A Framework for Stepwise Life Cycle Assessment during Product Design with Case-Based Reasoning

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Abstract—Life cycle assessment (LCA) is a systematic method of analyzing the environmental load throughout the entire life cycle of a product and evaluating potential environmental effects. It can be useful for ecodesign and for dealing with environmental regulations. However, the LCA process generally requires considerable time and money to collect relevant data and information. Although various studies have been made on the streamlined LCA in an effort to overcome these limitations, the result is still unsuitable for active ecodesign in the early design stage. We therefore propose an approximate LCA method for the early stage of product design and a systematic selective LCA method for use after the detail design stage. For the approximate LCA, we used the function behavior structure environmental effect expression to develop an environmental character evaluation matrix and a case-based reasoning system. This case-base reasoning system can be used in each design stage by referring to the LCA results of a product or a part or module. In addition, the concept of relative importance is used to select the important parts or modules considered in the selective LCA. A case study involving a mobile phone confirms that the proposed stepwise LCA method can be effectively applied to the design of eco-products.

I. INTRODUCTION

In recent years, an increase in environmental consciousness and the introduction of strict environmental regulations have challenged designers to consider the environmental performance of products together with traditional design objectives in the early stages of design. Many companies are therefore striving to obtain green certification as they endeavor to cope with environmental legislation, particularly with regard to WEEE (waste of electrical and electronic equipment), RoHS (restriction of hazardous substances directive) and EuP (energy using product) [1]. However, effective environmental assessment tools are needed because designers have difficulty assessing the environmental characteristics of their products. Life cycle assessment (LCA) is now the most representative and sophisticated tool for analyzing and quantifying the consumption of resources and their environmental impact throughout the entire life cycle of a product. It has been standardized by the ISO 14040~3 series for practical use in enterprise [2]. Fig. 1 describes general LCA stages and applications. However, it can be rather costly and time-consuming and requires specific data, which are normally not available in the early design stage. Moreover, quantitative LCA cannot be applied at the conceptual stage of product development [3]. The early stages of the design process are widely believed to be the most influential in defining the eco-factors of products [4]. Advanced methods of overcoming the limitations of the existing LCA method have consequently been proposed. The advanced LCA methods can be classified into three types. The first type is matrix-based qualitative or quantitative assessment [2], [5]. This type, though useful in the early design stage because of its simplicity, is more likely to reflect the subjective views of designers. The second type involves partial elimination of complicated LCA procedures or product attributes, though it has no systematic means of selecting the concerned life stage and attributes [6]. The third type involves the substitution of a genetic algorithm or multi-regression equation for complicated LCA processes [7], [8]. One of the drawbacks of these new algorithms is that they are limited to specific product domains, such as small energy-consuming electronic devices. To sum up, only a qualitative evaluation can be used in the concept design of a product because there are no specifications of the product. Similarly, after the detail design stage, we can evaluate the environmental effect of the product with most specifications. Unfortunately, active eco-friendly product design is difficult to achieve because the product is generally designed without any environmental evaluation [9].

We propose a framework for a stepwise LCA method that overcomes the limitations of existing methods. Case-based reasoning (CBR) is used as an indirect assessment method for
concept and system-level design stages. Furthermore, we developed an environmental character evaluation matrix (ECEM) for the purpose of searching for product attributes not found in the CBR system and for giving feedback to later design processes and selective LCA processes via a bill of materials (BOM). In addition, we propose a CBR-based systematic selective LCA method that involves the calculation of the relative environmental importance of parts.

The rest of the paper is organized as follows: In section II, we give an overview of the proposed research framework and a description of the ECEM, CBR for LCA, and the selective LCA process. In section III, we describe a case study of the proposed method. Finally, in section IV, we discuss our conclusions and future research issues.

II. STEPWISE LCA

A. Overview of the Proposed Method

To achieve a better ecodesign approach, we divide the design process into three stages, as shown in Fig. 2.

