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A NEW COMPREHENSIVE METHODOLOGY FOR THE EVALUATION OF PRODUCT SUSTAINABILITY AT THE DESIGN STAGE OF CONSUMER ELECTRONICS PRODUCTS

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ABSTRACT OF THESIS

A NEW COMPREHENSIVE METHODOLOGY FOR THE EVALUATION OF PRODUCT SUSTAINABILITY AT THE DESIGN STAGE OF CONSUMER ELECTRONICS PRODUCTS

The aim of this thesis is to investigate and generate quantifiable measures of sustainability elements that apply to manufactured products in terms of environmental, social and economic benefits. This paper presents a new comprehensive methodology for sustainability evaluation of a new product at the design and development stage focusing on consumer electronics products through a “Sustainability Scoring” method. A new product is evaluated 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 to assess a given product in comparison with a similar product, such as a prior or a subsequent model, or one from a competitor. The proposed six major integral sustainable elements are: product’s environmental impact, societal impact, functionality, resource utilization and economy, manufacturability and recyclability/remanufacturability. Each of these elements has corresponding sub-elements and influencing factors which are categorized using appropriate weighting factors according to their relative importance to the product.

KEYWORDS: sustainable products, processes, design, manufacture.

Niranjali de Silva

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A NEW COMPREHENSIVE METHODOLOGY FOR THE EVALUATION OF PRODUCT SUSTAINABILITY AT THE DESIGN STAGE OF CONSUMER ELECTRONICS PRODUCTS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

Director: Dr. I. S. Jawahir, Professor of Mechanical Engineering

Lexington, Kentucky

2005
To my family
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CHAPTER 1
INTRODUCTION

This chapter introduces the current status of the electronics industry in the United States, and presents some of the challenges and obstacles they encounter regarding the disposal of electronic products while trying to implement “Sustainability”.

1.1 Sustainability

Sustainability is a frequently and carelessly used term across the world by researchers and corporations. According to the United Nation’s Brundtland commission (WBCD, 1987), sustainable development was defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”[1]. As responsible citizens, we must try to conserve our resources to provide for use by future generations to meet their needs and this adds pressure for OEMs (Original Equipment Manufacturers) to be cautious when designing and manufacturing products so that these products do not harm the environment, society or the economy.

Sustainable products are those products providing environmental, social and economic benefits while protecting public health, welfare, and environment over their full commercial cycle, from the extraction of raw materials to final disposition according to the Sustainable Products Corporation in Washington DC [2]. Although the concept of sustainability has been in practice worldwide over centuries, the application towards
consumer products has always been overshadowed by costs and extra efforts manufacturers have to encounter. But, with regulations implemented by federal and state governments, nationally and locally and by foreign countries, OEMs are beginning to understand the consequences of damage that could be caused by harmful chemical and hazardous materials which results from improper conduct of design, manufacture and disposal.

The idea of highlighting sustainability aspects and making the consumers aware of the potential harmful effects they contain is probably the most challenging in the current industry, but as sustainable products are known to be more profitable than non-sustainable products, by as much as ten times,[3] OEMs are showing a string of interest by making decisions to make their products ‘green’.

The need to incorporate sustainability into products and processes becomes evident when exploring the effects on the environment, economy and society (Figure 1.1). These three elements are the most widely used classification or grouping for sustainability. The three P’s commonly used for ‘People’, ‘Planet’ and ‘Profit’ also correspond to these same elements. Many researchers have studied the impacts on the environment and have conducted extensive research on manufacturing sustainable products by integrating environmental requirements at various stages of the manufacture [4].
Sustainable development is a significant aspect in our society today and many scholars are now attempting to build models for sustainable development to include all aspects of environment, society and economy. But what does sustainable manufacture, which concerns all products manufactured, correspond to? One such model was proposed by Jawahir and Wanigaratne [5], showing the integral role of sustainable development and sustainable manufacture in sustainable development by illustrating other relevant elements involved. It can be clearly observed from Figure 1.2 that sustainable development is a vital part since it is linked to environmental, economic and societal sustainability.
1.2 Product End-of-Life (EoL)

With the rapidly growing world population, the wastes created by humans are also increasing at an alarming rate. We as humans have come to rely on many electronics products to achieve a higher quality of life and new products are continuously by being produced at a faster rate to keep up with the increasing demand. Electronic products are becoming obsolete everyday for many reasons such as failure or the introduction of a new model, and at a faster rate as new products are introduced. The technological development is inevitable as shown in Figure 1.3 where the cycle times of the waves are getting shorter, as technological advancement rapidly increases [6]. An interesting question to answer is, what happens to the old consumer electronics that are obsolete?
In industry, electronic waste is called “E-waste”. There are millions of E-waste that ends up in landfills every year because of the growing technology. This is a growing concern for the manufacturers and also to the local and federal governments with legislations being imposed [7] as landfill and incineration is not an option for the disposal of these products for their many adverse effects on the environment. In this regard, sustainability plays a vital role in its premise to conserve resources for the future and design in manufacture of “green” products. However, the question is not only about the increasing landfills, but also the harmful contaminants that they contain such as lead, mercury, hexavalent chromium. For example, a single cathode ray tube (CRT) monitor can contain up to four pounds of lead on average [8]. Lead poisoning in children can lead to brain damage and nervous system disorder, behavior and learning problems, and even hypertension in adults. In 1998, 13 million computers became obsolete and only 13% was recycled [8].

Figure 1.3: The evolution of technology [6].
There has been significant demand and improvement in the EoL of electronics by OEMs, researchers and specially law makers in the last decade. The reason for this is mostly initiated by the European Union and Asian countries for their lack of land to be used for landfills. There are many regulations that are successfully implemented and also pending to be effective this year, and some of these regulations are discussed later in this chapter.

Although the concept of sustainable products has existed for long, it was only recently that researchers have realized the need and potential for this research and model development in sustainability. Among previously conducted research, environmental and economic models are commonly investigated and improved. The Sustainability Target Method (STM) is a model developed to show the relationship with the economic value of a product with the environmental impacts, which calculates indicators for Resource Productivity and eco-efficiency which leads to and end-of-life decisions [9]. There are also many models that only consider environmental effects at the design stage of a product development [10-11]. Recently, the traditionally known Life Cycle Assessments (LCA) methods have been modified and incorporated into the design stages of product development, but once again these methods concentrate almost entirely on environmental impacts [12-13]. Research is also focused on recyclability and disassembly of a product. Among the most prominent models are the ELDA (End-of-Life Design Advisor) created at Stanford University [14] and a Web-based Electronic Product Materials Recovery and Recycling Management System by Texas Tech University [15]. These models not only
help OEMs decide on a suitable end-of-life option for their products but recyclers also can determine the best available option for different product categories.

