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An evidential reasoning-based AHP approach for the selection of environmentally-friendly designs

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ABSTRACT

Due to the stringent environmental regulatory requirements being imposed by cross-national bodies in recent years, manufacturers have to minimize the environmental impact of their products. Among those environmental impact evaluation tools available, Life Cycle Assessment (LCA) is often employed to quantify the product's environmental impact throughout its entire life cycle. However, owing to the requirements of expert knowledge in environmental science and vast effort for data collection in carrying out LCA, as well as the common absence of complete product information during product development processes, there is a need to develop a more suitable tool for product designers. An evidential reasoning-based approach, which aims at providing a fast-track method to perform design alternative evaluations for non-LCA experts, is therefore introduced as a new initiative to deal with the incomplete or uncertain information. The proposed approach also enables decision makers to quantitatively assess the life cycle phases and design alternatives by comparing their potential environmental impacts, thus effectively and efficiently facilitates the identification of greener designs. A case application is carried out to demonstrate the applicability of the proposed approach.

1. Introduction

Manufacturers have taken serious actions to address the pressing need in complying with the recently enacted environment-related regulations. Environmental impacts, emissions, or resources consumptions throughout a product's lifecycle are often determined during its design and development processes. A company that aims at developing eco-friendly products has to take the whole product life cycle into consideration, but not just on the areas related to legal responsibilities (Hauschild et al., 2005). Unlike a product's length or weight, which can be easily measured, it is not easy for a manufacturer to estimate the potential environmental impacts or carbon emissions of design alternatives. Thus, a handy and objective approach to support the environmental impact assessment is needed. When some eco design tools have already been devised for a considerable time, manufacturers are, however, still grappling with such evaluations. Environmentalists tend to focus on the environmental issues of products, thereby introduced some eco design tools that can be employed to perform products' environmental evaluations, but the poor or partial integration of those eco design tools with product development processes has made the adoption by designers unready (Filho et al., 2007). In addition, the existing eco design tools often require qualitative judgements on weight elicitation, which means that different results would be generated when the weights are determined by different decision makers. Practically, product designers, especially those in small-and-medium size manufacturers, tend to pay little attention to environmental issues. They would like to have a user-friendly and less time consuming tool to assess their products for meeting the regulatory requirements.

Life Cycle Assessment (LCA) has been widely employed to quantitatively assess the full range of environmental impact along a product's life cycle from the stage of natural resources consumption to production, transportation and distribution, use, and disposal. However, LCA is generally regarded as not suitable for product development because of its complexity (Lindahl, 2006). Also, a full LCA is often described as a costly study as it requires a great amount of data collection effort. Most of these data have to be collected from different companies or industries, so much effort and time are required (Luca and Jiri, 2009). LCA suffers from uncertainty issues as well. Such uncertainties may include data gaps caused by missing environmental data in LCA libraries, data inaccuracy due to the measuring equipment's calibration errors, the lack of a standard way to interpret or present LCA results, as well as data incompatibility from different LCA libraries (Björklund, 2006; Finnveden et al., 2009; Reap et al., 2008b). Furthermore, the missing of Life Cycle

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Inventory data for some materials or production processes often discourages the use of comprehensive LCA for environmental impact evaluations. Therefore, a fast-track approach which can be handled by product designers to support such evaluations is needed.

Analytic Hierarchy Process (AHP) is a mathematical technique to solve multi-criteria decision making problems (Saaty, 1980). AHP has been applied in many decision problems related to green issues including eco design selections, green manufacturing processes evaluations in electrical panel industries, and evaluation of barriers in a supply chain, etc. (Costantino et al., 2011; Gupta et al., 2015; Luthra et al., 2016). Specifically, some approaches that combine LCA and AHP have been developed to support sustainability assessment (Petrillo et al., 2016; De Felice and Petrillo, 2014; De Felice and Petrillo, 2013). Although AHP is a systematic approach to deal with complex decision making problems, it cannot process uncertain variables (Yang and Singh, 1994a; Wang et al., 2008). In many applications, the use of crisp values is insufficient to deal with the uncertainty because of the vagueness of human subjective judgements or the inherent uncertainty associated with the environmental data. In this connection, an approach to support decision making with incomplete information is needed. Evidential Reasoning (ER) (Chan et al., 2014) is therefore applied because of its ability to handle uncertain or incomplete information. The use of AHP is to evaluate the environmental impact of the criteria (i.e. life cycle phrases) of the AHP hierarchy through pairwise comparisons as the level of impact generated from different life cycle phases are relative to each other (Chin et al., 2008). However, the environmental impact values among the alternatives should normally be independent of each other, so the evaluations of design alternatives' environmental impacts should conform to a common scale instead of comparing by their relativity. Therefore, the belief structure of ER might be more suitable for evaluating design alternatives (Chin et al., 2008).