![Fig. 2. The framework of stepwise LCA](image)

The first stage is concept development. The concept of the product is sketched, and the function and characteristics of the product are clarified, though usually in an abstract or qualitative form. Thus, a quantitative evaluation, such as a general full LCA, is difficult to conduct at the concept development stage. To overcome this problem, we propose a new LCA method that involves the use of CBR; this method can be evaluated on the basis of existing LCA results. At the same time, we constructed a product ECEM that can be used to search for product-oriented characteristics not found in CBR. The ECEM results are included in a BOM. By applying these two methods, we can determine the important environmental attributes and that information can be used in the third stage.

The second stage is the system-level design stage, where important parts and modules are constructed. Generally, if some parts or modules have the same function, they may be compatible with another product even if that product is a different type of product. Therefore, once we construct the module-based case memory of CBR in the first stage, we can perform a module-based environmental effect assessment at the system-level stage.

According to existing research, even though modules have a different shape or structure, their environmental effect is similar whenever they perform a similar function [6]. Therefore, if we compose the case memory of existing full LCA results on the basis of the modules, we can estimate the environmental effect of a particular module by converting the CBR results in a proper manner. After that, we can minimize the environmental problems of a product by exchanging a problematic module with an eco-friendly module [10].

The third stage is the detail design stage. In this stage, necessary information on the product geometry, material and process is obtained for the performance of a full LCA. However, the acquisition of a life cycle inventory, material and process information for an entire life cycle is costly and time-consuming. We therefore propose a selective LCA method based on the important product attributes, modules, and life cycle stages considered in the first and second stages.

The selective LCA method can eliminate unimportant product attributes and life cycle stages and act as a surrogate external life cycle inventory to simplify the LCA procedures. Hence, it can evaluate the environmental effects of a product easier and more quickly than a full LCA. Although several studies have been made on selective LCA, little is known about systematic methods of selecting important product attributes or life cycle stages. Furthermore, in the existing LCA method, the selection of parts to be included in the assessment is based solely on the quantity of matter. So if a particular part has a small mass but a serious environmental effect as a result of the manufacturing process, it could produce the wrong results.

However, we already selected the important attributes of the product and life cycle stage in the first and second stages, and we can exclude some parts by calculating the relative importance on the basis of the CBR results. In this way, our method overcomes the drawbacks of the existing selective LCA.

B. ECEM

As mentioned above, we propose an ECEM that can search for product environmental attributes not found in the CBR system and provide feedback for a later design stage and selective LCA. Fig. 3 shows the general form of the ECEM.

![Fig. 3. General form of the ECEM](image)

Each row describes the product life stage and each column shows the environmental stressor. Each blank cell is divided into an upper part and a lower part. The upper part is
for a numeric evaluation on a scale of 1 (weak) to 5 (serious). Evaluation should rely on product environmental specialist. We can estimate the LCA results by adding up the upper part of the cells. The lower part of the cells contains a list of problematic parts and material. This information is recorded in specifications or a BOM in compensation for the CBR results of the first and second stage. Finally, the ECEM results can be expressed in a spiderweb chart for efficient selection of an important life cycle stage or problematic part [11].

C. CBR System

Generally, the CBR system is comprised of case representation, case memory organization, case recall, and case adaptation [12]. In this section, we propose case representation by using Function-Behavior-Structure (FBS) expression and a memory organization method.

1) An FBS environmental effect model for the CBR system in LCA

The FBS model provides the basis for classifying the information within a case as a function, behavior or structure [13]. Each case is represented in terms of a multilayered representation that expresses the function, behavior, and structure of the design entity. Therefore, the FBS model is an effective way of using reasoning at various levels of abstraction to perform a design activity.

We propose a new FBS environmental effect (FBSε) expression which enables a general FBS expression method to be used in LCA. Each element is defined as follows:

- **Function**: The purpose of the design (product) (e.g. the purpose of a cellular phone is to make or receive calls without wires; the purpose of a beam is to carry a load over a distance; the purpose of a cup is to hold liquid)
- **Behavior**: Required functional module/parts and manufacturing process (e.g. cellular phone shows graphical information by LCD panel (functional module); cup holds liquid by providing an enclosed volume (functional part); enclosed volume of cup is made by steel forging (manufacturing process))
- **Structure**: Description of the physical characteristics of the object (e.g. geometry size, material, color)
- **Environmental Effect**: Description of the environmental effect of a product (e.g. global warming, ozone layer depletion, acidification)

Fig. 4 shows the general form of LCA results when FBSε expression is used.