1.3 Regulations

The European Union (EU) has already realized the need for enforcing regulations for manufacturers to abide by the environmental standards when designing their products. Also, the EU has regulations on product take-back on vehicles etc., when the product life has terminated. With inspiration from the EU, the U.S. has also recently been interested in environmentally benign design and manufacture of products with product take-back options. However, this is not an easy task to accomplish. There are many factors that have to be taken into consideration before a manufacturer decides on a product take-back options and recycling methods.

1.3.1 European Union (EU) Directives

The EU has been issuing many directives with regard to disposal of electronics. The council on Waste Electrical and Electronic Equipment (WEEE) has approved the second directive on e-waste in their member states. According to the 2002/96/EC directive, the rate of recovery for computers and printers will be increased to a minimum of 75% by average weight per appliance and component material, and substance reuse and recycling will be increased to 50% by weight per appliance by the end of 2006 [16].
Another very important directive is the Restriction of Hazardous Waste (RoHS) Directive [17] where the electronic product has restrictions on using certain harmful chemical substances. The restricted substances on new electronics are, lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) to be effective as of July 2006.

Apart from the directives, some member countries in the European Union have certain standards the electronic products need to qualify to be on the market. One such standards is the Blue Angel certifications [18] implemented by Germany where it regulates the energy use, and minimizes the adverse effects on the environment.

1.3.2 United States

Although the United States has no federal regulations for all states, many states have implemented their own regulations for disposal of e-waste. Most of these states have a high density population and no landfill or waste treatment facilities. These individual state regulations and programs will help to set standards with environmental goals, policies, and priorities at the federal level as well as write flexible, health-based regulations that reflect ecological risks and environmental justice and to assist and assume leadership roles in environmental education [8].

In addition to the state efforts, the Environmental Protection Agency (EPA) has implemented many strategies in their efforts to eliminate landfill increase and to control the hazardous waste disposal. One of their acts is the Resource Conservation and
Recovery Act (RCRA) which regulates all this waste under the control of the Office of Solid Waste (OSW). Their primary goals are to protect the society from the hazards of waste disposal, conserve energy and natural resources by recycling and recovery, reduce or eliminate wastes, and clean up wastes, which may have spilled, leaked, or been improperly disposed [8].

Similar to the Blue Angel standards, the US also has the Energy Star certification administered by the EPA. This monitors the energy use of electronic products and currently many countries are participating in this certification [8].

1.4 Current Industry Practices

EPA has started their own campaign to increase electronics recycling awareness among consumers and manufacturers and to reduce electronics that contribute to municipal wastes each year. In January 2003 they launched “Plug-In To eCycling”, a program dedicated to collection and recycling of consumer electronics [8]. This program has been quite successful in relative terms with their collection programs and also involving manufacturers to take the responsibility for recycling their products.

EPA also has other environmentally friendly programs such as the Design for Environment (DfE) program where they work with industry, compare and improve the performance and human health and environmental risks and costs of existing and alternative products, processes, and practices [8].
The National Recycling Coalition (NRC) was founded in 1978 with the intention of resource conservation, solid waste reduction, environmental protection, energy conservation and social and economic development [19]. This non-profit organization has one of the most active recycling programs that reach out at the national level as well as at the state level. This organization also commits to educate the public and the manufacturers on the importance of recycling and related issues. Currently there are affiliated recycling coalitions located in 20 states in the United States, with each of these states implementing their own laws on e-waste and conducting appropriate collection programs aimed at reducing residential eWaste.

Even though there are many recycling methods, there may only be a few that are economically and socially acceptable. Currently, the two major methods used for electronics recycling are disassembly/reuse and shredding. With the disassembly option, the product is disassembled into components and remanufactured/reconditioned with some parts replaced, or parts are sold separately. The other option takes the total product and feeds into a shredder and the material is then separated. This is a common method that recyclers like to use because the shredded material can be sold once again as raw material. Although these options are popular, the best is a combination of the two, where the product is disassembled then shredded separately and sold as raw material.

At present Epson Corporation in Japan is employing this method as one of their product recycling methods. Atmix Corporation in Japan which is a part of Epson Group is one of the manufacturers of powder metal from recycling, which are then sold to
companies for injection molding etc. In their recycling process, disassembly and separation of the collected electronics products are performed first, then, the base materials are carried to Atmix where they are melted in high-frequency induction furnaces. Afterwards, using water atomization, the molten metal becomes a mixture of powder and metal and later the slurry is dried to separate the powder metal. This powder metal is sorted by particle size into different grades and shipped to buyers for reuse as raw material [20].

Epson is also taking other precautions in preserving the environment. They have achieved a Zero Emission Level 1, which is to achieve 100% recycling of their products by the end of FY2003. Their next target is to achieve Level 2 which is the reductions in total amount of waste emissions and a higher level of recycling. They expect to achieve a 40% reduction over FY2002 by FY2010.

There are also private companies in the Untied States who are contract recycling companies. One such company is Intercon Solutions in Chicago, Illinois. They work with many companies in recycling e-waste by collecting and shipping e-wastes to one of their facilities which include five other locations in the US and Canada, and disassemble and separate metals, plastics, etc., for raw material preparation [21].

Hewlett Packard (HP) in their efforts to comply with the upcoming EU initiatives has initiated design changes for their products. These changes will make the recycling process easier and environmentally friendly. Some of these changes are [22],
• Eliminating glues and adhesives from product construction by using snap-in features
• Marking plastic parts weighing more than 25 grams according to ISO 11469 international standards. This speeds up material identification during recycling
• Reducing the number and types of materials used in HP products
• Using single plastic polymers
• Using molded-in colors and finishes instead of paint, coatings or plating
• Relying on modular design for ease of disassembly of dissimilar recyclable materials

In addition to these companies, most corporations have their own e-waste collection programs, where some companies provide discounts for returning used cartridges, etc. What the public does not know is that sometimes the cost of recycling is already factored into the cost of a new cartridge, and therefore the consumer is paying for recycling costs. But this is not the case with all companies, and some companies such as DELL will charge you directly for returning used electronics.

1.5 Research Motivators

The importance of the types of assessments discussed in Section 1.3 is highlighted by the growing amount of electronic wastes and the concerns for the social and economic welfare of the future. In a society where everything is perceived by “numbers”, the need
to create indices and/or performance metrics to evaluate sustainability becomes important.

