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An integrated MA-AHP approach for selecting the highest sustainability index of a new product

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Abstract

Since the development of engineered, discrete and physical products is the major cause of today's environmental problem in over the world, many approaches have been introduced to make a more sustainable product. To design new sustainable products, which may have several important sustainability concerns refer to environment, economic and social aspects, selecting the highest sustainability index among the new products generated is a multi-criteria decision-making problem. This paper proposes an integrated approach for the decision-making problem that combines the Morphological Analysis (MA) and the Analytical Hierarchy Process (AHP). The combination of both approaches enables product designers to widen design element concepts and evaluate the product sustainability at the early stage of product development process.

Keywords: sustainable product; sustainability index; Morphological analysis; AHP; product development process

1. Introduction

From the perspective of the current trends in worldwide industries, successful product development results in products that can be produced and less environmental impacts, yet sustainability concerns is often difficult to assess quickly and directly at design phase. Sustainable products are defined as the process of making products in a more sustainable way throughout their entire lifecycle, from conception to end-of-life [1]. Modifying the design and material composition of a product is one of the successively approaches to achieve the sustainable products, so they generate less pollution and waste throughout their life cycle [2]. Indicators are a key tool for encouraging progress towards sustainable development (SD) due to the complicated definition of SD [3]. In general, indicators are designed to capture the ideas inherent in sustainability and transform them into a manageable set of quantitative

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measures and indices that are useful for communication and decision making [4]. Jawahir et al. [5] presented six major elements of product sustainability along with identified sub-elements as the basic for developing generic product sustainability indicators as shown in Fig. 1.

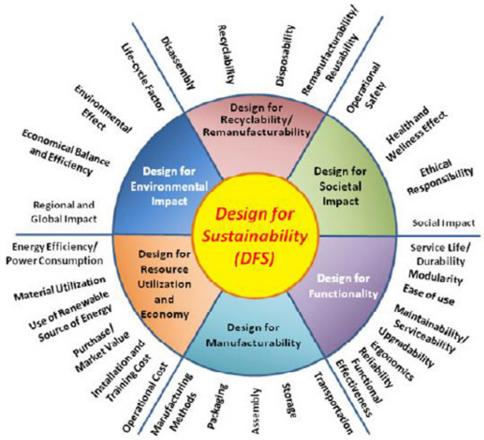

Fig. 1. Product sustainability wheel (Jawahir et al. [5])

Assessing product sustainability during design phase has become an imperative apprehension for most industries in relation to product development. Life cycle assessment (LCA) is an environmentally fundamental methodology which is used to comprehensively and quantitatively evaluate the significance of potential environmental impacts and to systematically identify hot spots incurring heavy environmental impacts [6]. However, LCA is often cumbersome, expensive to perform and designed to measure primarily resource use and environmental impact with no allowance for qualitative analysis [3]. Regarding to this matter, many approaches have been proposed extensively. The approach is not designed to replace the LCA process but aims to be quicker by focusing on specific areas of concern through the product life cycle, and so it provides a more cost-effective, systems-based and pragmatic product assessment [3]. Vinodh and Rathod [7] proposed the integration of environmentally conscious quality function deployment (ECQFD) and LCA approaches for ensuring sustainable product. Sheng and Soo [8] and Serban et al. [9] presented an integration of Theory of Inventive Problem-Solving (TRIZ) with eco-efficient elements and design for environment approaches. In other study, Vinodh [10] introduced an approach using CAD modeling of product followed by sustainability analysis to determine environmental impacts.

In this paper, an integrated approach is used that combines Morphological Analysis (MA) and Analytical Hierarchy Process (AHP). MA is used to widen design element concepts and generate many products from the combination of variety concepts for each design element of product, whereas AHP is used to assess the generated products by providing a weightage of sustainability influencing factors and finalize the decision-making by selecting the highest sustainability index of the product. The proposed approach is outlined in the next section, followed by a case study as the application of the proposed approach, and conclusions for this study in the last section.