<table>
<thead>
<tr>
<th>Environment attribute</th>
<th>Behavior attribute</th>
<th>Structure attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidification</td>
<td>Function attribute</td>
<td>Global warming</td>
</tr>
<tr>
<td>Oxidant creation</td>
<td>Behavior attribute</td>
<td>Material attribute</td>
</tr>
<tr>
<td>Acidification</td>
<td>Structure attribute</td>
<td>Color attribute</td>
</tr>
</tbody>
</table>

Fig. 4. General form of LCA results when FBSε expression is used

FBSε expression can be applied to a specific module. It has the advantage of being able to conduct a case search for a product or module.

2) Case memory organization and reasoning process

Basically, we constructed a hierarchical case memory of a product structure [13]. Fig. 5 shows the case memory organization and the general CBR process.

The LCA results of whole products are saved at the top level of the case memory in an FBSε form; the sublevel of the case memory can be stored at the module level or submodule level of the LCA results. The left part of Fig. 5 shows the general process of the CBR system. In stage 2, we can search and retrieve the LCA results at the product level, the module level or the submodule level. Cases can be retrieved in stage 2.

3) Case retrieval and selection

When selecting the most applicable case for the problem in hand, there are generally several metrics and ranking schemes. Of these, we use a weighted average count of matching attributes that assesses the relevance of cases to the problem on the basis of the importance of each matching attribute and the global evaluation of all matching features. The similarity between new design and case A could be computed as follows:

\[
\text{Similarity} (\text{New Design, Case } A) = \frac{1}{\sum_{i=1}^{n} w_i} \sum_{i=1}^{n} \left[ w_i \times \text{sim}(f_i^D, f_i^A) \right]
\]

(Where, \( w_i \) is the weight of attribute \( i \)
\( \text{sim}(x,y) \) is degree of similarity by a real number between 0 and 1
\( f_i^D, f_i^A \) are the values for attribute \( f_i \) in the new design and case A, respectively)

Usually, weights vary according to the product, and it has great effect on the similarity computation result. Therefore, weighting scale has to be determined according to the kinds of product attributes in advance. In this study, we use real number between 1 (less important attribute) and 5 (very important attribute).

4) Case adaptation method

LCA results usually depend on the product material, the mass, the manufacturing process, and the scenario of the delivery, use, and disposal stage. Of these factors, the material and mass have the greatest effect. Accordingly, the correspondence of material should be checked, and any discrepancies in the mass should be corrected. In the event of...
any differences between the selected case and the new design, we can adapt the case to the new design as follows:

\[
\text{Adapted Environmental Effect} = \text{LCA Results of Case} \times \frac{\text{Mass}_{\text{New Design}}}{\text{Mass}_{\text{Case}}}
\]

D. Use of CBR results in the selection of important parts

Once we get the details of the design, we can use CAD software to construct the product BOM. In the LCA process, we don’t usually consider every part of the product. Existing research has evaluated how the quantity of matter affects the environment, but parts that are under a given threshold are generally excluded. However, even parts with a small mass can have a large environmental effect because of the manufacturing process. That is, when important parts are selected on the basis of the quantity of matter, the LCA results may be distorted. We therefore propose a part selection method based on CBR results.

For the proposed method, we use the following definition of the relative importance of a part so that we can compare the environmental effect of all parts:

\[
\text{Relative importance} = \frac{\text{Effect of part or module}}{\text{Total effect of product}}
\]

If the relative importance of a part or module is less than a critical value, we can exclude that part or module from the LCA list. This procedure is summarized as follows:

BEGIN
IF Relative importance of part/module < Critical value
THEN Remove the part/module from selective LCA list
END

The critical value is defined in terms of the purpose of eco-friendliness or regulations.

