assessment, and the result is directly introduced to the selection of DfE strategies followed by the multi-criteria decision-making process, in order to integrate business aspects. The proposed method may help the company systematically develop appropriate and profitable design for environment strategies for their product systems.

Keywords: product design; multi-criteria decision-making; design for environment; lifecycle assessment

1. Introduction

Engineers consider many aspects surrounding a product's life, in order to meet safety, reliability, quality, manufacturing, and cost requirements. Most of the time, this is done in an excellent way that results in state-of-the-art products offering broad functionality with high quality and a reasonable price. However, serious consideration and integration of environmental requirements are often omitted in early product development. All products contribute to a range of environmental problems. These problems arise through the entire lifecycle, from the materials acquisition stage to the disposal of products. Design for environment (DfE) is based on lifecycle thinking and involves design procedures that minimise material and energy consumption while maximising the possibility for reusing and recycling. DfE is the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process lifecycle (Fiksel 1996). It takes place early in a product's design or upgrade phase to ensure that the environmental consequences of a product's lifecycle are understood before manufacturing

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Table 1. Design for environment strategies.

Lifecycle stage	DfE strategies	Specific strategies
Raw materials	Material use optimisation	Design for resource conservation Reduction of material use Use renewable material Use recycled and recyclable material Design for low impact material Avoid toxic or hazardous substances Use of lower energy content material
Manufacturing	Clean manufacturing	Design for cleaner production Minimise the variety of material Avoid waste of material Select low impact ancillary material and process
Distribution	Efficient distribution	Design for efficient distribution Reduce the weight of the product Reduce the weight of packaging Ensure re-usable and recyclable transport packaging Ensure efficient distribution
Product use	Clean use/operation	Design for energy efficiency Design for material conservation Design for minimal consumption Avoidance of waste Design for low-impact use/operation Design for durability
End of life	End of life optimisation	Design for re-use Design for re-manufacturing Design for disassembly Design for recycling Design for safe disposal

decisions are final. DfE requires the coordination of several design-based and data-based activities, such as environmental impact metrics, data and data management, design optimisation, and others (Mizuki *et al.* 1996). The environmental impacts of a product can be reduced through a variety of strategies. A set of DfE strategies for optimising each lifecycle stage and specific strategies are presented in Table 1.

The key issue to success is how to select the most appropriate and effective strategies for a particular product to reduce the environmental impacts (Brezet and Hemel 1997). Although environmental issues related to product design are important, it is certain that no designer will consider the best DfE strategy if excessive company resources are required to evaluate multiple alternatives. Therefore it is crucial to consider environmental strategies without disregarding the business strategies in the decision-making process. In order to consider both strategies and choose a final optimised design, a new approach for selecting a design for environment strategy is proposed in this paper. First, the proposed methodology determines what DfE strategy is possible based on the results of the product's environmental performance captured from the lifecycle assessment. Next a multi-decision-making process is applied to integrate the business aspects of product design. The final optimised decision is selected based on the rating score from the analytic hierarchy process (AHP).

2. Literature review

The purpose of decision analysis is not to replace judgement, but to help organise it and to provide a model of the problem that can lead to greater understanding of the system. In order to integrate quantitative environmental consideration with the selection of DfE strategies, the concept of decision analysis must be included to facilitate optimised decision-making. Many computer-based lifecycle analysis (LCA) tools exist for assessing the environmental performance of the product, and a DfE practitioner can easily utilise these tools, even without in-depth knowledge of LCA. However, there are no tools that integrate both LCA and multi-criteria decision-making for the selection of DfE analysis. LCA has been developed with a weak link to decision analysis. In the early LCA literature, decision analysis was first mentioned in the context of weighting. Heijungs *et al.* (1992) proposed multi-criteria analysis (MCA) as a tool for weighting, and presented a calculation rule for the total environmental index based on a quantitative MCA. However, the calculation rule was not referenced to any specific methods used in the field of decision analysis. Consoli *et al.* (1993) suggested decision analysis as a procedure for weighting different environmental impacts but no examples of how to apply the techniques to weighting of impact categories is included. Weber and Borcherding (1993) presented some findings about the relation between weight determination and normalisation in the model. However, the concept of decision analysis in the context of the development of LCA is missing. Miettinen and Hämäläinen (1997) pointed out that decision analysis can be used as early as the goal and scope definition stage in the LCA to assist choosing feasible alternatives and an appropriate set of impact categories. In this way, decision analysis can enhance gathering of ‘correct’ data in the inventory analysis. Werner and Scholz (2002) also reported that a set of criteria for lifecycle inventory derived from decision analysis can be used to determine relevant product systems for the purposes of an assessment problem. Guinée (2002) proposed that multi-criteria analysis methods may be useful for grouping and weighting; however, none of the LCA case studies with applied decision analysis methods were shown in the study. Most of these applications have been confined to weighting issues, and there is a lack of integrating LCA results into decision analysis for the selection of an optimised strategy in the product design process. LCA results should be handled together with other criteria (*e.g.* economic aspects) in the decision-making process in order to utilise the results in the final decision context. In this paper, the result of LCA is applied to multi-decision analysis methods. A methodology has been developed to structure and model multi-dimensional decision problems in terms of a number of individual criteria where each criterion represents a particular dimension of the problem to be taken into account.

3. Methodology

Figure 1 shows the schematic diagram of an optimisation process for selecting DfE strategies that considers both environmental and business aspects of the system captured by the LCA model and the AHP model, respectively. There are three parts in the modelling process. The LCA model provided quantitative measurement of the environmental performance of a specific product through the entire lifecycle. The result from the LCA model was utilised to select the product lifecycle stage that has the highest priority to be solved for DfE practice. One of the multi-criteria decision-making methodologies (AHP) was then introduced to prioritise the optimised design for environmental strategies. The objective was to compare the relative importance of possible DfE strategies in terms of environmental and business aspects of the product design. A detailed description of methodologies is provided with the case study in this section.