2. Methodological Background

2.1 Morphological Analysis (MA)

Morphological analysis was introduced by Zwicky (1948) who had successfully used this method in the construction of reaction engines. The morphological analysis is widely accepted in the textbook (Dieter, 2000) [11] and by researchers (Li and Zhu [12]; Hsiao et al. [13]) as an effective technique for extracting and generating a new concept of design element.

The aim of morphological analysis is to widen the area of search for solutions to a design problem by decomposing a product into a number of independent form elements and then broken the form elements into variety of element types [12]. Hsiao et al. [13] identified specific steps of the optimization procedure are as follow:

- Identify the functional reach of the target product
- Itemize the acceptable solutions for each function in a morphological table
- Find the optimum by combining the suitable solutions for each function

2.2 Analytic Hierarchy Process (AHP)

AHP is one of the techniques that assist decision makers in solving complex problems by organizing thoughts, experiences, knowledge and judgments into a hierarchical framework, and guiding them through a sequence of pairwise comparison judgments [14]. The AHP method has been widely used in order to incorporate both qualitative and quantitative considerations of human perception. Turcksin et al. [15] used the AHP to set up the hierarchical decision tree and to determine criterion weights as one of the approaches for selecting the most appropriate policy scenario.

AHP methodology is capable to convert the human perception of importance into a numerical value. Basically, AHP involves the pairwise comparison of different criteria after identify the criteria within a hierarchy of various levels. These factors will be compared each other and a [4 x 4] comparison matrix for four identified factors is formed, as an example. The formed matrix is showed below.

	A	*B*	*C*	*D*
A	1	X_{12}	X_{13}	$1 / X_{14}$
B	$1 / X_{12}$	1	X_{23}	X_{24}
C	$1 / X_{13}$	$1 / X_{23}$	1	$1 / X_{34}$
D	X_{14}	$1 / X_{24}$	X_{34}	1

where, A, B, C and D are the factors and $X_{12,}$ X_{13} and X_{14} are the value from pairwise comparison of AB, AC and AD, respectively. The value is obtained from a fundamental scale of absolute numbers to capture the human perceptions with respect to quantitative and qualitative attributes [16].

After all matrices are formed, the relative weights and the maximum eigenvalue (λmax) for each matrix are calculated. The λmax value is used for calculating the consistency ratio (CR) of the estimated vector in order to validate the pairwise comparison matrix. The CR is calculated as per the following steps [16]:
Step 1: Calculate the relative weights and λmax for each matrix of order n
Step 2: Compute the consistency index (CI) for each matrix of order n by the formula,
$(CI = (\lambda max – n) / (n – 1))$
Step 3: The consistency ratio (CR) is then calculated using the formula $(CR = CI / RI)$

2.3 MA-AHP

The proposed MA-AHP approach for selecting the highest sustainability index of a new product is outlined in Fig. 2. The integrated approaches are correlated to each other, where at first, Morphological analysis is used to extract design elements of selected product, searching a new concept of design elements and generate new products. Secondly, AHP is applied to analyse the influencing factor of product sustainability on the generated products, calculating the influencing factor weights and calculating product sustainability index. With the identification of design elements and influencing factors of product sustainability, the relationship between them can be established. At the end of the processes, the highest sustainability index among the new generated product is identified[19].

3. Case Study

A case study has been conducted on personal digital assistant (PDA). Lin et al. [17] has identified design elements of PDA from the consumers' perceptions. The four identified design elements were used in this case study. Table 1 shows the morphological analysis of the PDA, with four design elements (i.e. top shape, bottom shape, function-keys arrangements, and colour treatment) and ten associated design element concepts of product.

