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Predicting the total environmental impact of product technologies

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ABSTRACT

Many eco design tools and product assessment methods have been developed to improve the environmental performance of products during design stage. Despite the efforts made at the product level, environmental impact in our society is increasing due to environmental impact associated with increased product volume. This article presents a new methodology for product life cycle design assessment to predict the total impact caused in the society by forecasting the market growth of emerging product technologies. A number of products were used to prove the validity of the proposed model and demonstrate the usefulness of the methodology.

1. Introduction

It is widely accepted in our society that our current way of living must change to mitigate the damage done to the ecosystem and ensure the sustainability of future generations. As a result, many engineering tools have been developed to assist manufacturers reduce their resource consumption and harmful environmental impact while aiming to improve existing products and processes [1]. From product design and development perspective, the environmental impact need to be reduced while improving the functionality in order to ensure competitiveness of the manufacturer, be more responsible for the ecosystem and satisfy customer demand. Despite the development of many eco design tools however [2], overall environmental impact in the society is continuing to increase [3]. This problem can be attributed to overlooking the issue of increasing volume of products in a wider range of functionality that are being consumed in the market [4]. Therefore, the environmental assessment of products in relation to design features need be conducted with respect to total volume to identify the required improvement at product level. In addition, the influence of technology change on the environmental impacts also needs to be considered as new technologies offer increasing functionality in a growing market demand [4,5]. This article presents a methodology of predicting the total environmental impact of given product technology by integrating environmental assessment of product design with volume forecasting using Standard Logistics Function (SLF, S-Curve) [6]. In doing so, the necessary improvement required at product level is identified as a step to reaching targeted environmental impact during the product design stage.

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2. Background

2.1. Existing product assessment tools

Many eco design tools have been developed to aid decision making process during the design stage of product life cycle [2]. The aim of improving the product life cycle during the design stage is the result of discovering that up to 80% of economic, environmental and social impacts are determined during design stage [7]. To improve environmental performance of products, the concept of Design for Environment was developed to study the impacts of each life cycle stage of products [8]. Through identifying the hot spots in the life cycle, improvement opportunities are identified for a holistic approach to impact assessment. On the other hand, methods such as modular design aim to reduce resource use by grouping similar functional components and sharing common parts. When the functional requirements change, modular design assists in easy serviceability through interchanging of components [9] and can be achieved through adaptable design platforms [10]. Using modular design concept, life cycle improvement can be achieved through grouping of parts depending on life cycle stage such as end-of-life scenarios [11]. In addition, there are also general guidelines such as The Ten Golden Rules that assist in qualitative assessment and decision making to prolong the life of product while reducing the resources used [12].

2.2. Current trends

Despite these improvement efforts, the total environmental impact in the society is still on the rise when the volume supply is considered. For example, three different products were assessed for the total environmental impact for each year's volume supply: LCD TV, Automotive vehicle and Tablet PC – iPad®. The products were analysed as a ratio from a chosen reference year (Fig. 1): 2005 for LCD TV (2006 for 40–44 in.), 2011 for automotive vehicle and 2010 for Tablet PC. Although specific units of measure were used to assess the environmental impact for each product, applying the ratio method used for benchmarking allows easy comparison across different products and assessment methods since ratios are unit-less number [13]. The rationale for assessing products as a function of volume supply is due to the issue of increasing market demand for more products: this can be attributed to changes in purchasing behaviour of consumers as they choose improved functionality offered by new technologies and/or growing market size [14]. Fig. 1 demonstrates the increasing trends in total environmental impact of products and it is more prominent for higher functionality for the case of LCD TV – using the screen size as the main functionality (larger size).

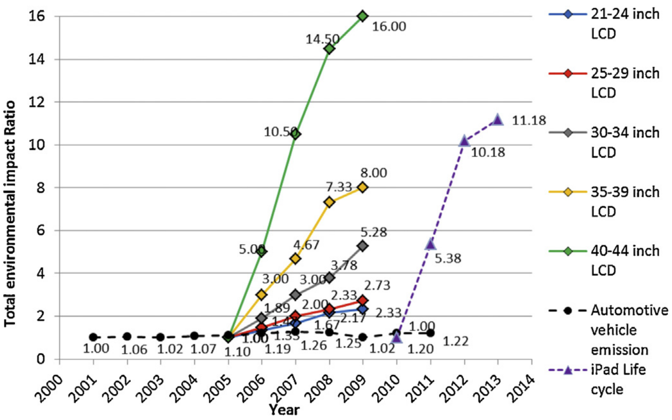

Fig. 1. Current trends in environmental impact of various products.