Although there are numerous sustainability assessment methods available today, there is a lack of comprehensive data accumulation and processing involving the different aspects of product development. The proposed procedure includes factors that make this more comprehensive than other models currently available and is designed for consumer electronics but with sufficient data it could be customized to other products. It is also a simplified scoring methodology where the inputs of the model consist of data that is available at a design stage of a product development and electronic manufacturers are in need of such models [23].
CHAPTER 2
LITERATURE REVIEW

This chapter will take a closer look at design elements contributing to the enhancement of product sustainability including a review of and previous work conducted by researchers on the end-of-life of consumer electronics products.

2.1 Summary of Previous Research Review

Although the subject of sustainability application in product design and manufacture has not yet been studied systematically, many scholars are attempting to build models or create indices and metrics for the measurement of sustainability. But, the preliminary understanding has to be that the traditional manufacturing and business imperatives have to transform to sustainable innovations. This is portrayed in Figure 2.1, where the traditional growth is shown in terms of shareholder value, and compared with the sustainable growth that needs to take place. Innovation-based sustainability could vary from efficient energy use to product management, and several key aspects are addressed by researchers with attempts to quantify this dynamic quality.

With regard to manufacturing, it also needs to transform from traditional manufacturing to sustainable manufacturing. An automobile life-cycle is shown in Figure 2.2 to depict the sustainable life-cycle, where the traditional life-cycle was only from the design cycle to the use cycle.
Figure 2.1: The business imperative of the concept of growth [24]

Figure 2.2: Automobile life cycle (adapted from [25])
While many measurable metrics involve environmental aspects, a variety of other sustainability measures are also emerging. The most common among these metrics are to measure the environmental “friendliness” or impacts. Among the prominent methodologies available today is the Life Cycle Assessment (LCA) method, where the total process of production is evaluated in terms of adverse environmental impacts with regard to material inventory, goals and scopes [6]. According to the ISO 14040, LCA techniques can be used to improve environmental impacts, to make strategic decisions in government, non-government and industry, and to make selection of relevant indicators and marketing [26]. LCA is a very quantitative analysis that requires many data from the full product cycle, and it only assesses the environmental impacts, but it has been proved that it is feasible to include sustainability elements such as socio-ecological principles and make it a more qualitative assessment [13].

Many companies use LCA software available today to assess the impacts of their products as part of the requirements on their sustainability reports. An example of software available today is GaBi4 software created by the University of Stuttgart and PE Europe GMBH, includes analysis of LCI (life-cycle inventory), cost, social and working environment models [27]. SimaPro, another similar software package produced by PRé Consultants, also provides users with overall environmental impacts from the full product life-cycle and a tool for product comparison for process improvements [28]. Another environmental impact assessment software created by PRé Consultants, is the Eco-Indicator 95, and Eco-Indicator 99, where a single score is available for each material
type to assess the environmental impact and a database of commonly used materials is given in IdeMat [29].

Another consideration of prominent environmental measure is ‘industrial ecology’, explained as an approach to the design of industrial products and processes that evaluates such activities through the dual perspective of product competitiveness and environmental interactions. This concept looks at systems in isolation, as well as in interaction with other systems, to evaluate sustainability in technological, economic, and cultural areas to optimize resources, energy and capital [6].

For electronics products, the end-of-life strategies and planning software, ELDA (End of Life Design Advisor) created by Stanford University is well known and it performs an excellent function. The ELDA will determine the appropriate end-of-life option for a given product after the evaluation of such factors such as external characteristics, material characteristics, disassembly, inverse supply chain and technical characteristics including the size, number of parts and wear-out-life [30]. Although this methodology could be used at the design stage, the final result is the recommended end-of-life option for the product, and does not depict any sustainable level of the product.

A similar Web-based program has also been created by the Advanced Manufacturing Lab at Texas Tech University to determine the recyclability and end-of-life options of consumer electronics products. This program takes into account six basic functions which are product disassembly, product recycling material assessment,
environmental impact assessment, product evaluation, and product and material information management, and it manages material recycling for the OEM [15].

2.2 Design for X

The design stage of product development is known to be the most critical part in determining the characteristics of a product, and therefore it is at this stage the major decisions are made to enhance the product value. The concept of Design for Environment (DFE) which is a technique for evaluating the environmental responsibility of products [31], has existed for quite some time, and researchers have extended this concept to incorporate sustainability ideas and concepts to formulate other aspect of product design. These design elements are represented as “Design for X” (DFX) where X can be any design attribute such as, assembly (A), compliance (C), disassembly (D), environment (E), material logistics and component applicability (MC), reliability (R), safety and liability prevention (SL), serviceability (S) and testability (T) [6]. Some of these research areas have been studied extensively and analyzed, and some areas are still not quantified or well established as science, and there seems to be some contradictions on the definition of DFX.

While some define DFX as above, independent of each factor, some attribute design elements into the “Design for Environment”. These are design for disassembly (DFD) and design for recycling (DFR) which deals with the end-of-life of products and incorporates modular design [32]. DFS is also associated with optimizing the interaction
between the environmental impacts and the economic implications for manufacture in sustainable development [33].

In Design for Disassembly (DFD), one of the key parameters to consider is the number of disassembly steps in order to get the product to a viable recycling condition. Graedel and Allenby [6] discuss how the disassembly and landfill costs are related in terms of the number of disassembly steps involved for a product to be recycled. They claim that to minimize end-of-life costs, a product has to have minimal disassemble steps or landfill becomes a financially preferable option as the disassembly cost increases. The main objective of DFD is to design a product to assure that the product carries an optimum disassembly sequence.

![Figure 2.3: Landfill and disassembly cost comparison [6]](image)

Design for Disassembly (DFD) is followed by Design for Recyclability (DFR) where the final stage of the product cycle translates into the next life of a product as
recycled material, is reused or used in remanufacturing. Some of the early works in this area includes a ‘recyclability map’ which was created to improve advance planning and tracking improvements in product families over several generations, robust design for recyclability and assessments of product designs under alternative recycling processes [34].

