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Journal of Environmental Management 83 (2007) 1–24

Journal of Environmental Management

www.elsevier.com/locate/jenvman

# An integrated impact assessment and weighting methodology: Evaluation of the environmental consequences of computer display technology substitution

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Received 6 June 2005; received in revised form 13 December 2005; accepted 16 January 2006

## Abstract

Computer display technology is currently in a state of transition, as the traditional technology of cathode ray tubes is being replaced by liquid crystal display flat-panel technology. Technology substitution and process innovation require the evaluation of the trade-offs among environmental impact, cost, and engineering performance attributes. General impact assessment methodologies, decision analysis and management tools, and optimization methods commonly used in engineering cannot efficiently address the issues needed for such evaluation. The conventional Life Cycle Assessment (LCA) process often generates results that can be subject to multiple interpretations, although the advantages of the LCA concept and framework obtain wide recognition. In the present work, the LCA concept is integrated with Quality Function Deployment (QFD), a popular industrial quality management tool, which is used as the framework for the development of our integrated model. The problem of weighting is addressed by using pairwise comparison of stakeholder preferences. Thus, this paper presents a new integrated analytical approach, Integrated Industrial Ecology Function Deployment (I2-EFD), to assess the environmental behavior of alternative technologies in correlation with their performance and economic characteristics. Computer display technology is used as the case study to further develop our methodology through the modification and integration of various quality management tools (e.g., process mapping, prioritization matrix) and statistical methods (e.g., multi-attribute analysis, cluster analysis). Life cycle thinking provides the foundation for our methodology, as we utilize a published LCA report, which stopped at the characterization step, as our starting point. Further, we evaluate the validity and feasibility of our methodology by considering uncertainty and conducting sensitivity analysis.

*Keywords:* Environmental assessment for computer displays; I2-EFD; Weighting; QFD

## 1. Introduction

Presently, the design of environmentally friendly products is not only required by government and the general public, but it can also be economically viable for proactive manufacturers. Survey results on the relationship between consumer behavior and the "greenness" of products (Frear, 2002) show that American consumers turn to green products in broad fields driven by health and environmental concerns, e.g., hybrid cars, arsenic-free lumber, organic food, and fiberglass insulation products. With increasing environmental concerns from different stakeholders, particularly for specific product systems in the rapidly expanding field of electronics, one important issue in materials selection and technology substitution is to make an evaluation of the environmental performance through the entire product chain including upstream and downstream activities. Taking the environment into consideration creates new challenges for managers accustomed to focusing on engineering performance and cost.

Environmental impact assessment (EIA) methodologies cannot efficiently address the issues needed for such evaluation. Despite its literal interpretation, EIA is limited in applicability because EIA methodologies generally aim at specific projects and human activities instead of product

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doi:10.1016/j.jenvman.2006.01.006

systems (Petts, 1999). The purpose of an EIA report is to obtain permission for projects from regulatory decision authorities by providing information on the possible environmental consequences of planned projects. As a result, EIA methodologies have a limited scope of applicability to product systems.

Over the last two decades, an important quantitative analysis tool, Life Cycle Assessment (LCA), has been developed and utilized for the evaluation of potential environmental impacts of product systems. Although the conceptual "from cradle to grave" framework of LCA is widely acknowledged, LCA also has some methodological limitations when applied to product design.

First of all, in practice LCA often stops at the Life Cycle Inventory (LCI) analysis or characterization step in Life Cycle Impact Assessment (LCIA), which leaves the results of such preliminary analyses open to different interpretations. The remaining impact assessment steps of *normalization*, *grouping* and *weighting* are not well defined in official LCA guidelines. LCA methodology lacks the explicit mechanism to reflect the preference structure or value systems of different stakeholders. For instance, the ISO14042 definition of *normalization*, "calculating the magnitude of category indicator results relative to reference information," is a vague guideline that does not indicate specific methods or objectives. This is problematic because before the *normalization* step, there are different impact indicators with different units for each impact category. It is not an easy task for an evaluator without sufficient environmental expertise to find the appropriate reference information. Appropriate completion of the normalization step serves the purpose of removing such variation and transforming the indicators to a common proper unit according to one arbitrary reference system. The combination of *normalization* and *weighting* together serves to provide a single dimensionless environmental score for comparing alternatives. However, the corresponding normalization reference or threshold data are not often consistent and may be region-specific. For example, most of the manufacturing processes for desktop displays occur in Asian countries; the differences in working environment, geographic characteristics, atmospheric dispersion model and background exposure of the receiving ecosystem (Potting et al., 1998) bring difficulties to the selection of reference data. Another problematic issue is the need to distinguish static from dynamic environmental consequences. The temporal boundaries, e.g., the discrepancy between current and prospective impact, influence the calculation of the normalized impact value when importing the reference data for normalization. The other two steps within the LCIA, *grouping*, which is defined to be "sorting and possibly ranking of the impact categories" (ISO14042, 2001), and *weighting*, which is defined to be "converting and possibly aggregating indicator results across impact categories using numerical factors based on value choices" (ISO14042, 2001), are both inherently dependent on the value system and preference structure.

Secondly, many other factors, including economic, ideological, political, and social facets, make it difficult to obtain a consensus for the implementation of these steps in a global context (Schmidt and Sullivan, 2002). Except for the common argument from spatial and temporal aspects, the ambiguous causal relationships between the LCA inventory and their corresponding environmental impacts, especially impact on human health and the ecological system, as well as the environmental mechanisms involved, are complicated and not validated scientifically. Furthermore, the cause-effect relationship between the environmental impact and ultimate environmental consequences, and the monetary valuation of those environmental consequences give rise to more uncertainties, although they may go beyond the scope of basic LCA. Many LCA practitioners do not carry out quantitative estimations of uncertainty or sensitivity analysis.

Thirdly, LCA focuses mostly on the physical-chemical and ecological attributes, and lacks the ability to evaluate trade-offs between technological, economical and social attributes.

Currently, there are substantial efforts being made within the LCA community and industry to create better product system assessment tools that take into account environmental effects in the early product design phase. Chen and Chien (2004) integrate the response surface method with generic algorithms for LCA optimization. The existing LCA data are used as training data to predict the approximate environmental performance of a new product during the early design stage. Chung et al. (2003) construct a web based eco-design support system, which consists of a number of assessment tools and relevant databases targeted at the electric and electronic industry. Katz et al. (2005) present a short introduction on the development of an electronic products environmental assessment tool (EPEAT), but this tool has not been put into the implementation phase. Kuo (2003) applies fuzzy logic theory to Quality Function Deployment (QFD) to provide a framework for green product design. Middendorf et al. (2003) presents the approach of integrating environmental assessment tools and environmental performance indicators in product development in Germany. Sakao et al. (2004) describe the approach of the Quality Function Deployment for Environment (QFDE) model, an eco-design tool in which QFD is modified and extended to incorporate environmental aspects. Xiang et al. (2003) propose another LCA tool for electromechanical product green design, which provides four basic product life cycle management functions. Despite the success of these efforts, there is room for further improvement.

In the present work, we focus on the use of established management decision-making tools in order to address some of the limitations in implementing LCA. Through our previous methodological development and research results (Zhou and Schoenung, 2003, 2004), we find a strong similarity and close affiliation in the theoretical foundation and the mathematical representations between decision-making tools and LCA. This paper describes an integrated