3.1. *Lifecycle analysis model*

For the purpose of analysing the integration of environmental aspects for product design improvement, a charcoal grill product system was studied. The product system includes every lifecycle stage of the charcoal grill from raw material extraction to end of life. LCA is a well-known process

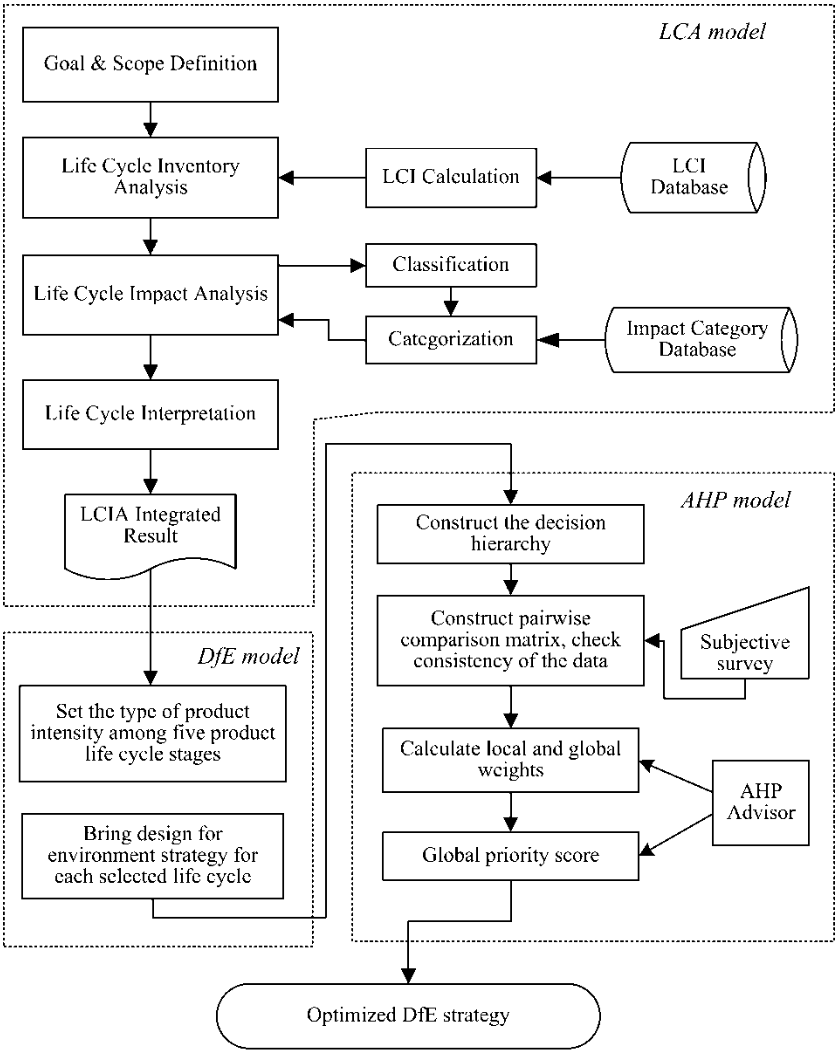

Figure 1. Schematic diagram of selecting the best design for the environment strategy.

and practice for evaluating the environmental profile of product and process systems throughout their entire lifecycle. The objective of the analysis is determined in the goal and scope stage. It clarifies the goal of the analysis and specifies the functional unit to be used in the analysis. In addition, the product system boundaries and study limitations should be clearly described in this stage. Among many processes and activities, some are significant while others are minor. It is very time-consuming and meaningless to include every process and activity of a product system from a practical and economical viewpoint. Mass-based or energy-based decision rules are often used to determine product system boundaries, and less significant processes can be excluded by this rule. In this case study, mass inclusion is utilised as decision rule. The product composition is sorted by weight percentage and the cumulative weight percentage is calculated. Only the cumulative weight percentage of components comprising 72% has been considered in this analysis. Figure 2 illustrates that only six out of 33 total components were selected for the analysis based on weight percentage.

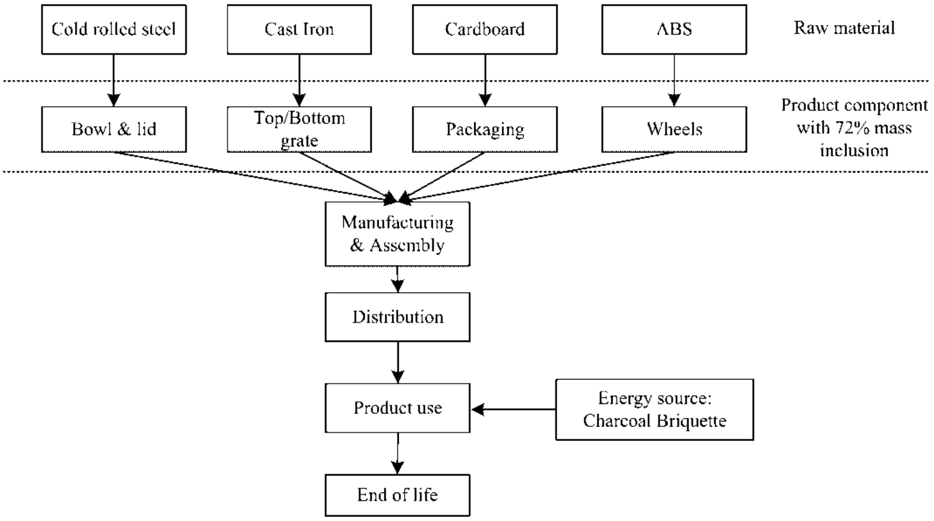

Figure 2. System boundary and process tree of the lifecycle of a charcoal grill.

For an effective DfE implementation, lifecycle thinking and evaluation of the significant environmental aspects of a product are important, and it requires systematic quantitative information covering the entire lifecycle. Quantitative modelling of the product over the entire lifecycle of the product is based on realistic scenarios and assumptions as described in Table 2.

3.2. *Lifecycle inventory analysis*

In the lifecycle inventory analysis stage, environmental loads of the product in the lifecycle are calculated to estimate the relative amount of natural resources, energy use and generated waste streams such as air, land, and water emissions for the production of the charcoal grill. Lifecycle inventory databases (LCI DB) have been developed by many different institutes and consultants, and the use of existing LCI DB greatly simplifies the lifecycle inventory analysis. Table 3 presents the data used for this study.