2.2.1 Design for Sustainability

The idea of Design for Sustainability (DFS) is that it uses all of the aspects affecting sustainability, namely environment, economy and society, and uses tools and methods on improving the current standards and measurable factors. The DFS is aimed at offering efficiency to the design process, focusing on reduction of materials, choosing the right and eco-friendly source of energy, optimizing and giving a more lasting capability for products and especially with designing for disassembly from the very early stage of product development [35]. This also means that in every step of product design and development, DFS has to be applied in order to achieve an optimum mix of sustainability measures in a product. One of the research initiatives at the University of Kentucky has been to extend the 3R concept (Reuse, Reduce and Recycle) into a more comprehensive and sustainable 6R concept (Recover, Reuse, Recycle, Redesign, Reduce and Remanufacture) (See Figure 2.4) [36]. This shows not only that the different design elements are associated with the life-cycle of a product, but also the realization that multi-life cycles can be associated with a single product.
When comparing DFS with traditional engineering design methodologies, it is evident that concurrent engineering takes a leading role. To successfully implement sustainability, it is not only the science that is needed, but also innovation in education and other disciplines such as economy and management [37]. Figure 2.5 shows that additional phases need to be added beyond the traditional product life-cycle phases needed for competing on ecology [38].
2.3 Sustainable Electronics Manufacture

By now it is well established that all products need to be sustainable to some level and the electronics industry is advancing with a great deal of effort with attempts to produce, ”green products” while obeying regulations.

A successful application for sustainability measures depends on the prior knowledge of the end-of-life path of each product or component [39]. Therefore, designers should be careful in choosing certain criteria in the early stages as they may have a larger impact on end-of-life options. Recently, consumer electronics
manufacturers have been emphasizing on recycling and remanufacturing as one of the most important stages in the sustainable product life-cycle. The most important considerations include interactions between the recyclers, designers, dealers and users so that every concern or problem can be addressed. A recycling process with focus on interactions is shown below in Figure 2.6 [39].

![Recycling process diagram](image)

Figure 2.6: Recycling process [39]

Although many manufacturers would like to claim that the landfill rate for their products is zero or minimal, consumers will contribute to landfill percentages across the world if they do not return the obsolete product for recycling.

Material selection is also one of the most important decisions a designer will make when designing a new product or modifying a current design. Villalba et al. [40] explains recyclability of a material by taking account of the value of recycled material as well as the properties lost or gained through a recycling process. The recyclability is defined by a the function of how much the material has gained its original properties from recycling using a devaluation function of how much properties the material lost after use.
2.4 Consumer Value

In recent years, OEMs have shown interest in consumers’ preferences and values placed on “green products”. Although consumers’ perceptions are thought to be subjective, surveys and questionnaires have been successful in discovering their basic needs. Models have been created to incorporate environmental requirements and cost estimation, relating to the consumers’ willingness to pay for products [41]. Certain guidelines have also been identified and established to produce and market “green products” that consumers would like to buy for OEMs. The research also shows the need and the importance of involving environmental stakeholders for their influence on consumer behavior, and also targets children as stakeholders for the future and emphasizes the importance of continuous education starting at an early stage [42]. More scientific studies that involve customer requirements have been introduced into sustainable manufacturing at various stages of product design. This includes energy and water usage, source volume recycling and reuse, waste and emission and recycled material [10].

There is also inadequate evidence that consumers will pay more for sustainable product than a product from a company that does not practice sustainability [43]. But, the main understanding has to be that scientists have to use marketing as a tool to get through to the consumer, if sustainability needs to be achieved [44].
CHAPTER 3
THE PROPOSED PRODUCT SUSTAINABILITY ASSESSMENT MODEL

This chapter describes the major elements and methodologies influencing the sustainable level of a product. Although this is for consumer electronics, it will fulfill most products in the absence of a comprehensive sustainability rating model. Also, major findings of a survey of consumer interest have been evaluated and integrated into the model for achieving fine results. A comparison of consumer ideas with the OEM results is later discussed in Chapter 4.

3.1 Assessment Criteria for Product Sustainability

Six major ‘Sustainability Elements’ have been identified and introduced in this model. These are Environmental Impact, Societal Impact, Functionality, Resource Utilization and Economy, Manufacturability and Recyclability/Remanufacturability [5] (see Figure 3.1). Each of these elements was further analyzed and a sub-element level was developed with influencing factors (see Table 3.1).

The need for introducing six elements that differ from the conventional three elements (Environment, Society and Economy) was to incorporate criteria for processes and systems that are significant in sustainability decision making. The 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.

![Figure 3.1: Six major sustainability elements](image)

According to Jawahir and Wanigaratne [5], many sub-elements have been identified stemming from the sustainability elements to assess product sustainability, but these sub-elements were refined to suit the consumer electronics product criteria. The descriptions of the six ‘new’ elements are given below. Each element contains ‘sub-elements’ that contribute to the assessment of each element, and similarly there are ‘influencing factors’ that contribute to the sub-elements (see Table 3.1).
Table 3.1: Elements and factors that contribute to the electronic product sustainability scoring methodology.

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

Being the most identified and quantified of all sustainability aspects, the environmental effects have caught the eyes of the consumers and OEMs in recent years. Today, almost all research involves ecological balance evaluations and global effects for the future. This parameter measures the emissions that results from the use of product and also toxic substances that may have been used in the manufacture of the product. Therefore, the two sub-elements contributing to this element are life-cycle factor and environmental effects. The life cycle factor is described to be the level of expectation for multi-life-cycles and the best level will be 1.

\[
Life\_cycle\_factor = k_1 \left[ RTE\_RCVRY \ast CST\_RCVRY \ast LIFE\_PTL \right]
\]

(3.1)

In the above equation, taking the terms on the right hand side of the equation and plotting against life-cycle factor, a best curve fitting can be used to determine what the constant \( k_1 \) should be. By using arbitrary values, a curve can be created to show the relationship of the life-cycle factor and the rate of recovery of the product and the
following graph can be presented. Figure 3.2 shows an approximate relationship between the life-cycle factor and the rate of recovery.

The best fit exponential curve can be expressed as,

\[ y = 1.3896e^{-1.4086x} \]  

This model is derived from fictional data therefore when there is actual data available the constants of the equation may change. But this is an example of the methodology that will be used to determine constants once empirical data is available. The generic equation for the relationship between life-cycle factor and rate of recovery will be,

\[ y_1 = A_1 e^{B_1 x_1} \]  

where, \( A_1 \) and \( B_1 \) will be decided upon empirical data.
In the next section of the equation, the cost of recovery has to be established with respect to the life-cycle factor. This relationship will also be an exponential function and therefore can be given as,

$$y_2 = A_2 e^{B_2 x_2}$$  

(3.4)

where $y$ is the life-cycle factor, $x$ is the cost of recovery and $A_2$ and $B_2$ are constants.