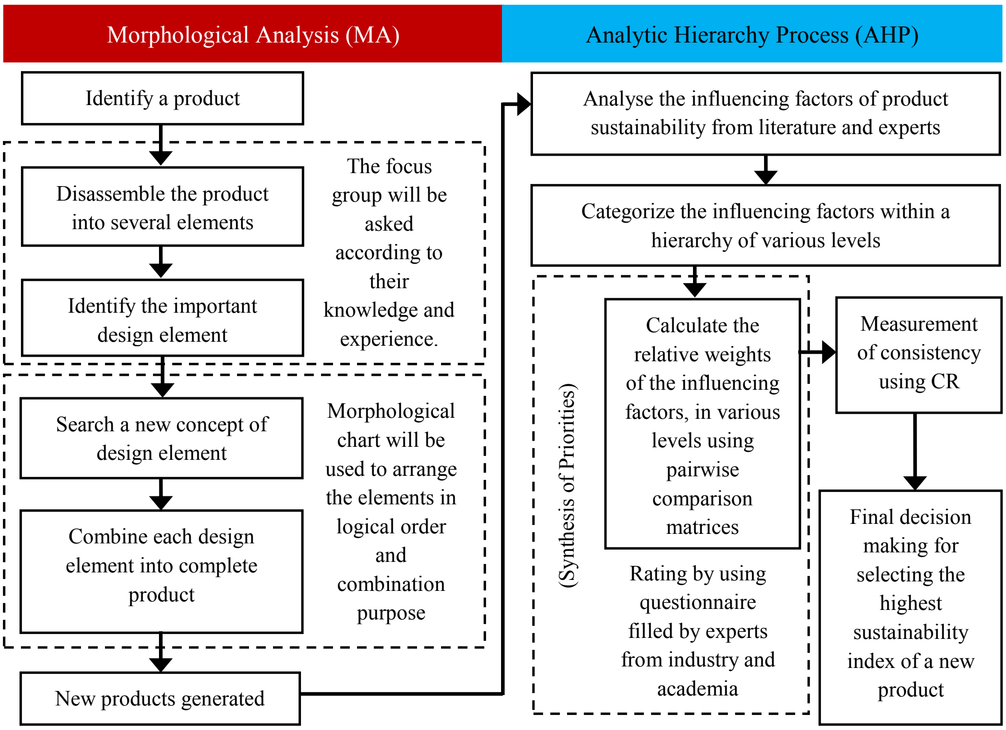

Fig. 2. The proposed MA-AHP approach

Table 1. Morphological analysis of PDA design elements

Design element	Concept of design element		
Top shape	Line	Chamfer	Fillet
Bottom shape	Fillet	Chamfer	Arc
Function-keys arrangement	Line	Symmetry	
Colour treatment	Non- colour	Colour	

The total combination of PDA design is 36 (3x3x2x2) with different combination of design element concepts on each design element. In this study, ten combinations of PDA design have been selected randomly in order to obtain a preliminary result for the proposed approach. The ten representatives of PDA design are illustrated in Fig. 3.

AHP has been used in the next step to obtain the product sustainability index. As the first step of the AHP method, the influencing factors of product sustainability were analysed. Since the key tool for encouraging progress toward sustainable development is indicators, the influencing factors have been referred to product sustainability hierarchy developed by Gupta et al. [18]. To obtain the product sustainability index of the ten representatives of PDA design, the AHP fundamental scales for pairwise comparison is used. Considering the evaluation of five design-related workers, each of whom had at least two years of relevant experience, the judgment matrix of the indexes have been completed. Global priority of the influencing factors that obtained from Gupta et al. [18] have been referred and multiplied the weights with the individual product scores to evaluate the total product sustainability index, as shown in Table 2.