In Table 3, only primary raw materials and major air emission inventories are included for the simplified LCA. Other environmental impacts, such as water and land emissions inventory data can be used for an extended study. After the LCI DB are collected, the inventory of total environmental load of the product is calculated using Equation (1) (Choi 2006). The first two terms of Equation (1) represent environmental loads from raw material and manufacturing stages. They are divided by a mass inclusion factor (), because a total weight decision rule was used for the selection of effective components. The second term calculates the environmental load of the distribution stage, which includes transportation of the product, and the third term evaluates the environmental loads of the product use stage. The final term captures the environmental load generated by the end-of-life scenarios as represented in the product modelling phase. A detailed modelling scenario for each product lifecycle stage can be found in Choi (2006).

$$\varepsilon_{total} = \frac{1}{\gamma}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\delta_{ij1}\Lambda_i + \delta_{ij2}\Omega_i\right) + \sum_{i=1}^{I}\sum_{j=1}^{J}\delta_{ij3}W_i d_i + \sum_{i=1}^{I}\sum_{j=1}^{J}\delta_{ij4}N_i\lambda_i + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\delta_{ijk5}\Pi_{ik}\Lambda_i \qquad (1)$$

Table 2. Product lifecycle scenario for charcoal grill study.

Lifecycle stage	Scenario
Raw material	1. The product composition is sorted by weight percentage and the cumulative weight percentage is calculated. Only the cumulative weight percentage of components less than 72% has been considered in this analysis. Figure 2 illustrates the six out of the total 33 components chosen for the analysis based on the weight percentage.
Manufacturing	1. Production technology: cutting and bending process (bowl: 3745 g; lid: 3115 g cold rolled commercial grade steel), die casting for cast iron (18.5 inch cooking grate: 1835 g; bottom charcoal grate: 1405 g), casting for stainless steel (triangle with hook: 640 g; damper control rod: 423 g; hex drive assembly; 190 g), cutting and gluing of box (1526 g cardboard), injection moulding (two 6-inch wheels: 1360 g ABS), extrusion (front and two rear legs: 1153 g aluminium) 2. Electricity consumption for the manufacturing of bowl and lid are assumed as 1.5 kWh each for bowl and lid, 0.7 kWh each for cooking grate and bottom grate, and 0.1 kWh for ABS wheels. In addition, LCI inventory data shows 0.64 kWh for cardboard packaging. 3. Production volume of charcoal grill is 4500 units/month. 4. There is less electricity consumed for assembling of charcoal grill because this product is designed to be assembled by the customers. However, there are relatively little amount of electricity consumed in assembling such as grill assembling of plastic parts (handles and handle supports), vent systems, etc., and this total electricity is assumed to be 1500 kWh/month.
Distribution	1. Packaging: Single-use cardboard box 2. Transportation: 4000 km by a 28-ton truck
Product use	1. Use scenario: burning 30 briquettes of charcoal to grill food outdoors three times twice a week, 36 weeks a year. The total uses add up to 270 times over the 5-year lifetime of the product. 2. Energy consumption: 6.25 kWh of charcoal briquette energy per use. Charcoal briquettes are composed of three main components – charcoal, binder and filler or burn-rate controller. Briquettes appear on the market in different shapes and sizes: oblong, egg-shaped, hexagonal and pillow-shaped. The pillow-shaped briquette usually used for home-use grilling purposes and its geometric size is about 45 mm × 45 mm × 25 mm approximately. 3. The standard property for briquettes is 25,000 kJ/kg and this can be converted to 6.9445 kWh/kg. One briquette is about 0.03 kg. Therefore 30 briquettes have energy of 6.25 kWh. 4. Waste generated: emission to air and land by use of charcoal briquettes.
End of life	1. Fasteners and joints: snap-fit and screws 2. Time for disassembly: 3 min 3. Rate of reusability: reuse of parts is not possible 4. Rate of recycling: 60% cold rolled steel and cast iron 5. Rate of landfill: 80% cardboard, 70% ABS 6. Rate of incineration: 40% steel and iron, 20% cardboard, 30% ABS

where i is the type of components ($i \in \{1, \ldots, I\}$), j is the type of environmental parameters ($j \in \{1, \ldots, I\}$), k is the type of end-of-life options ($k \in \{1, \ldots, K\}$), l is the type of product lifecycle stages ($l \in \{1, \ldots, L\}$), ε_t, is the total environmental load of the product system, δ_{ijl} is the database imported from LCI DB for the jth environmental parameter of the ith component in the lth product lifecycle, Λ_i is the total weight of the ith component, γ is the decision rule for the mass inclusion factor, Ω_i is the electricity consumed for the manufacturing of the ith component, d_i is the distance travelled for the ith component, λ_i is the heat energy used for one use of the ith component, N_i is the number of components used in the product lifetime, Π_{ik} is the percentage rate of the ith component with the kth end-of-life option, and W_i is the total weight of a product to be distributed.

The total lifecycle inventory analysis result is presented in Table 4 and the relative contribution of the five different lifecycle stages to the total environmental load can be identified in this stage.

As can be seen from Table 4, the charcoal grill product system has an enormous amount of coal and natural gas inventory compared with other natural resources and it generates large carbon dioxide emissions compared with other air emissions throughout its entire lifecycle.

Table 3. Simplified LCI DB for the charcoal grill.