The next parameter, potential for the next life is a very subjective parameter. This is the value that will indicate if this product has the potential to have multi-life cycles. The curve fitting for this function is a linear model.

![Life-cycle factor vs. potential for next life](image)

Figure 3.3: Life cycle factor and potential for life relationship

As seen in the above figure, the best fit curve is a first order polynomial

$$y = 0.333x$$  

(3.5)

With empirical data, the equation will be
\[ y_3 = C_3x_3 \]  

(3.6)

Now the life-cycle factor equation can be rewritten as, with a coefficient for the equal weighting of the influencing factors.

\[
\text{Life\_cycle\_factor} = \frac{1}{3} \left[ A_1 e^{-B_1x_1} + A_2 e^{-B_2x_2} + C_3x_3 \right] 
\]  

(3.7)

The environmental effect is derived from the influencing factors, emissions and toxic substances in the product.

\[
\text{Environmental\_effects} = k_2 \left[ \text{EMSN} \ast \text{TXC\_SUB} \right] 
\]  

(3.8)

The equation for environmental effects can also be established similarly using the best curve fit method.

For both emissions and toxic substances, the curve from Figure 3.2 can be used and rewritten as

\[ y_4 = A_4 e^{-B_4x_4} \]  

(3.9)

\[ y_5 = A_5 e^{-B_5x_5} \]  

(3.10)

where \( x_4 \) and \( x_5 \) are the emission and toxic substances included and \( y_4 \) and \( y_5 \) are the corresponding environmental effects. \( A_4, A_5, B_4, B_5 \) are constants derived from empirical constants.

The final equation for environmental effects will be,

\[
\text{Environmental\_effects} = \frac{1}{2} \left[ A_4 e^{-B_4x_4} + A_5 e^{-B_5x_5} \right] 
\]  

(3.11)
3.1.2 Product’s Societal Impact

Health and safety are two very important aspects of societal impacts where human factors are involved. This element includes the consumers’ well being as well as the operational and manufacturing safety of the people involved. The ethical responsibility the OEMs regarding to their products such as take-back options, or using and maintaining the proper conduct of production are regarded as societal impact. As policy makers are becoming aware of the importance of social well being, new laws and regulations are rapidly being proposed and enforced. This aspect is important to measure the humanity incorporated when manufacturing and marketing products.

\[ Ethical \_ \text{responsibility} = k_3 [TKBK \_ \text{OPT} * PROD \_ \text{PRC}] \] (3.12)

Take-back option is measured by the amount of products OEMs are able to take back and live up to the expectation of the consumer. Therefore, this also takes the same trend as Figure 3.3, and acts as a linear function between the ethical responsibility and the take-back option.

\[ y_6 = C_6 x_6 \] (3.13)

where \( y_6 \) is the ethical responsibility and \( x_6 \) is the take back amount.

The product price is best kept as low as possible for the satisfaction of the consumer and also it is the responsibility of the OEM to keep the price low. Therefore, the best fit curve will be as shown in Figure 3.4.
From the trend line the following equation can be formulated.

\[ y = -0.25x + 1 \]  \hspace{1cm} (3.14)

The generic form will be as equation 15 where \( y_7 \) will be the ethical responsibility and \( x_7 \) will be the product price. \( C_7 \) is the constant, which will be a negative value.

\[ y_7 = -C_7x_7 + 1 \]  \hspace{1cm} (3.15)

Societal impact itself becomes a sub-element of the element Societal Impact because the influencing factors, safety and quality of life directly relate to it. Here the societal impact is measured to be negative, and therefore for both influencing factors it is best kept low.

\[\text{Societal}_{\text{impact}} = k_4[SFTY * QLITY _LIFE] \]  \hspace{1cm} (3.16)

The influencing factors follow the trend from Figure 3.3, where \( y_8 \) and \( y_9 \) are the societal impacts, \( x_8 \) and \( x_9 \) are safety and quality of life respectively, and \( C_8, C_9 \) are constants.

\[ y_8 = C_8x_8 \]  \hspace{1cm} (3.17)

\[ y_9 = C_9x_9 \]  \hspace{1cm} (3.18)
The final equation for the sub-element “Societal Impact” will be,

\[
Societal\_impact = (1/2) [C_{8x8} + C_{9x9}] 
\]  
(3.19)

### 3.1.3 Product Functionality

One of the important aspects for consumers and OEMs both is the functionality of the product. This element includes the evaluation of many functional aspects as modularity, upgradeability and ease of use but also measures the reliability, maintainability which helps prolong the life of the products with effective functionality. This element was added to enhance the sustainability elements, but to enforce that the functionality of a product cannot be compromised when other elements are applied.

\[
Reliability = k_3 [TYPE\_MAT \times MNTCE] 
\]  
(3.20)

The sub-element reliability is the function of type of material and the maintenance the product needs to be effectively functional. The type of material that will be discussed later under the Resource Utilization and Economy element considers the environment, aspects of the material, and since the reliability does not depend on the environmental the material’s strength has to be included for this parameter. But since the OEMs are required to use materials which have qualified strengths, this can be eliminated from the equation. Therefore the Reliability sub element will only depend on maintenance, which will take the best fit curve as Figure 3.2.

\[
y_9 = A_9 e^{-B_9 x_9} 
\]  
(3.21)

\[
Reliability = A_9 e^{-B_9 x_9} 
\]  
(3.22)
Service life also depends on the maintenance of the product and takes the same form as equation 21.

\[
\text{Service Life} = k_6[MNTCE] \\
y_{10} = A_{10} e^{-B_{10}x_{10}} \\
\text{Service Life} = A_{10} e^{-B_{10}x_{10}}
\]  

The upgradeability has two influencing factors, upgrade option and the installation. The upgrade option will be determined by the number of options available, such as memory slots, USB ports.

\[
\text{Upgradeability} = k_7[UPGD_OPT \ast INSTL]
\]  

The upgrade options will take the form of Figure 3.3, where the more options available the upgradeability will be higher.

\[
y_{11} = C_{11}x_{11}
\]  

The installation is subjective and will be measured by the level of difficulty with 0 being the easiest to install and 10 being the most difficult. The best fit curve will be as Figure 3.4.

\[
y_{12} = -C_{12}x_{12} + 1
\]  

The final equation for upgradeability is,

\[
\text{Upgradeability} = (1/2) [C_{11}x_{11} - C_{12}x_{12} + 1]
\]  

The next sub-element modularity solely depends on the modules available for the product. Therefore the trend is similar to Figure 3.3.