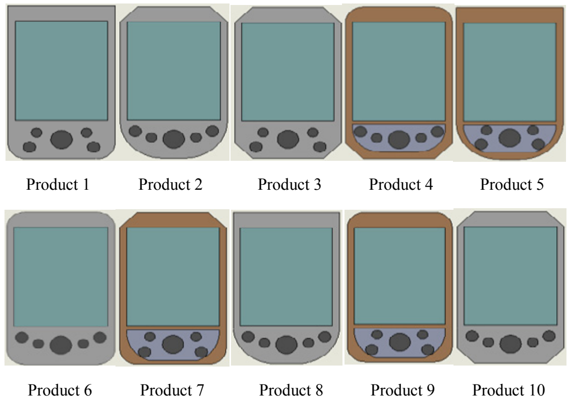

Fig. 3. Ten representatives of PDA design

Table 2: Influencing factors and sustainability index for the ten representatives of PDA design

Influencing factors	Global priority	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6	Prod 7	Prod 8	Prod 9	Prod 10
I1Pm1: Material extraction	0.029	0.00046	0.00696	0.00696	0.00168	0.00046	0.00168	0.00168	0.00046	0.00168	0.00696
I1Pm2: Design for environment	0.083	0.00554	0.03208	0.01388	0.00164	0.00164	0.00554	0.00164	0.00554	0.00164	0.01388
I1Pm3: Material processing	0.024	0.00964	0.00033	0.00091	0.00091	0.00430	0.00091	0.00091	0.00430	0.00091	0.00091
I1Mn1: Production energy used	0.016	0.00583	0.00034	0.00070	0.00086	0.00266	0.00070	0.00070	0.00266	0.00086	0.00070
I1Mn2: Hazardous waste	0.116	0.01374	0.03269	0.03269	0.00417	0.00227	0.00417	0.00417	0.00417	0.00417	0.01374
I1Mn3: Renewable energy used	0.026	0.00260	0.00260	0.00260	0.00260	0.00260	0.00260	0.00260	0.00260	0.00260	0.00260
I1Us1: Emission	0.025	0.00296	0.00705	0.00705	0.00090	0.00049	0.00090	0.00090	0.00090	0.00090	0.00296
I1Us2: Functionality	0.005	0.00090	0.00010	0.00090	0.00010	0.00090	0.00010	0.00090	0.00010	0.00090	0.00009
I1Us3: Hazardous waste	0.032	0.00320	0.00320	0.00320	0.00320	0.00320	0.00320	0.00320	0.00320	0.00320	0.00320
I1Pu1: Recyclability	0.043	0.00430	0.00430	0.00430	0.00430	0.00430	0.00430	0.00430	0.00430	0.00430	0.00430
I1Pu2: Re-manufacturability	0.04	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400
I1Pu3: Redesign	0.021	0.00210	0.00210	0.00210	0.00210	0.00210	0.00210	0.00210	0.00210	0.00210	0.00210
I1Pu4: Landfill contribution	0.036	0.00548	0.00548	0.00548	0.00078	0.00078	0.00548	0.00078	0.00548	0.00078	0.00548
I2Pm1: Recovery cost	0.018	0.00723	0.00025	0.00068	0.00068	0.00068	0.00322	0.00068	0.00068	0.00322	0.00068
I2Pm2: Potential for next life	0.041	0.00410	0.00410	0.00410	0.00410	0.00410	0.00410	0.00410	0.00410	0.00410	0.00410
I2Pm3: Raw material cost	0.057	0.00097	0.02618	0.00451	0.00451	0.00140	0.00451	0.00451	0.00140	0.00451	0.00451
I2Pm4: Labour cost	0.023	0.00957	0.00079	0.00265	0.00041	0.00079	0.00265	0.00041	0.00265	0.00041	0.00265
I2Pm5: Storage cost	0.011	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110
I2Mn1: Production cost	0.039	0.01500	0.00165	0.00647	0.00080	0.00080	0.00311	0.00080	0.00311	0.00080	0.00647
I2Mn2: Packaging cost	0.014	0.00140	0.00140	0.00140	0.00140	0.00140	0.00140	0.00140	0.00140	0.00140	0.00140
I2Mn3: Energy cost	0.035	0.01322	0.00071	0.00132	0.00132	0.00482	0.00132	0.00132	0.00482	0.00482	0.00132
I2Mn4: Transport cost	0.007	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070
I2Us1: Modularity	0.008	0.00080	0.00080	0.00080	0.00080	0.00080	0.00080	0.00080	0.00080	0.00080	0.00080
I2Us2: Maintenance cost	0.005	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050
I2Us3: Repair cost	0.004	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040
I2Us4: Consumer injury cost	0.011	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110	0.00110
I2Us5: Consumer warranty cost	0.003	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030
I2Pu1: Recycling cost	0.006	0.00091	0.00091	0.00091	0.00013	0.00013	0.00091	0.00013	0.00091	0.00013	0.00091
I2Pu2: Disassembly cost	0.007	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070