		Environmental load (g)									
		Coal	Crude oil	Iron ore	Natural gas	CO_2	Methane	CO	NO_2	SO_2	VOC
Raw material (for 1 kg production)	ABS	138.8	810.4	0.89	1334	3146	10.22	3.43	11.27	10.24	0
	Cast iron	1970	482	1630	28.24	3898	16.1	25.46	6.8	22.59	4.46
	Cold rolled steel	1243	85.9	1160	21.92	1614	8.55	29.97	2.55	4.89	1.15
	Cardboard	19.78	212	0.04	9438	709	0.89	0.35	2.14	9.9	1.76
Manufacturing (1 kWh use)	Electrical energy	618.96	8.47	0	5.57	979	4.26	0.125	2.52	4.02	0.1
Distribution (28-ton truck, 1 ton-km)	Transport	12.1	64.8	6.74	1.28	207.2	0.35	0.62	2.02	0.50	0.82
Product use (1kWh)[a]	Charcoal energy	195.22	11.09	1.39	0.28	316.3	2.5	18.1	0.27	1.73	0.16
End of life (for 1 kg)	Landfill cardboard	0.56	5.14	0	889.2	19	0.03	0.08	1.24	1.08	0.10
	Recycle cardboard	–44.2[b]	–1.4	–0.68	202	–727	–0.08	–0.69	–0.003	–0.04	–0.03
	Incineration of steel	4.43	1.1	1.03	1.91	16.26	0.03	0.05	0.46	0.01	0.08
	Recycling of steel	–351	–23.1	–1290	–10.06	–389.5	–1.97	–0.44	–2.21	–2.42	–0.16
	Incineration of ABS	0.78	3.28	0.09	1224.6	2600	0.03	0.229	0.6	0.09	0.1
	Landfill ABS	0.17	4.22	0	234	110	12.2	0.08	0.2	0.04	0.09

[a] Includes energy for manufacturing of charcoal.

[b] Negative value means there is an environmental benefit or positive environmental impact accrued from recycling.

Table 4. Lifecycle inventory analysis result of the charcoal grill (kg/grill).

	Raw materials	Manufacturing	Distribution	Use	End of life	Total
Coal	60.7	4.71	0.88	329	–2.14	393.62
Crude oil	28.7	0.06	4.72	18.7	–0.13	52.04
Iron	50.3	0.00	0.49	2.35	–7.81	45.36
Natural gas	195	0.03	0.09	0.47	1.50	197.29
CO_2	169	5.03	15.1	534	–1.67	721.42
Methane	0.65	0.02	0.03	4.22	0.00	4.91
CO	1.07	0.00	0.05	30.5	0.00	31.59
NO_2	0.41	0.01	0.15	0.46	–0.01	1.02
SO_2	0.92	0.02	0.04	2.92	–0.01	3.88
Volatile Organic Compound (VOC)	0.13	0.00	0.06	0.27	0.00	0.46

3.3. *Lifecycle impact analysis*

This phase aims at evaluating the significance of potential environmental impacts using the results from lifecycle inventory analysis. Lifecycle inventory results cannot be applied directly to assess the environmental impact of the product without the establishment of assessment criteria. The relationship between inventory analysis and the impact category is shown in Figure 3. Inventory parameters from the lifecycle inventory analysis are connected to the relevant impact categories. Once the inventory parameters are classified into impact categories, the relative contribution of each inventory parameter to a given impact category is quantified using a characterisation factor (Graedel and Allenby 2003).

Characterisation factors are defined by researchers in many ways (Hauschild and Wenzel 1998). The environmental design of industrial products impact method was applied for the characterisation of the impacts for this study. The environmental design of industrial products impact assessment method was coded into a spreadsheet to allow comprehensive analysis based on environmental impact themes to be performed. Table 5 presents the characterisation factors of inventory parameters of the charcoal grill. Only five impact categories are applicable to the inventory outputs: global warming potential, acidification potential, eutrophication potential, photochemical oxidant potential, and resource depletion potential. Ozone depletion potential factors are not

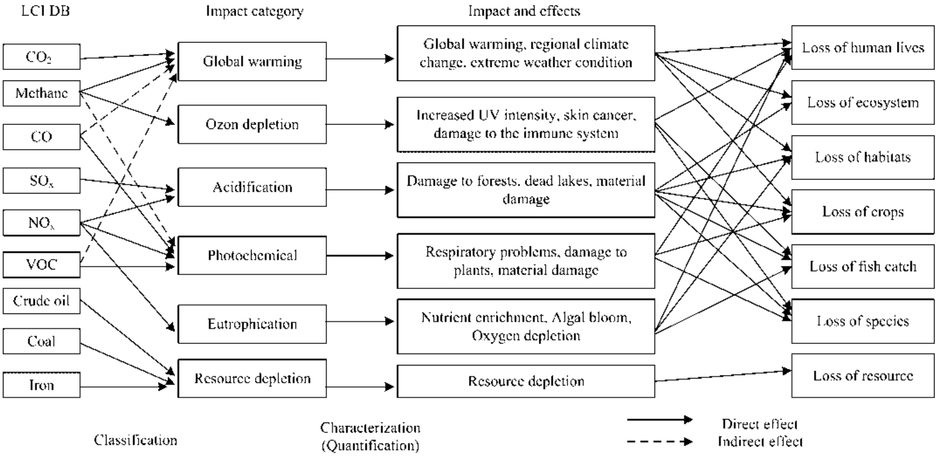

Figure 3. Classification and characterisation in lifecycle impact assessment.

Table 5. Characterised impact of the charcoal grill.

Parameter	Global warming potential (g CO_2eq/g)	Acidification potential (g SO_2eq/g)	Eutrophication potential (g NO_2eq/g)	Photochemical ozone potential (g C_2H_4eq/g)	Resource depletion potential (g/g)
	Characterisation factor				
Coal					0.01
Crude oil					0.039
Iron					0.085
Natural gas	3.00				0.052
CO_2	1.00				
Methane	25.00			0.007	
CO	2.00			0.03	
NO_2		0.7	1.35		
SO_2		1.00			
Volatile Organic Compound (VOC)	3.00			0.40	

shown in this table since no chlorofluorocarbon (CFC) information is included in this study's lifecycle inventory stage.

The characterisation factors presented in Table 5 are multiplied by the inventory analysis result from the previous step to identify the impact. Figure 4 shows an integrated view of the total environmental impact of the product system through the lifecycle stage. The global warming impact from raw material and product use is large compared with impacts from other lifecycles.

