A New Comprehensive Methodology for the Evaluation of Product Sustainability at the Design and Development Stage of Consumer Electronic Products

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Abstract

This paper presents quantifiable sustainability elements in manufactured consumer electronic products. A "Sustainability Scoring" method is introduced at the design stage. A new product can be evaluated using this method for its integral elemental and the overall sustainability contents impacting the product when it reaches the end-of-life by considering the entire life-cycle including the effective residual use of recovered materials in the subsequent life-cycles of the same or different products. This procedure can also be used by design engineers for comparison with a similar product, such as a prior or a subsequent model, or one from a competitor.

Keywords

Electronic products, sustainability, life-cycle, environment, society

1 INTRODUCTION

Electronic products frequently become obsolete due to the rapid technology advancement in the industry. In general, new products are being introduced at a faster rate than that at which the current products are being discarded. This is a growing concern for the Original Equipment Manufacturers (OEMs), and also for the government regulatory organizations such that the landfill and incineration options are significantly being reduced or eliminated due to their adverse environmental effects [1]. In this regard, the evaluation of "product sustainability" plays a major role in its long-term aim of conserving resources for the future by the design and manufacture of "green" products. The societal value of such products is ever-increasing while the emerging economic benefits are shown to be significant [2-3] and design engineers need a goal to estimate these characteristics at an early stage of the product design cycle.

Although the concept of sustainable products has existed for a long time, it is only in the last two decades that researchers have realized the need for further research and for the potential for model creation with predictive capability. The Sustainability Target Method (STM) is one such model developed to express the overall relationship of the economic value of a product with the environmental impacts. This method provides a calculation of indicators for resource productivity and eco-efficiency, and decides if an end-of-life option is feasible [4]. There are models that consider environmental effects at the design stage of a product development [5-6]. Recently, Life Cycle Assessment (LCA) methodologies have also been modified and incorporated into the design stages of product development, but once again, these methods heavily concentrate on environmental impacts [7-8].

While significant research and application efforts continue on the effects of environment, society and economy in the design of products, processes and systems, very little has been reported on quantitative modeling of a product for its inherent overall sustainability level. A comprehensive and simple guide to design and manufacture of sustainable products is still lacking. While the LCA and other life-cycle models require an extensive amount of data, product development engineers are in need of a simple model that is quick and easy to use [9] and the proposed model can

help the design engineers make prompt and early decisions on their design choices.

The importance of this type of assessment is highlighted by the growing quantity of electronic waste and the concern for the welfare of future generations and preserving resources. Although there are various partial sustainability assessment methods available today for products, none of these methods provide a comprehensive evaluation to take into account of all possible, and often conflicting influencing factors which would obviously require a trade-off. The proposed new method is directly applied to consumer electronic products, but with sufficient data, this method could be customized to other products too. This method provides a simplified product sustainability scoring technique where the inputs of the model consist of data available at a design stage of a product development, and electronic products manufacturers are in need of such predictive models for their product range [10].

2 SUSTAINABILITY ELEMENTS

Six major "Sustainability Elements" have been identified and introduced in this model. These are: product's environmental impact, societal impact, functionality, resource utilization and economy, manufacturability and recyclability/remanufacturability [11] (see Figure 1). Each of these elements was further analyzed and a sub-element level was achieved with identified influencing factors (see Table 1).

The need for introducing six specific elements that differ from the conventional three broad categories (environment, society and economy) was to incorporate processes and systems criteria that are significant in sustainability decision making. Functionality is a key aspect of a product where upgradeability, modularity, and maintainability all contribute to sustaining a product. Manufacturability deals with assembly, transportation and packaging where new legislations are coming into effect. Recyclability/remanufacturing is a very extensive element where the electronics industry has to focus heavily on waste minimization and resource preservation.

With the introduction of the above six sustainability elements and corresponding influencing factors, a new

framework can be developed to measure the level of sustainability built into a product at the design stage as shown in Figure 2. The inputs of the model consist of data available at the design stage of the product development process and the output is an index that indicates the level of sustainability in the product. Data is used to create 44 different influencing factors belonging to 24 sub elements (see Table 1). This index will represent the six elements individually to gain a greater understanding of the product's relationship with sustainability.

Figure 1: Six Major Sustainability Elements.

Figure 2: A New Framework for Product Sustainability Model.