I2Pu3: Disposal cost	0.003	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030
I2Pu4: Remanufacturing cost	0.003	0.00046	0.00046	0.00046	0.00007	0.00007	0.00046	0.00007	0.00046	0.00007	0.00046
I2Pu5: Recycled material value	0.011	0.00428	0.00016	0.00075	0.00027	0.00075	0.00186	0.00027	0.00164	0.00027	0.00075
I3Pm1: Worker health	0.02	0.00200	0.00200	0.00200	0.00200	0.00200	0.00200	0.00200	0.00200	0.00200	0.00200
I3Pm2: Worker safety	0.029	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290
I3Pm3: Ergonomics	0.007	0.00009	0.00283	0.00099	0.00022	0.00022	0.00022	0.00099	0.00022	0.00099	0.00022
I3Mn1: Work ethics	0.023	0.00230	0.00230	0.00230	0.00230	0.00230	0.00230	0.00230	0.00230	0.00230	0.00230
I3Mn2: Ergonomics	0.012	0.00016	0.00485	0.00169	0.00038	0.00038	0.00038	0.00169	0.00038	0.00169	0.00038
I3Mn3: Worker safety	0.04	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400	0.00400
I3Us1: Product pricing	0.003	0.00116	0.00013	0.00013	0.00006	0.00013	0.00032	0.00006	0.00064	0.00006	0.00032
I3Us2: Human safety	0.019	0.00190	0.00190	0.00190	0.00190	0.00190	0.00190	0.00190	0.00190	0.00190	0.00190
I3Us3: Upgradability	0.003	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030	0.00030
I3Us4: Complaints	0.005	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050	0.00050
I3Pu1: Quality of life	0.01	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
I3Pu2: Take back options	0.009	0.00090	0.00090	0.00090	0.00090	0.00090	0.00090	0.00090	0.00090	0.00090	0.00090
I3Pu3: Reuse	0.01	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
I3Pu4: Recovery	0.007	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070	0.00070
Total product sustainability index		0.14271	0.16904	0.13422	0.06498	0.06876	0.08355	0.06769	0.08563	0.07389	0.10850

From the Table 2, sustainability index for the ten representatives of PDA design have been evaluated based on the relationship between the design element concepts and the influencing factors of product sustainability. Product 2 of the PDA design has the highest sustainability index among the other represented products, in which this product has combined for each design element with Chamfer concept for Top shape, Arc concept for Bottom shape, Line concept for Function-key arrangement and Non-colour for Colour treatment. Therefore, the product designers can determine the desirable design element concepts of product for a new PDA design according to the sustainability index.

4. Conclusion

In this paper, an integrated MA-AHP approach for selecting the highest sustainability index among the new products is presented. The approach is consists of Morphological Analysis (MA) and Analytical Hierarchy Process (AHP). A case study has been conducted on personal digital assistant (PDA). The result has demonstrated that the relationship between design element concepts and the influencing factors of product sustainability can be established for developing a sustainable product. Therefore, the proposed approach can be used as the decision-making at the early stage of product development process and helping product designers to meet sustainable requirements for a desirable product design element for sustainable product development.

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