3.4. *Analytic hierarchy process model*

AHP is a powerful and flexible multi-criteria decision-making tool for complex problems where both qualitative and quantitative aspects have to be considered (Saaty 1980). AHP helps the analyst organise the critical aspects of a problem into a hierarchical structure similar to a family

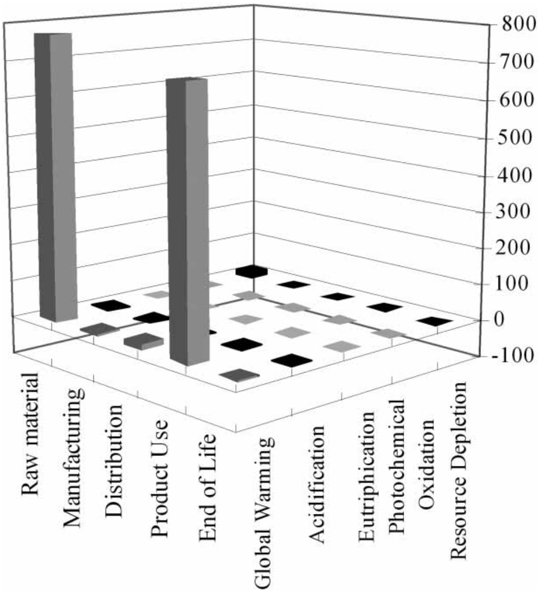

Figure 4. Integrated view of the total impact (kg).

tree. AHP reduces complex decisions to a series of simple comparisons and rankings, and then synthesises the results. Thus, AHP not only helps the analyst to arrive at the best decision, but also provides a clear rationale for the choices made (Saaty 1995). A spreadsheet-based AHP tool was developed for this study and a questionnaire was developed to collect the subjective decisions from various experts, such as product designer, manager, and engineer. Subjective data were used for the construction of the pairwise comparison matrix. A brief description of the procedure of AHP is shown as follows but details about the methodology can be found in Saaty (1980).

1. Structure the problem and determine the goal.
2. Design a questionnaire and collect data.
3. Construct the hierarchy from the top through the lowest level of criteria.
4. Construct a set of pairwise comparison matrices for each criterion.
5. After completing all the pairwise comparisons, the consistency is determined using the eigenvalue to calculate the consistency index (CI).
6. The judgement of consistency can be checked by comparing the consistency ratio (CR) of CI with an appropriate value. The CR is acceptable if it does not exceed 0.10. If it is larger, the judgement matrix is inconsistent.
7. Determine the normalised weights for alternatives to assist decision-making.

3.5. *Structure of AHP model*

In designing the AHP hierarchical tree, the aim is to develop a general framework that satisfies the needs of the designer to select the best DfE strategy. Figure 5 shows the decision hierarchy structure for the present study.

Quantitative results of LCA provide and guide users in determining the goal of the AHP modelling. For example, the result of the LCA impact analysis shows that the raw material phase has the largest environmental impact. Therefore, optimising the raw material phase was selected as the goal for this study and five different specific DfE strategies for material use optimisation (weight reduction, use of renewable material, use of low-energy content material, use of recycled, recyclable material, and the use of non-toxic material) were weighted and the relative importance of these five strategies compared by the AHP structure. Following this, two strategic factors – namely environmental and business aspects of product design – were identified to achieve this goal in the second level of hierarchy. In this study, integration of business aspects does not mean that the result of the analysis will yield the trade-off decision between environmental and business aspects. Instead, it illustrates the notion that internal and external business aspects of decision are integrated in selecting the optimised design for environment strategy for the raw material stage. The third level of the hierarchy consists of the criteria that define the two strategic factors of the upper level. Five different criteria for the entire product lifecycle stages are used for identifying the environmental aspects of the product system. In addition, two different criteria including internal and external business drivers represent the business aspect of the product system in the third level. Each criterion in level 3 consists of five different subcriteria, which are the desired improvement options for the fourth level of hierarchy. The strategic factors, criteria and subcriteria used in these three levels of the AHP hierarchy can be assessed using the basic AHP approach of pairwise comparisons. The fifth level of the hierarchy contains the rating scale. This level is different from the usual AHP approach in that a rating scale was assigned to each subcriterion related to every alternative, instead of assessing pairwise comparisons among alternatives in the usual fashion (Liberatore 1987). The major advantage of this method is to overcome the increase in the number of required comparisons when the number of alternatives is large. The main reason for adopting this method is that the evaluation sometimes involves a large number of details consisting of several subcriteria. It may be practically too difficult to make pairwise comparisons