\[
\text{Modularity} = k_8[MODTY]
\]
\[ y_{13} = C_{13}x_{13} \]  
(3.31)

\[ Modularity = C_{13}x_{13} \]  
(3.32)

Ergonomics for this product depends on the safety of the consumer, and production ergonomics is not accounted for here.

\[ Ergonomics = k_{s}[SFTY] \]  
(3.33)

This also takes the same form as Figure 3.3 and can be shown as the equations below.

\[ y_{14} = C_{14}x_{14} \]  
(3.34)

\[ Ergonomics = C_{14}x_{14} \]  
(3.35)

The last sub-element in the Functionality element is maintainability, which depends on the maintenance of the product. Therefore, it takes the same form as reliability above.

\[ Maintainability = k_{10}[MNTCE] \]  
(3.36)

\[ y_{15} = A_{15}e^{B_{15}x_{15}} \]  
(3.37)

\[ Maintenance = A_{15}e^{B_{15}x_{15}} \]  
(3.38)

### 3.1.4 Product’s Resource Utilization and Economy

Resource utilization can be divided into two parts which are environmental effects resulting from extraction to use, and also the economics involved. The reason for the resource utilization to be merged into the same element as economy, was that the common unit resources measured are in monetary values, and therefore considered in the
The energy efficiency depends on the energy for the production, use and recycling of the product.

\[
\text{Energy efficiency} = k_{11} \left[ \text{PROD}_\text{EGY} \times \text{USE}_\text{EGY} \times \text{RCY}_\text{EGY} \right] \tag{3.39}
\]

All three energy types take the form of Figure 3.4 where the less energy consumption is efficient.

\[
y_{16} = - C_{16}x_{16} + 1 \tag{3.40}
\]

\[
\text{PROD}_\text{EGY} = - C_{16}x_{16} + 1 \tag{3.41}
\]

\[
\text{USE}_\text{EGY} = - C_{17}x_{17} + 1 \tag{3.42}
\]

\[
\text{RCY}_\text{EGY} = - C_{18}x_{18} + 1 \tag{3.43}
\]

\[
\text{Energy efficiency} = \frac{1}{3} \left[ - C_{16}x_{16} - C_{17}x_{17} - C_{18}x_{18} + 3 \right] \tag{3.44}
\]

The material utilization is dependent on the type of material, quantity and cost. The type of material uses data from the eco-indicator 95 values, which implies the environmental impact from that material [28].

\[
\text{Material utilization} = k_{12} \sum_{i=1}^{n} \left[ \text{eco_indicator_value} \times \text{QTY}_\text{MAT} \times \text{CST}_\text{MAT} \right] \tag{3.45}
\]

where \( i = \text{TYPE}_\text{MAT} \)

The quantity of the material has to be multiplied by the eco-indicator 95 value to get the environmental impact for any material.

The cost of material follows the trend as Figure 3.3.
\[ y_{19} = C_{19}x_{19} \] (3.46)

\[ CST\_MAT = C_{19}x_{19} \] (3.47)

Material\_utilization = \frac{1}{2} \left[ \sum_{i=1}^{n} \text{eco\_indicator} \times \text{QTY\_MAT} \right] + C_{19}x_{19} \] (3.48)

The renewable source of energy sub-element measures the options available for the use of other energy sources. The best fit curve is as Figure 3.3.

\[ \text{Renewable\_energy} = k_{13}[\text{RNW\_EGY}] \] (3.49)

\[ y_{20} = C_{20}x_{20} \] (3.50)

\[ \text{Renewable\_energy} = C_{20}x_{20} \] (3.51)

For a product to be sustainable in the market the price has to remain low, or somewhat reasonable from the consumer’s point of view. Therefore the market value will take the form of the trend line in Figure 3.4.

\[ \text{Market\_value} = k_{14}[\text{MKT\_PRC}] \] (3.52)

\[ y_{21} = -C_{21}x_{21} + 1 \] (3.53)

\[ \text{Market\_value} = -C_{21}x_{21} + 1 \] (3.54)

The final sub-element in the resource and utilization element is the operational cost. Any cost has to be kept low for a product to be sustainable, and therefore will be similar to Figure 3.4.

\[ \text{Operational\_cost} = k_{15}[\text{CST\_OPR}] \] (3.55)

\[ y_{22} = -C_{22}x_{22} + 1 \] (3.56)

\[ \text{Operational\_cost} = -C_{22}x_{22} + 1 \] (3.57)
3.1.5 Product’s Manufacturability

This is an element where the consumer is least familiar with. The sub-elements include manufacturing methods, packaging, assembly, transportation and also storage of products. Although this element has not gained much popularity among the consumers, it is an important element for the OEMs as they have to minimize costs in this area to earn profits, and also to practice proper conduct of operations.

Packaging sub-element is compromised by the take-back options, packaging material and the quantity of packaging material used. The new EU regulations coming into effect will require that OEMs take-back the packaging that was used for the original packaging.

\[
\text{Packaging} = k_{16} [\text{TKBK\_OPT} \cdot \text{PKG\_MAT} \cdot \text{QTY\_PKGMAT}] 
\]

(3.58)

The take-back option is measured by the level of commitment from the OEM. Therefore it follows the trend as Figure 3.3.

\[
y_{23} = C_{23}x_{23} 
\]

(3.59)

\[\text{TKBK\_OPT} = C_{23}x_{23} \]

(3.60)

The packaging material quality is measured by the amount of recycled material used in packaging.

\[
y_{24} = C_{24}x_{24} 
\]

(3.61)

\[\text{PKG\_MAT} = C_{24}x_{24} \]

(3.62)

The quantity of the packaging material is best kept minimum.
$y_{25} = -C_{25}x_{25} + 1$  \hspace{1cm} (3.63)

$QTY_{PKGMAT} = -C_{25}x_{25} + 1$  \hspace{1cm} (3.64)

Packaging = $(1/3) [C_{23}x_{23} + C_{24}x_{24} \times (-C_{25}x_{25} + 1)]$  \hspace{1cm} (3.65)

Although there are many aspects that affect the assembly operation, only the number of parts is considered for the product. The best fit curve is similar to Figure 3.4.

$$Assembly = k_{17} [NUM \_PTS]$$  \hspace{1cm} (3.66)

$y_{26} = C_{26}x_{26} + 1$  \hspace{1cm} (3.67)

$NUM\_PTS = -C_{26}x_{26}+1$  \hspace{1cm} (3.68)

$Assembly = -C_{26}x_{26} + 1$  \hspace{1cm} (3.69)