3 METHODOLOGY

Each influencing factor can be quantified differently, and they are all on a scale of 0-1, where 0 is the lowest and 1 being the highest rating. The method of quantifying was decided by knowledge of the data which was available at the design stage of the product such as the type of material to be used, number of components and energy consumption. In addition to the data from design engineers, recycling information is also required from the OEMs' recyclers with regard to recycling methods, cost and market value of recovered materials.

After all elements, sub-elements and influencing factors are identified for a specific product, each influencing factor is assigned with a factor code as shown in Table 1. Three categories are introduced to represent the relative importance of all influencing factors against each other: high, medium and low, and these categories are expected to be determined by the manufacturers of the product in collaboration with their respective design and environmental teams that work in conjunction with a

marketing team conducting frequent and regular customer surveys. This grouping technique creates a weighting factor as well as the simplification for any customization or changes for the future. Specific weighting can also be calculated according to the number of influencing factors in each category.

The measures for the influencing factors are created by a combination of currently existing models using already established indicators such as eco-indicator 99 [12] and also important regulations that are or will soon be in effect. Some of the measures from the directives include hazardous substances that need to be eliminated by July 2006 [13] and recycling and recovery standards that need to be achieved by December 2006 [14]. This is a critical issue as OEMs need to be ready to implement these standards if they market their products in the European Union.

4 CASE STUDY

An application for the proposed product sustainability scoring model was developed and validated through a case study on a laser printer manufactured by Lexmark International. After reviewing the sub-elements of product sustainability, Lexmark chose 10 out of 24 as important sub-elements for their products, and these were further grouped into five 'high' and five 'medium' importance categories. The 'low' importance category was omitted due to lack of interests by the project sponsor of this case study. The chosen sub-elements included a few influencing factors that the manufacturers or the recyclers had insufficient data and therefore those factors were also omitted for this study. Figure 3 shows an approximate procedure adopted for the proposed sustainability scoring method.

Figure 3: Flowchart of Lexmark's Product Model.

Table 2 shows the list of high and medium importance sub-elements, their corresponding influencing factors, and the relevant quantification methods. These ten sub-elements are defined as:

Energy efficiency: measured by the use of power consumption of the printer and the average value is set at 80Wh.

Material utilization: measured by grouping the materials into categories such as glass, metal and plastics and multiplying the corresponding eco-indicator value (pt/kg) with the weight (kg). This creates an index which indicates the environmental effects generated by the used materials.

Sustainability Elements	Sub-elements of Sustainability	Influencing Factors	Factor Code
Environmental Impact	Life-cycle factor Environmental effects	Recovery rate after first life Recovery cost Potential for next life Toxic substances Emission	RTE_RCVRY CST_RCVRY LIFE_PTL TXC_SUB EMSN
Societal Impact	Ethical responsibility Societal impact	Take-back options Product Pricing Safety Quality of life	TKBK_OPT PROD_PRC SFTY QLITY_LIFE
Functionality	Reliability Service life/ Durability Upgradeability Modularity Ergonomics Maintainability/ Serviceability	Type of material Maintenance Schedule Maintenance Schedule Ease of installation Option for upgrade Modules available Safety Maintenance Schedule	TYPE_MAT MTNCE MTNCE INSTL UPGD_OPT MODTY SFTY MTNCE
Resource Utilization and Economy	Energy efficiency Material utilization Use of renewable source of energy Market value Operational cost	Production energy Energy for use Recycle energy Type of material Quantity of material Cost of material Option for other energy sources Current market value Cost to operate	PROD_EGY USE_EGY RCY_EGY TYPE_MAT QTY_MAT CST_MAT RNW_EGY MKT_PRC CST_OPR
Manufacturability	Packaging Assembly Transportation Storage	Take-back options Packaging material Quantity used Number of parts/components Cost of transportation Cost for storage Duration of storage	TKBK_OPT PKG_MAT QTY_PKGMAT NUM_PTS CST_TSP CST_STRG TIME_STRG
Recyclability/ Remanufacturability	Recyclability Disposability Remanufacturability Disassembly Recovery of materials	Cost of recycling Recycle energy Recycling method Type of material Separability Value of recycled material Disposal options Number of recovered parts Number of parts/components Number of parts/components Type of material	CST_RCY RCY_EGY MTD_RCY TYPE_MAT SPRB VAL_RCYMAT DIS_OPT NUM_RCVPTS NUM_PTS NUM_PTS TYPE_MAT

Table 1: Elements and Factors that Contribute to the Electronic Product Sustainability Scoring Methodology.