The overlooking of the issue of increasing volume and functionality can be attributed to the framework of Life Cycle Assessment (LCA) because the functional unit definition specified in ISO14040 guideline assumes that products of comparisons offer equivalent/alternative functionality [15]. However, this is not the case because consumer's perception of product features changes according to Kano's model in a growing market [16].

2.3. Influence of technology change

In order to manage the issue of technology change, many tools were developed. Growth of new technologies in the market (market share) can be predicted using S-Curves and remaining technology life can also be determined using this technique [17]. The change in the range of functionality can be assessed with corresponding volumes to determine the total environmental impact [4,5]. From product design perspective, co-evolution of design feature and manufacturing process was developed using cladistics for managing product evolution to prolong the life of manufacturing systems [18]. By incorporating cladistics with TRIZ and Streamlined LCA, enhanced decision making tool was developed [19]. The problem however, is that concurrent assessment of environmental impact, increasing functionality and volume of products is still lacking and they are not characterised by functional feature of the product. Therefore, a product assessment method that can perform environmental assessment of products as a function of feature and volume in a predictive manner is required to identify required improvement at product design level. This will assist in identifying necessary steps to reaching environmental sustainability in product development.

3. Methodology

In order to achieve the proposed product assessment, the environmental assessment of products needs to be performed both at individual product level and total volume supply level. The anticipated volume for subsequent generations of products needs to be forecasted using SLF to allow predictive assessment. By applying the ratio method used in benchmarking at volume level, any increases in total environmental impact can be easily identified so that necessary improvement can be quantified at product level. This allows improved management of product development.

3.1. Product level assessment

The environmental impact of products can be determined by LCA but it does not assess any interdependency (couplings) between the Functional Requirements (FRs) and associated Design Parameters (DPs). To overcome this limitation, the design equation in Axiomatic Design Theory [20] can be incorporated with LCA as shown in Eqs. (1) and (2). In doing so, the environmental impact assessment with respect to FRs and DPs can be performed for products with n function(s) and identify improvement opportunities through decoupling of functions.

$$\text{Product Environmental Impact(PE)} = \sum_{i}^{n} FR_i \tag{1}$$

$$FR_i = \sum E_{ij} DP_j \tag{2}$$

The equation can be further applied to life cycle analysis by identifying the environmental matrix E_{ij} with DP vector representing the life cycle stages. Then, the environmental impact of each product/function according to the life cycle stages can be determined as shown in Eq. (3). This will show the influence of each function on the life cycle impacts assuming they are independent from each other. If however, there are any couplings between the life cycle stages, the matrix will have additional variables/constants accordingly.

$$\text{Environmental impact}_{\text{Product or } FR} = \begin{bmatrix} x_1 & 0 & 0 & 0 \\ 0 & x_2 & 0 & 0 \\ 0 & 0 & x_3 & 0 \\ 0 & 0 & 0 & x_4 \end{bmatrix} \{\text{Production Usage Transport Recycling}\} \tag{3}$$

3.2. Forecasting volume and total environmental impact

Predictive assessment of total environmental impact of products is needed for improved management of product life cycle design. This can be achieved by forecasting the total volume of products to determine the total environmental impact and identify the necessary improvement amount at product level. This approach is used so that when the next generation of products are benchmarked from previous generation, the overall environmental impact in society does not keep rising. This can be achieved by using the SLF that predicts the growth pattern of emerging products using initial market share/volume [6]. The following equation is the SLF where p is the parameter of interest (such as volume or market share), L is the natural limit, a and b are constant scale and shape parameter respectively and t is time. Using the following function, it is possible to predict the growth pattern of emerging products at time t.

$$\text{Volume} = p(t) = \frac{L}{1 + ae^{-bt}} \tag{4}$$

Once the environmental impact of product and corresponding volume is determined, the total environmental impact can be determined by multiplying individual impact by the volume supply as shown in Eq. (5) – assuming it is a linear relationship between impact and volume [4].

$$\text{Total Environmental Impact(TE)} = PE \times p(t) \tag{5}$$