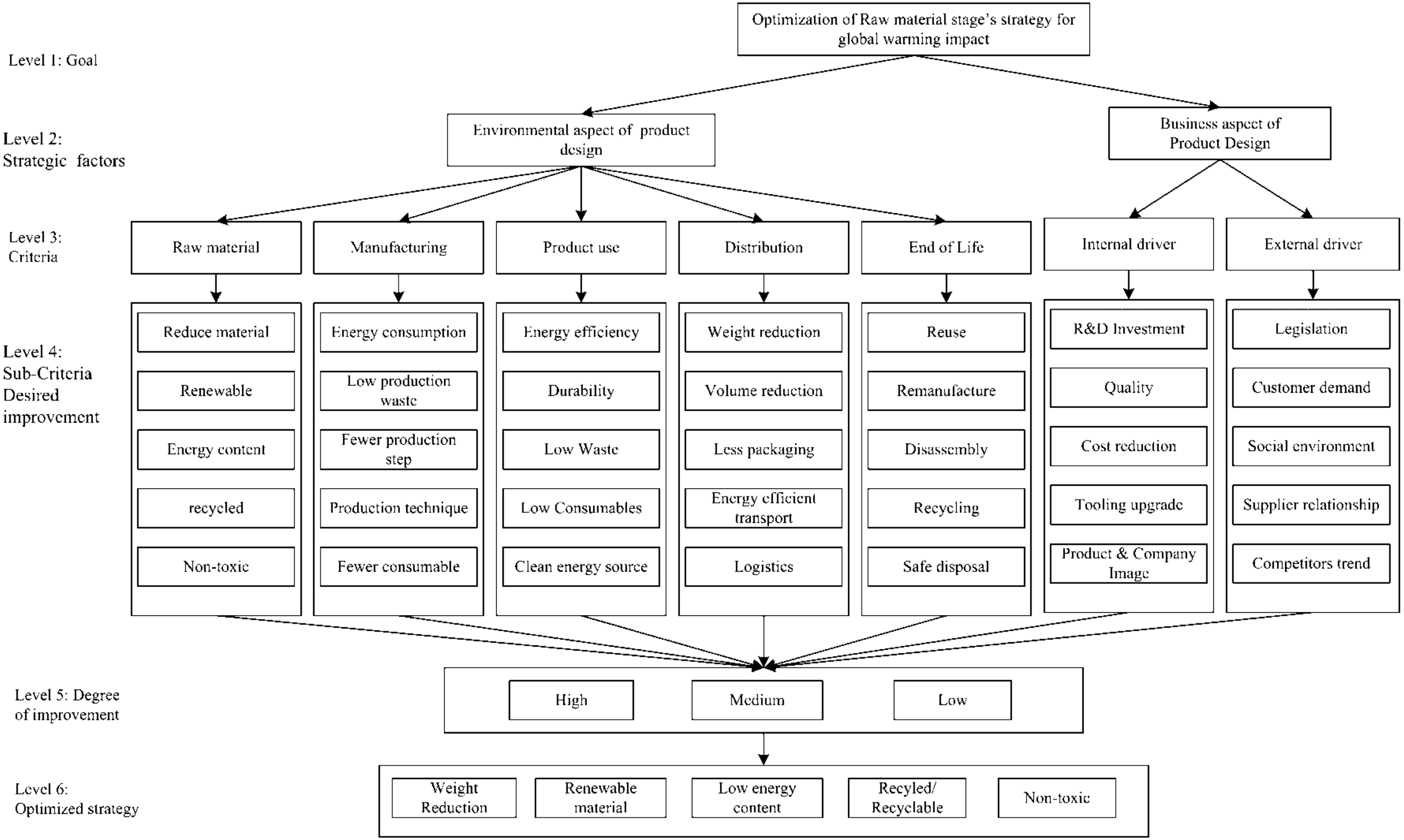

Figure 5. Overall hierarchy of the AHP.

Table 6. Pairwise comparison judgement matrices of the strategy selection problem.

Environment	Raw materials	Manufacturing	Distribution	Use	End of life	Priority
Raw material	1.00	5.00	2.00	5.00	3.00	0.401
Manufacturing	0.20	1.00	0.25	2.00	0.33	0.078
Distribution	0.50	4.00	1.00	6.00	4.00	0.321
Use	0.20	0.50	0.17	1.00	0.33	0.054
End of life	0.33	3.00	0.25	3.00	1.00	0.146
CR						0.049
Internal driver	RD	QT	COR	TU	CI	Priority
R&D investment	1.00	1.00	0.33	2.00	0.25	0.129
Quality	1.00	1.00	1.00	4.00	1.00	0.234
Cost reduction	3.00	1.00	1.00	4.00	2.00	0.319
Tooling upgrade	0.50	0.25	0.25	1.00	0.33	0.067
Company image	4.00	1.00	0.50	3.00	1.00	0.250
CR						0.06
External driver	LG	CD	SE	SR	CT	Priority
Legislation	1.00	4.00	4.00	4.00	4.00	0.479
Customer demand	0.25	1.00	3.00	1.00	3.00	0.196
Social environment	0.25	0.33	1.00	0.50	1.00	0.087
Supplier relation	0.25	1.00	2.00	1.00	1.00	0.138
Competitor trend	0.25	0.33	1.00	1.00	1.00	0.100
CR						0.043
Raw material	MR	RE	EC	RC	NT	Priority
Material reduction	1.00	2.00	3.00	2.00	0.33	0.232
Renewable	0.50	1.00	2.00	3.00	0.33	0.180
Energy content	0.33	0.50	1.00	2.00	0.50	0.128
Recycled	0.50	0.33	0.50	1.00	0.50	0.098
Non-toxic	3.00	3.00	2.00	2.00	1.00	0.362
CR						0.096
Manufacturing	EC	PW	PS	PT	FC	Priority
Energy consume	1.00	3.00	4.00	3.00	4.00	0.432
Production waste	0.33	1.00	1.00	0.33	2.00	0.124
Production step	0.25	1.00	1.00	0.33	0.50	0.088
Production technique	0.33	3.00	3.00	1.00	3.00	0.253
Fewer consumable	0.25	0.50	2.00	0.33	1.00	0.104
CR						0.056
Product use	EE	DUR	LW	LC	ES	Priority
Energy efficiency	1.00	3.00	2.00	3.00	4.00	0.384
Durability	0.33	1.00	0.33	0.50	3.00	0.124
Low waste	0.50	3.00	1.00	3.00	3.00	0.277
Low consumables	0.33	2.00	0.33	1.00	2.00	0.143
Energy source	0.25	0.33	0.33	0.50	1.00	0.072
CR						0.054
Distribution	WR	VR	LP	ET	LOG	Priority
Weight reduction	1.00	1.00	2.00	0.50	2.00	0.207
Volume reduction	1.00	1.00	2.00	0.33	2.00	0.197
Less packaging	0.50	0.50	1.00	0.50	2.00	0.143
Efficient transport	2.00	3.00	2.00	1.00	1.00	0.318
Logistics	0.50	0.50	0.50	1.00	1.00	0.135
CR						0.094
End of life	REUSE	RM	DISA	RECY	SD	Priority
Reuse	1.00	3.00	3.00	4.00	4.00	0.438
Remanufacturing	0.33	1.00	2.00	2.00	3.00	0.214
Disassembly	0.33	0.50	1.00	2.00	2.00	0.152
Recycling	0.25	0.50	0.50	1.00	3.00	0.124
Safe disposal	0.25	0.33	0.50	0.33	1.00	0.072
CR						0.047

with respect to every subcriteria. Also, it is a time-consuming process. Finally, the lowest level of the hierarchy consists of the alternatives; namely, the different design for environmental strategies for optimising the raw material stage.