III. CASE STUDY: MOBILE PHONE

The effectiveness of the stepwise LCA method is illustrated with a demonstrative example of a mobile phone produced by an electronics manufacturer in Korea.

A. Selected product and specifications

We selected a 2007 slide-type mobile phone. Fig. 6 shows a photograph of the phone and the abridged specifications. Our focus is on the mobile phone itself, not the battery charger or packing materials.

First, we disassembled the mobile phone as shown in Fig. 7. The mobile phone has three major parts: the housing, the electronics, and the battery. In this case study, we measured the mass of the parts or modules and checked the kind of material to be used in the LCA.

B. The LCA results and case representation

The ISO 14000 series offers representative guidelines for LCA. Therefore, to perform the LCA of the mobile phone, we referred to the 2004 best practice of ISO 14040 series [14]. For our evaluation, we also referred to the national life cycle inventory of the Korea National Cleaner Production Center at the Korea Institute of Industrial Technology [15].

The details of the LCA procedure are omitted because they are irrelevant to the purpose of this study. Fig. 8 shows the normalized environmental effect of the entire mobile phone [16].

In Fig. 8, GW stands for global warming, AD is acidification, EU is eutrophication, POC means photochemical oxidant creation, and ARD stands for azoic resource depletion. The abbreviation “pe-yr” stands for population equivalent for a year; and “fu” stands for functional unit, which in this case is one mobile phone.

The LCA results shown above can be converted into FBSe form and stored in the CBR system as a case. Fig. 9 shows the LCA results expressed in the FBSe form.

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**Fig. 6. Mobile phone and specifications**

<table>
<thead>
<tr>
<th>Phone</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phone type</td>
<td>Slide</td>
</tr>
<tr>
<td>Size (mm)</td>
<td>93(L) X 46(W) X 16.9(H)</td>
</tr>
<tr>
<td>Weight(g)</td>
<td>94.9</td>
</tr>
<tr>
<td>LCD size</td>
<td>2.0 inch</td>
</tr>
<tr>
<td>LCD Color</td>
<td>262K Color</td>
</tr>
<tr>
<td>LCD resolution</td>
<td>176 X 220</td>
</tr>
<tr>
<td>Capacity</td>
<td>800mAh</td>
</tr>
<tr>
<td>Type</td>
<td>Li-ion polymer</td>
</tr>
<tr>
<td>Voltage</td>
<td>3.7V</td>
</tr>
</tbody>
</table>

---

**Fig. 7. Disassembled mobile phone**

**Fig. 8. The LCA results of the mobile phone**
The results of this case can be retrieved from the case memory. The material and mass information in the structure attribute can then be used in the case selection and adaptation procedure.

Designers generally like to use the LCA results of a part or module in the system-level design stage. The LCA results of common parts or modules should be pre-computed and selective LCA.

The results of this case can be retrieved from the case memory. The material and mass information in the structure attribute can then be used in the case selection and adaptation procedure.

**Stage 1: ECEM and use of CBR for whole product**

Fig. 11 illustrates how the ECEM for the mobile phone is constructed. There, the “-” means that each value of all parts are roughly equal to the eco impact.

<table>
<thead>
<tr>
<th>Life stage</th>
<th>GW</th>
<th>AD</th>
<th>EU</th>
<th>POC</th>
<th>ARD</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-manufacture</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Battery pack</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Housing/PC</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LCD</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PCB</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Battery Pack</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Product Delivery</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Display module</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Power source</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Product Use</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Refurbishment,</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Recycling</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Average</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Stage 2: Use of CBR for part or module**

In stage 2, we can estimate the LCA result of part or module by using CBR system. Two LCD module cases were prepared to show the case selection by similarity computation and case adaptation. New problem and Case 2 are LCD module of bar type mobile phone, and Case 1 is LCD module of slide type which is presented in Fig. 6. A simple comparison between new problem and each retrieved cases is presented in Fig. 14 with attribute weighting and degree of similarity.

The ECEM results show that the stages of product delivery and product use can be excluded from the assessment on account of their small effect. Because their average values are below 1 (less important value). In addition, the eutrophication and the photochemical oxidant creation are not major environmental stressors. We can therefore perform the LCA rapidly without either of those two stressors.