High Importance Sub-elements	Influencing Factors	Method of Quantifying
Energy efficiency	Energy for use	Average power consumption of the printer
Material utilization	Type of material Quantity of material	Group materials and use eco indicator-99 values [12] Weight of each material group
Life-cycle factor	Recovery cost Potential life of printer	Cost per kilogram of recovery Assumed number of functional years of printer
Environmental effects	Toxic substances Emission	RoHS directive restrictions [13] CO2 emissions during the use of printer
Recyclability	Cost of recycling Recycling method Separability Value of recycled material	Cost per kilogram of recovery Percentage of separation before shredding Amount of time to separate material in printer Market price of recycled material
Medium Importance Sub-elements	Influencing Factors	Method of Quantifying
Reliability	Type of material	Group materials and use eco indicator-99 values [12]
	Maintenance Schedule	Level of maintenance
Service life/ Durability	Maintenance Schedule	Level of maintenance
Ethical responsibility	Take back options Product Pricing	Availability of a take-back option Price of printer
Packaging	Take back options Packaging material Quantity used	Availability of a take-back option Percentage of recycled material included in packaging Kilogram value of packaging material
Upgradeability	Ease of installation Option for upgrade	Level of installation Option to install upgrades such as USB port, memory slot.

Table 2: The Proposed Lexmark Method for the Evaluation of Product Sustainability.

Life-cycle factor: a sub element where the printer's life expectancy is combined with the recovery cost for the next life of the product cycle. It is generally known that the maximum number of functional years for a printer is set at 5 years, and the recovery cost is set at \$1.00 per kg of material by the manufacturer.

Environmental effects: considers only the direct environmental effects by the use of printer, such as emissions which is measured by CO₂ output of the printer. Also, this sub-element includes the product evaluation for restricted hazardous material as required by the RoHS directive.

Recyclability: measures all aspects related with recycling the printer at the end-of-life. This includes the cost, separability which is measured by the time taken to separate materials (8 hrs. maximum), if not shredded. If the product is completely shredded, the index for separability will be 0. The cost of recycled materials is measured against the non-recycled virgin material for comparison of lost value.

Reliability: this depends on the type of material which is used for the printer and scheduled maintenance. Since laser printers do not require maintenance other than the toner cartridge change, the input is simply reduced to a yes/no attribute criterion.

Service life/ Durability: includes maintenance schedule.

Ethical responsibility: this measures the societal commitment of the OEM by considering the take-back options at the end-of-life of the printer where the input will be the economic value at the collection. The available options are: free collections where neither the OEM nor the consumer carries the burden of payment, OEM pays the consumer for returns such as discounts on a new product upon returning old product and the last option is where the consumer pays to have the electronic product recycled or returned. The other parameter measured is the product's price which is compared with the current market price of a similar product.

Packaging: this takes into account the packaging material's recycled content and also the quantity used. Take-back of packaging material included with the purchase of the printer is also considered.

Upgradeability: Although printers are seldom upgraded by a consumer, this measures the options available for such an occasion such as the availability of USB ports, connectors, and extra memory slots. The difficulty level of installations is also measured.

After the relevant product sustainability data is collected, compiled and used, the influencing factors are calculated, and then appropriate weighting is applied to formulate the product's sustainability level. There are two stages where weighting is applied to the model (Figure 3): once at the

sub-element level, and after reaching the importance category selection level. The weighting for both levels were determined by the design and environment teams' relative importance, largely reflecting their extensive practical product design experience (see Table 3). As seen, the energy efficiency and reliability rank among the highest of the categories which belong to the resource utilization and economy, and the functionality elements of our proposed product sustainability elements, respectively. The weighting was created to amount to 100% in each category.

High Importance	Weighting (%)
Energy efficiency	29
Material utilization	20
Life-cycle factor	13
Environmental effects	19
Recyclability	19
Medium Importance	Weighting (%)
Reliability	27
Service life/ Durability	22
Ethical responsibility	16
Packaging	21
Upgradeability	14

Table 3: OEM Survey Results on Weighting for High and Medium Categories.