3.6. *AHP process and result*

After structuring the AHP hierarchy, the next step is assigning pairwise comparisons to the strategic factors, criteria and subcriteria used in the AHP hierarchy. The nine-point scale as suggested by Saaty (1980) is used to assign pairwise comparisons of all elements in each level of the hierarchy. Each of these comparison matrices is then translated into the corresponding eigenvalue problem and is solved to find the normalised and unique priority weights for each criterion. Table 6 shows the example of the pairwise comparison matrices for different criteria in the hierarchy.

A spreadsheet-based AHP advisor was developed and used to determine the normalised priority weights, CI and CR. The CR shows the consistency in assigning pairwise comparison judgements of the evaluator. Every CR value in Table 6 is well below the rule-of-thumb value of 0.1, which

Table 7. Composite priority weight for subcriteria.

Strategic factor	Local weight	Criteria	Local weights	Subcriteria	Local weight	Global weight
Environment	0.5	Raw material	0.401	Reduce material	0.232	0.046
				Renewable	0.180	0.036
				Energy content	0.128	0.026
				Recycled	0.098	0.020
				Non-toxic	0.362	0.073
		Manufacturing	0.078	Energy consume	0.432	0.017
				Production waste	0.124	0.005
				Production step	0.088	0.003
				Product technique	0.253	0.010
				Fewer consumable	0.104	0.004
		Product Use	0.321	Energy efficiency	0.384	0.062
				Durability	0.124	0.020
				Low waste	0.277	0.044
				Low consumables	0.143	0.023
				Clean energy source	0.072	0.012
		Distribution	0.054	Weight reduction	0.207	0.006
				Volume reduction	0.197	0.005
				Less packaging	0.143	0.004
				Efficient transport	0.318	0.009
				Logistics	0.135	0.004
		End of life	0.146	Reuse	0.438	0.032
				Remanufacturing	0.214	0.016
				Disassembly	0.152	0.011
				Recycling	0.124	0.009
				Safe disposal	0.072	0.005
Business	0.5	Internal drive	0.500	R&D investment	0.129	0.032
				Quality	0.234	0.058
				Cost reduction	0.319	0.080
				Tooling upgrade	0.067	0.017
				Company image	0.250	0.063
		External drive	0.500	Legislation	0.479	0.120
				Customer demand	0.196	0.049
				Social environment	0.087	0.022
				Supplier relation	0.138	0.035
				Competitors trend	0.100	0.025
					Total	1.000

confirms the consistency of the subjective data used for this study. In the next step the solution for the strategy selection problem is synthesised. The normalised local priority weights of strategic factors, criteria, and subcriteria were found followed by the global weights as presented in Table 7.

The spreadsheet-based AHP advisor was used to determine these global priority scores. For the priority weight scale, Liberatore's five-point rating scale (Outstanding, Good, Average, Fair, and

Table 8. GPS for optimising raw material strategies.

		Strategic criterion (i)									
		Strategy 1[a]		Strategy 2[b]		Strategy 3[c]		Strategy 4[d]		Strategy 5[e]	
Subcriterion (j)	Global weight	Rating	GPS	Rating	GPS	Rating	GPS	Rating	GPS	Rating	GPS
Environment											
Raw material											
Reduce material	0.046	H	0.034	L	0.003	L	0.003	L	0.003	L	0.003
Renewable	0.036	L	0.002	H	0.027	L	0.002	M	0.007	M	0.007
Energy content	0.026	L	0.002	L	0.002	H	0.019	M	0.005	M	0.005
Recycled	0.020	L	0.001	M	0.004	M	0.004	H	0.014	L	0.001
Non-toxic	0.073	L	0.005	M	0.014	M	0.014	L	0.005	H	0.053
Manufacturing											
Energy consume	0.017	H	0.012	M	0.003	M	0.003	M	0.003	L	0.001
Production waste	0.005	H	0.004	L	0.000	L	0.000	L	0.000	L	0.000
Production step	0.003	M	0.001	L	0.000	L	0.000	L	0.000	L	0.000
Production technique	0.010	M	0.002	L	0.001	M	0.002	L	0.001	M	0.002
Consumable	0.004	L	0.000	L	0.000	L	0.000	L	0.000	L	0.000
Use											
Energy efficient	0.062	M	0.012	M	0.012	H	0.045	M	0.012	L	0.004
Durability	0.020	L	0.001	L	0.001	L	0.001	L	0.001	L	0.001
Low waste	0.044	M	0.009	L	0.003	L	0.003	M	0.009	L	0.003
Consumables	0.023	L	0.001	L	0.001	L	0.001	L	0.001	L	0.001
Energy source	0.012	L	0.001	H	0.009	H	0.009	L	0.001	M	0.002
Distribution											
Reduce weight	0.006	H	0.004	L	0.000	L	0.000	L	0.000	L	0.000
Reduce volume	0.005	M	0.001	L	0.000	L	0.000	L	0.000	L	0.000
Less packaging	0.004	H	0.003	L	0.000	L	0.000	L	0.000	L	0.000
Efficient transport	0.009	H	0.006	L	0.001	L	0.001	L	0.001	L	0.001
Logistics	0.004	L	0.000	L	0.000	L	0.000	L	0.000	M	0.001
End of life											
Reuse	0.032	L	0.002	L	0.002	M	0.006	M	0.006	M	0.006
Remanufacturing	0.016	L	0.001	L	0.001	M	0.003	M	0.003	M	0.003
Disassembly	0.011	M	0.002	L	0.001	L	0.001	L	0.001	L	0.001
Recycling	0.009	L	0.001	M	0.002	M	0.002	M	0.002	M	0.002
Safe disposal	0.005	L	0.000	M	0.001	M	0.001	L	0.000	H	0.004
Business aspect											
Internal driver											
R&D investment	0.032	M	0.006	M	0.006	M	0.006	M	0.006	M	0.006
Quality	0.058	M	0.012	L	0.004	L	0.004	L	0.004	L	0.004
Cost reduction	0.080	H	0.059	M	0.016	M	0.016	H	0.059	L	0.005
Tooling upgrade	0.017	L	0.001	L	0.001	M	0.003	L	0.001	L	0.001
Company image	0.063	L	0.004	H	0.046	M	0.012	H	0.046	H	0.046
External driver											
Legislation	0.120	L	0.008	M	0.024	M	0.024	M	0.024	H	0.088
Customer	0.049	M	0.010	M	0.010	M	0.010	M	0.010	H	0.036
Social	0.022	M	0.004	H	0.016	M	0.004	H	0.016	H	0.016
Supplier	0.035	L	0.002	L	0.002	L	0.002	M	0.007	M	0.007
Competitors	0.025	M	0.005	H	0.018	M	0.005	M	0.005	M	0.005
Total GPS	1.000		0.219		0.233		0.210		0.255		0.318
Normalised GPS			0.178		0.188		0.170		0.207		0.258

Rating: H, high; M, medium; L, low. [a]Weight reduction. [b]Renewable material. [c]Low energy content. [d]Recycled/recyclable material. [e]Non-toxic material.