ER is a mathematical approach devised from the Dempster-Shafer (D-S) theory (Dempster, 1967; Shafer, 1976). ER can be applied to evaluate the attributes with inherent uncertainty caused by imprecise information. Sometimes, only preliminary product information is available in the initial product development process and uncertainties might thus arise. As such, an approach that integrates AHP, with ER is developed to support design evaluations during early product development processes. There are two new advantages of using the proposed approach. First, the LCA results can be directly linked to the combined AHP and ER approaches to support objective evaluation on the design alternatives. Second, the deficiency of LCA related to incomplete or inaccurate information can be tackled by ER, where it enables the fast-track environmental impact evaluation which the full LCA studies often cannot be carried out. The subsequent sections of this paper are structured as follows: Section 2 outlines the steps of going through the rough-cut LCA, AHP, and ER. Section 3 describes the key steps of the proposed approach. A case implementation is presented in Section 4 and the results are discussed in Section 5. Section 6 draws our conclusions.

2. Rough-cut LCA, Analytic Hierarchy Process (AHP) and Evidential Reasoning (ER)

2.1. Rough-cut LCA

The rough-cut LCA (Ng and Chuah, 2014) can be accomplished by limiting the scope of the study.The rough-cut LCA is a "fast-track" approach or a simplified version of LCA, which aims to provide an immediate environmental performance checking on an alternative. Hence, the less-than-perfect results might be obtained using this "fast-track" approach, but these less-than-perfect results can still be very useful for prompt analyses which are better than no results at all (Barton and Love, 2000). The results of rough-cut LCA are directly connected to AHP and ER to support the evaluation of the environmental impacts of life cycle phases and alternatives respectively. In order to focus on the discussion of the proposed approached, only the key information of this rough-cut LCA is given here. Similar to the conventional LCA methodology, this rough-cut version consists of several key steps. The first step is to define the goal and scope of the study. The key tasks include problem definition, selection of system boundaries, and functional units. The second step is to perform Life Cycle Inventory analysis. The environmental impact will only be considered based on the information drawn from the design specifications or related bill of materials. This inventory analysis can be carried out using the SimaPro or Eco-it (Goedkoop et al., 2006). The third step is to conduct Life Cycle Impact Assessment. The CML method, developed by Institute of Environmental Sciences at Leiden University (Guinée et al., 2001; Myhre et al., 2013), is adopted as the impact assessment method to represent the alternatives' environmental impacts. Global Warming Potential (GWP) is related to emissions of greenhouse gases. Factors are expressed in kg carbon dioxide kg emission. The CML method converts the identified chemical contents of the life cycle inventory data including carbon dioxide, nitrous oxide, methane, chlorofluorocarbon, and hydrofluorocarbon to CO2 equivalent. The results obtained will then be used to support the evaluations on the environmental impacts of life cycle phases and alternatives. The preference assignments using the rough-cut LCA results are detailed in Section 3 and a case example is given in Section 4.

2.2. Analytic Hierarchy Process (AHP)

The AHP technique is employed to evaluate the relative importance of decision elements through pairwise comparisons. A typical AHP approach uses the 1–9 scale to represent the relative importance, where 1 represents equally important and 9 represents extremely important (Table 1). The weight of each decision element can be calculated once the pairwise comparison matrices have been constructed. The relative weights of the decision elements can then be calculated using the standard AHP computations. The consistency checks can be done by obtaining the corresponding consistency ratios (Saaty, 1980).

2.3. Evidential Reasoning (ER)

ER uses the belief decision matrix that enables each attribute to be described by a distribution assessment based on a belief structure (Yang and Singh, 1994a). The uncertainty caused by the imprecise information can be tackled by the distribution assessment. The steps and related equations are summarized in Appendix A.

3. The proposed approach

Since the aim of the proposed approach is to provide an objective evaluation and the result is used for internal reference purposes, the estimates or engineering judgement can be frequently applied (Curran, 2006). The target audiences of the study are product managers, designers, research and development engineers, production engineers, and suppliers. As shown in Fig. 1, the proposed approach

Table 1
The linguistic terms of preferences for pairwise comparisons.

Linguistic terms	Relative difference	Crisp values	Reciprocal
Extremely important	80%–100%	9	1/9
Highly important	60%–80%	7	1/7
Moderately important	40%–60%	5	1/5
Slightly important	20%–40%	3	1/3
Equal	0–20%	1	1