The cost of transportation is similar to Figure 3.2.

$$Transportation = k_{18} [CST \_TSP]$$

$Y_{27} = A_{27} e^{-B_{27}x_{27}}$  \hspace{1cm} (3.70)

$Transportation = A_{27} e^{-B_{27}x_{27}}$  \hspace{1cm} (3.71)

The storage factor depends on the cost and time of storage.

$$Storage = k_{19} [CST \_STRG \times TIME \_STRG]$$

$Y_{28} = A_{28} e^{-B_{28}x_{28}}$  \hspace{1cm} (3.72)

$CST\_STRG = A_{28} e^{B_{28}x_{28}}$  \hspace{1cm} (3.73)

$Y_{29} = A_{29} e^{-B_{29}x_{29}}$  \hspace{1cm} (3.74)

$TIME\_STRG = A_{29} e^{B_{29}x_{29}}$  \hspace{1cm} (3.75)

$Storage = (1/2) [A_{28} e^{-B_{28}x_{28}} + A_{29} e^{-B_{29}x_{29}}]$  \hspace{1cm} (3.76)
3.1.6 Product’s Recyclability/ Remanufacturability

The last of the six elements, which is also most important in end-of-life strategy, is the recyclability and/or the remanufacturability of products. The disassembly, recycling methods, reuse are measures associated with recycling and remanufacturing. This element is important to the third party recyclers who need to optimize their recycling capabilities and processes as the demand increases.

\[ \text{Recyclability} = k_{30} \left[ \text{CST}_{RCY} \times \text{RCY}_{EGY} \times \text{MTD}_{RCY} \times \text{TYPE}_{MAT} \times \text{SPRB} \times \text{VAL}_{RCYMAT} \right] \]

(3.77)

Since the cost of recycling is high for smaller amount of recycling, and low for a higher amount of products Figure 3.2 is chosen for the best fit curve.

\[ \text{CST}_{RCY} = A_{30} e^{B_{30}x_{30}} \]

(3.78)

The method of recycling is based on the products separation before shredding. As shredding is an economically feasible practice, many recyclers prefer shredding the total product. But this method degrades the quality of the shredded material value, especially in plastics. Therefore it is best to separate before shredding. This function is similar to an exponential function as shown in Figure 3.5.
The equation of the function is

\[ y = 0.0012e^{1.4086x} \]  

(3.79)

In generic form it can be shown as

\[ y_{31} = A_{31} e^{B_{31}x_{31}} \]  

(3.80)

\[ MTD\_RCY = A_{31} e^{B_{31}x_{31}} \]  

(3.81)

The type of material considered here for the recyclability is mainly are materials that are hard to recycle. But, since in electronics everything can be recycled by shredding, this can be eliminated. The separability is the amount of time taken to separate the material from the product, if it is being separated before shredding. This is a linear function and will be as follows.

\[ SPRB = -C_{31}x_{31} + 1 \]  

(3.82)
Next, the value of the recycled material is measured by the value that the material loses by recycling. This is measured by the price of recycled material against the price of the virgin material.

\[
Recyclability = \frac{1}{5} [A_{30}e^{B_{30}x_{30}} - C_{18}x_{18} + A_{31}e^{B_{31}x_{31}} - C_{31}x_{31} + 2 + VAL_{RCYMAT}]
\]

\[(3.83)\]

A disposal option is a key factor contributing to the disposability sub-element. It could also be seen as linear as Figure 3.3 since having more disposable options will be better.

\[
Disposability = k_{21}[DIS\_OPT]
\]

\[(3.84)\]

\[
Disposability = C_{32}x_{32}
\]

\[(3.85)\]

Remanufacturability depends on the number of recovered parts that are not recycled. This is also a linear scale since remanufacturability will increase if more parts are recovered.

\[
Remanufacturability = k_{22}[NUM\_RCVPTS]
\]

\[(3.86)\]

\[
Remanufacturability = C_{33}x_{33}
\]

\[(3.87)\]

The disassembly function is the same as the assembly function with the number of parts as influencing factors.

\[
Disassembly = k_{33}[NUM\_PTS]
\]

\[(3.88)\]

\[
Disassembly = -C_{34}x_{34} + 1
\]

\[(3.89)\]
The final sub element is the recovery of materials where the recovery from parts/components is assessed. There are two factors influencing which are number of parts and the type of materials they contain.

\[
\text{Recovery of materials} = k_{24}[\text{NUM } \times \text{PTS } \times \text{TYPE } \times \text{MAT}]
\] (3.90)

The number of pars will be a linear function against the sub-element and the type of material is only used if the material is valuable and can be substituted by the value of recycled material.

3.2 Methodology

This section discusses the method of identifying and quantifying the criteria and influencing factors mentioned in Section 3.1. It is a simple methodology that enables the manufacturers to assess the sustainability according to their preferences and importance of their product. After the factors have been grouped appropriate weight will be given to prepare for the final stages of the assessment.

With the above elements, sub elements and 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 3.6. The inputs of the model consist of data available at a design stage of a product development 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 3.1). This index will represent the six elements
individually to give a better understanding of the product’s relationship with sustainability.

![Figure 3.6: A New framework for product sustainability model](image)

3.2.1 Grouping

After all the sustainability assessment criteria and their corresponding influencing factors have been identified, a further selection is needed for refining the model. The sub-elements can be categorized in order of importance. The influencing factors can be categorized into three areas as high, medium and low importance. This method of grouping will simplify the model and also any other influential elements can be eliminated or added relating to sustainability.
3.2.2 Scoring Methodology

While the grouping can be subjective and customizable, the scoring methodology can be applied and evaluated for any variation of grouping.

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 were be 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 3.1. 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 [44] and also important regulations [17-18] that are in or will be in effect. Some of the measures from the directives include hazardous substances that need to be eliminated by July 2006 [17] and recycling and recovery standards that need to be achieved by December 2006 [18]. This is a critical issue as OEMs need to be ready to implement these standards if they market their products in the European Union.

3.2.3 Weighting

Weighting is an important part of this model as it is used for the refinement of data used to create the index. Currently there are no specific standards available and therefore it is applied with the information from OEMs and consumers relative importance to these elements and sub-elements.
3.3 Consumer Oriented Model

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.