Poor) was modified to a three-point rating scale of high, medium, and low, and each weight was determined as 0.735, 0.199, and 0.065, respectively.

Table 8 presents the result of this study. The global weight for each criterion found from the previous table is multiplied by each assigned rating scale to find the global priority scores (GPS). Then the total GPS were found by summing the GPS for each strategy. These total GPS were normalised for the comparison of optimised strategy selection. Based on the normalised GPS of the five strategies, strategy 5 ('non-toxic material') has the highest weight with 0.258. This result indicates that the decision-making group may place more priority on the utilisation of non-toxic materials along with other strategies during product development.

4. Conclusion

Integrating environmental and business aspects of a product system will become more profitable as consumers become more informed and knowledgeable about the environmental impacts of products. Contribution of this proposed methodology is the integration of both quantitative and qualitative data in the decision-making process. The LCA model provided quantitative measurement of the environmental performance of a specific product through the entire lifecycle. The LCA result was utilised to select the product lifecycle stage that has the highest priority to be solved for DfE practice. One of the multi-criteria decision-making methodologies, AHP, is then introduced to prioritise the alternative design for environment strategies. By using the AHP, the problem is structured systematically and the criteria for strategy selection are defined. This enables decision-makers to examine the strengths and weaknesses of each strategy by comparing appropriate criteria. AHP is qualitative in the sense that it utilises subjective data collected from experts through a questionnaire. It is also a quantitative method, since it utilises the structured pairwise comparison matrix to evaluate the local/global rating scores and it calculates the eigenvalues and eigenvectors to verify the consistency of the data. Different companies have different strategies in terms of environmental and business policies, and each company should identify and set their own goals and criteria before practicing the proposed methodology. In this study, the step by step process of LCA and AHP was described to provide detailed information of how environmental performance can be captured for eco-design and how the systematic decision-making process integrates the business aspects of the product development with the selection of DfE strategies. The proposed methodology should not necessarily be viewed as a complex and time-consuming method. An additional contribution to this methodology will be to integrate uncertainty analysis. Even though AHP is useful for a number of reasons, it forces decision-makers to converge vague judgements into single numeric preferences in order to construct the pairwise comparisons of all pairs of objectives and decision alternatives. The resultant ranking of alternatives cannot be tested for statistical significance and variation due to several kinds of uncertainties involved in the decision-making processes. Uncertainty analysis would be extremely useful when there are only small differences in the final normalised global priority scores between strategies, and the decision-maker cannot be certain how to discriminate their relative importance among alternatives. The incorporation of uncertainty in the decision analysis that can test the statistical significance of the final rankings and the development of a computerised integrated tool is an ongoing extension of this study.

References

Brezet, H. and Hemel, C.V., 1997. *Ecodesign – a promising approach to sustainable production and consumption*. New York: UNEP.

Choi, J.K., 2006. *A systematic methodology for designing sustainable product system*. Thesis (PhD). Purdue University, USA.

Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A.A., de Oude, N., Parrish, R., Perriman, R., Postlethwaite, D., Quay, B., Séguin, J. and Vigon, B., eds., 1993. Guidelines for life-cycle assessment: a 'code of practice'. *In*: *Workshop of society of environmental toxicology and chemistry (SETAC)*, 31 March–3 April 1993 Sesimbra, Portugal. Belgium: SETAC, 32–37.

Fiksel, J., 1996. *Design for environment: creating eco-efficient products and processes*. London: McGraw-Hill.

Graedel, T.E. and Allenby, B.R., 2003. Industrial Ecology. 2nd edition. New Jersey: Prentice Hall, 97–99.

Guineé, J.B., ed., 2002. *Handbook on life cycle assessment – operational guide to the ISO standards*. Dordrecht: Kluwer Academic.

Hauschild, M. and Wenzel, H., 1998. *Environmental assessment of products, Vol. 2; Scientific background*, London: Chapman and Hall, 47–51.

Heijungs, R., Guinée, J.B., Huppens, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., van Duin, R. and de Goede, H.P., 1992. *Environmental life-cycle assessments of products*. NOH report 9266. Leiden: Centre of Environmental Science.

Liberatore, M.J., 1987. An extension of the analytic hierarchy process for industrial R&D project selection and resource allocation. *IEEE Transactions on Engineering Management*, 34 (1), 8–12.

Miettinen, P. and Hämäläinen, R.P., 1997. How to benefit from decision analysis in environmental life cycle assessment (LCA). *European Journal of Operational Research*, 102, 279–294.

Mizuki, C., Sandborn, P.A. and Pitts, G., 1996. Design for environment – a survey of current practices and tools. *In*: *Proceedings of 1996 IEEE international symposium on electronics and the environment*, 6–8 May 1996 Dallas, TX. New York: IEEE Conference Xpress, 1–6.

Saaty, T. L., 1980. *The analytic hierarchy process*. New York: McGraw-Hill.

Saaty, T.L., 1995. *Decision making for leaders – the analytic hierarchy process for decisions in a complex world*. Pittsburgh, PA: RWS.

Weber, M. and Borcherding, K., 1993. Behavioural influences on weight judgments in multi-attribute decision making. *European Journal of Operational Research*, 67 (1), 1–12.

Werner, F. and Scholz, R.W., 2002. Ambiguities in decision-oriented life cycle inventories. *International Journal of Life Cycle Assessment*, 7 (6), 330–338.