Sustainability Calculations - Product 1 (Model 2)			
High Importance Sub Elements	Weight (W)	Index (I)	W*I
Energy efficiency	0.29	0.75	0.22
Material utilization	0.2	0.12	0.02
Life-cycle factor	0.13	0.35	0.05
Environmental effects	0.19	1.56	0.3
Recyclability	0.19	0.35	0.07
<i>Weighting</i>	0.7		0.65
Total (High importance sub-elements)			0.46
Medium Importance Sub Elements			
Reliability	0.27	0.56	0.15
Service life/Durability	0.22	1	0.22
Ethical responsibility	0.16	0.94	0.15
Packaging	0.21	0.56	0.12
Upgradeability	0.14	0.2	0.03
<i>Weighting</i>	0.3		0.67
Total (Medium importance sub-elements)			0.2
Product Sustainability Index			0.66

Table 4: Calculated Product Sustainability Score for Product 1 (Model 2).

By using the weighting guidelines provided by the Lexmark's team, the following specific calculations were performed to reach precise product scoring.

High Importance Category Index = (Energy Efficiency Index * 29) + (material Utilization Index * 20) + (Life-cycle

Factor Index * 13) + (Environmental Effects * 19) + (Recyclability * 19) (1)

Medium Importance Category Index = (Reliability Index * 27) + (Service Life Index * 22) + (Ethical Responsibility Index * 16) + (Packaging Index * 21) + (Upgradeability Index * 14) (2)

The next level of the flow chart includes the weighing criteria for the 'high' and 'medium' categories by the relative importance also provided by the industry sponsor. Therefore, the final evaluation will be made as:

Total Product Score = (High Importance Category Index * 70%) + (Medium Importance Category Index * 30%) (3)

Table 4 shows details of the calculated product sustainability index (score) of 0.66 for Model 2 of Product 1. This is more acceptable than the score of 0.59 calculated for the earlier model (Model 1) of this product, while more improvements are envisioned for the next model of the product.

5 FUTURE DIRECTIONS IN SUSTAINABLE PRODUCT DEVELOPMENT

Another important aspect of this research is that the consumer-oriented model where the factors included are assessed by a consumer survey. The survey included questions regarding the pricing of the electronic product, safety and ease of use, take-back options, recycling methods and energy consumption. This finding shows that consumers were not as interested in the same sustainability factors as the electronics manufacturers (see Table 5 and Figure 4). The manufacturers ranked functionality as the most important aspect, immediately followed by the environmental aspect, whereas the consumers ranked the societal impact including personnel health and safety as their top choice, with product's functionality, resource utilization and cost closely following. The manufacturability aspect was excluded from the consumer survey as the average consumer is unlikely to be knowledgeable about manufacturing processes. Quite notably, the OEMs pay a greater attention to environmental aspects than the consumers, and the consumer expectations are greater for societal and recycling aspects.

Sustainability Element	OEM (%)	Consumer (%)
Environmental Impact	30.5	18.3
Societal Impact	8.0	22.9
Functionality	31.5	22.3
Resource Utilization & Economy	10.0	20.2
Manufacturability	10.5	N/A
Recyclability/ Remanufacturability	9.5	16.3

Table 5: Results of the Consumer Survey.

The successful production and marketing of a sustainable product solely depend on how well the manufacturers' and consumers' ideologies and expectations merge together. Although the consumer belief is difficult to change rapidly, it is a major challenge that all manufacturers have to deal with and possibly conquer with more societal benefits in mind in the future. This type of simple evaluating methodologies can also be customized for consumers' interest for their preferences in product choices in the market. As seen in Figure 4,

there is a broad gap that needs to be bridged between expectations of the consumers and the manufacturers and this proposed model can be considered as the first necessary step in the right direction to perform this useful service. Inevitably, OEMs will be required to focus significantly on implementing concurrent engineering principles, involving product teams at the product design stage, along with this proposed model to provide a comprehensive evaluation methodology for product sustainability with consumer preferences and demands through marketing and sales groups.

Figure 4: Results of Consumer Survey.

6 CONCLUDING REMARKS

Based on the data from Lexmark and the proposed new methodology, it can be concluded that this is a simple model which is useful in decision making at the design stage of product development. Although this scoring model is designed for consumer electronics, with sufficient data, it could be customized to other products. This work is currently continued at the University of Kentucky to refine the model to a wider range of products.

A consumer-oriented approach will be considered in the successful implementation of this proposed model in the future. Also, future work in this area would include expanding the survey to several OEMs and policy makers for a better understanding of the consumer electronics industry and its impact on the societal growth.

ACKNOWLEDGMENTS

We sincerely acknowledge the help provided by Kunal Joshi and Anand Venkatachalam in preparing this paper manuscript.

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