In stage 1, we can also estimate LCA result of whole product by using CBR, and this can be summarized in BOM with ECEM result, as shown in Fig. 13. Designers will be able to change product constitution for more eco-friendly one with this BOM. There, level refers to the hierarchical product structure.
Case 1 is more similar due to attribute “Display module”, and we estimate the LCA result of new problem by adapting the result of Case 1. Because the material of new problem corresponds with Case 1 material, we can easily adapt the Case 1 results to the new problem by simple transformation formula as mentioned before, and this can be documented in BOM, as shown in Fig. 15. Also, the LCA results of whole product in Stage 1 and other parts or modules can be estimated with same procedure.

### Table: LCA results of part selection procedure

<table>
<thead>
<tr>
<th>Level</th>
<th>Part Name</th>
<th>Material</th>
<th>Mass (g)</th>
<th>Environmental Effect (pe.yr/fu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cellular Phone</td>
<td>NMP, LiCoO</td>
<td>0.57</td>
<td>1.00E-03</td>
</tr>
<tr>
<td>2</td>
<td>Battery Pack</td>
<td>NMP, LiCoO</td>
<td>0.01</td>
<td>7.00E-06</td>
</tr>
<tr>
<td>3</td>
<td>FRT Pannel PC</td>
<td>PC</td>
<td>0.005</td>
<td>3.00E-06</td>
</tr>
<tr>
<td></td>
<td>FRT CASE ASSY</td>
<td>STEEL</td>
<td>0.001</td>
<td>1.00E-06</td>
</tr>
<tr>
<td></td>
<td>Slide UPR PC</td>
<td>STEEL</td>
<td>0.01</td>
<td>1.00E-06</td>
</tr>
<tr>
<td></td>
<td>Slide UPR Pannel STEEL</td>
<td>0.01</td>
<td>1.00E-06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slide LWR Pannel PC</td>
<td>0.007</td>
<td>7.00E-06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Key PAD ASSY</td>
<td>0.005</td>
<td>5.00E-06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Key PAD RUBBER</td>
<td>0.10</td>
<td>1.00E-06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Battery ASSY</td>
<td>NMP, LiCoO</td>
<td>0.001</td>
<td>1.00E-06</td>
</tr>
</tbody>
</table>

Fig. 15. Stage 2 BOM: CBR for part or module

Environmentally problematic part or module can be checked and replaced by eco-friendly one easily.

**E. Stage 3: Use of CBR results for the selection of important parts**

After the detail design stage, a BOM can be obtained. It should include information on the product structure, the parts, the material, the mass, the manufacturing process, and so on. As mentioned above, we can supplement a general BOM with CBR information on the relative importance of each part or module. If some parts or modules have specific material or involve a specific manufacturing process that differs from the CBR results, the ECEM results can be used to prevent erroneous case reasoning. This preventive effect is possible because a specific or problematic part or module can be recorded in the specification document during the concept design stage. Fig. 16 describe a CBR results for the part selection procedure.

**Fig. 16. Stage 3 BOM: Use of CBR for the part selection procedure**

In this example, the critical value was limited to 0.02, which means less than 2% of the total effect. According to our evaluation, the keypad assembly, slide upper panel and screws are under critical value. Therefore this part is consequently excluded from the selective LCA.

### IV. CONCLUDING REMARKS

In this study, we proposes stepwise LCA method as a means of overcoming the limitations of the existing full LCA; the proposed method enables the LCA to be performed in the early design stage. The results of our study have confirmed the importance of the following important concepts:

- Selective LCA with ECEM support
- FBSe expression for CBR
- Framework of the CBR system for LCA in the early design stage
- Use of CBR results for the selection of parts in selective LCA
- Integration of stepwise procedure by environmentally extended BOM

**ACKNOWLEDGMENT**

The authors would like to thank the EEWS Initiative of the Korea Advanced Institute of Science and Technology for supporting this research with financial assistance.

**REFERENCES**