Although sustainable products are considered to be more profitable, it is the consumer who has the final decision in purchasing the product, to make the products
profitable. The OEMs have to market the “green” products to suit the consumer’s preference to have a better market.
Table 3.2: Consumer survey

Survey on Choosing Consumer Electronics Products

<table>
<thead>
<tr>
<th>How important are these factors to you when you purchase consumer electronics?</th>
<th>Ranking 0-10 (0-Not important, 10-Very important)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Environmentally friendly/ &quot;Green&quot; product</td>
<td></td>
</tr>
<tr>
<td>2 High life cycle factor (useful life span)</td>
<td></td>
</tr>
<tr>
<td>3 Low toxicity</td>
<td></td>
</tr>
<tr>
<td>4 Low greenhouse gas emissions</td>
<td></td>
</tr>
<tr>
<td>5 Does not disturb ecological balance and efficiency</td>
<td></td>
</tr>
<tr>
<td>6 Safety</td>
<td></td>
</tr>
<tr>
<td>7 Improves quality of life</td>
<td></td>
</tr>
<tr>
<td>8 Durability</td>
<td></td>
</tr>
<tr>
<td>9 Modularity (if applicable)</td>
<td></td>
</tr>
<tr>
<td>10 Ease of use</td>
<td></td>
</tr>
<tr>
<td>11 Easy maintenance</td>
<td></td>
</tr>
<tr>
<td>12 Upgradeability (if applicable)</td>
<td></td>
</tr>
<tr>
<td>13 Reliability</td>
<td></td>
</tr>
<tr>
<td>14 Functional effectiveness</td>
<td></td>
</tr>
<tr>
<td>15 Low energy consumption</td>
<td></td>
</tr>
<tr>
<td>16 Use of renewable source of energy</td>
<td></td>
</tr>
<tr>
<td>17 Use of environmentally friendly materials</td>
<td></td>
</tr>
<tr>
<td>18 Low Price</td>
<td></td>
</tr>
<tr>
<td>19 Low Installation cost (if applicable)</td>
<td></td>
</tr>
<tr>
<td>20 Low supply cost (if applicable; such as ink cartridges)</td>
<td></td>
</tr>
<tr>
<td>21 The product can be recycled</td>
<td></td>
</tr>
<tr>
<td>22 Appropriate disposal available at the end of useful life</td>
<td></td>
</tr>
<tr>
<td>23 Reusability</td>
<td></td>
</tr>
<tr>
<td>24 Size/Weight</td>
<td></td>
</tr>
<tr>
<td>25 Brand name</td>
<td></td>
</tr>
<tr>
<td>26 How many consumer electronics did you purchase this year? (List number)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Other concerns: (please rank)</td>
<td></td>
</tr>
</tbody>
</table>
The above consumer survey was developed to capture the needs of the consumer regarding electronics products and it was the “pilot run” and also the inspiration for future work at UK. After the survey was completed the questions were categorized into the six sustainability elements as shown below.

*Environmental impact: Questions 1-5*

*Societal impact: Questions 6, 7*

*Functionality: Questions 8-14*

*Resource utilization & economy: Questions 15-20*

*Recyclability/ remanufacturability: Questions 21-23*

At the completion of the survey the results showed that consumers were more interested in societal, which included the safety and improvement of quality of life, and the functionality of the product than environment or recyclability. Resource utilization and economy was also ranked third where the price of the product was questioned.
By using the data gathered from the consumer survey, a new model can be formulated to use both consumer and OEM weighting and comparing the results. This model is a variation of the previous model in Figure 3.7.
Figure 3.9: Flowchart to compare the OEM and consumer models

By using this model a comparison can be made to estimate the OEMs expectations and the consumer’s expectations. The next chapter will demonstrate the comparisons in detail.
CHAPTER 4

CASE STUDY

This chapter explains the application of the model developed in Chapter 3 on a laser printer produced by Lexmark International Inc. Also, the consumer-oriented model discussed in Chapter 3.3 is compared with the OEMs feedback.

4.1 Lexmark’s Product Sustainability Model

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 this was 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 4.1 shows an approximate procedure adopted for the proposed sustainability scoring method.
Table 4.1 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:
Table 4.1: The proposed Lexmark method for the evaluation of product sustainability.

<table>
<thead>
<tr>
<th>High Importance Sub-elements</th>
<th>Influencing Factors</th>
<th>Method of Quantifying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency</td>
<td>Energy for use</td>
<td>Average power consumption of the printer</td>
</tr>
<tr>
<td>Material utilization</td>
<td>Type of material</td>
<td>Group materials and use eco indicator-99 values [45]</td>
</tr>
<tr>
<td></td>
<td>Quantity of material</td>
<td>Weight of each material group</td>
</tr>
<tr>
<td>Life-cycle factor</td>
<td>Recovery cost</td>
<td>Cost per kilogram of recovery</td>
</tr>
<tr>
<td></td>
<td>Potential life of printer</td>
<td>Assumed number of functional years of printer</td>
</tr>
<tr>
<td>Environmental effects</td>
<td>Toxic substances</td>
<td>RoHS directive restrictions [17]</td>
</tr>
<tr>
<td></td>
<td>Emission</td>
<td>CO₂ emissions during the use of printer</td>
</tr>
<tr>
<td>Recyclability</td>
<td>Cost of recycling</td>
<td>Cost per kilogram of recovery</td>
</tr>
<tr>
<td></td>
<td>Recycling method</td>
<td>Percentage of separation before shredding</td>
</tr>
<tr>
<td></td>
<td>Separability</td>
<td>Amount of time to separate material in printer</td>
</tr>
<tr>
<td></td>
<td>Value of recycled material</td>
<td>Market price of recycled material</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Medium Importance Sub-elements</th>
<th>Influencing Factors</th>
<th>Method of Quantifying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>Type of material</td>
<td>Group materials and use eco indicator-99 values [45]</td>
</tr>
<tr>
<td></td>
<td>Maintenance Schedule</td>
<td>Level of maintenance</td>
</tr>
<tr>
<td>Service life/ Durability</td>
<td>Maintenance Schedule</td>
<td>Level of maintenance</td>
</tr>
<tr>
<td>Ethical responsibility</td>
<td>Take-back options</td>
<td>Availability of a take-back option</td>
</tr>
<tr>
<td></td>
<td>Product Pricing</td>
<td>Price of printer</td>
</tr>
<tr>
<td>Packaging</td>
<td>Take-back options</td>
<td>Availability of a take-back option</td>
</tr>
<tr>
<td></td>
<td>Packaging material</td>
<td>Percentage of recycled material included in packaging</td>
</tr>
<tr>
<td></td>
<td>Quantity used</td>
<td>Kilogram value of packaging material</td>
</tr>
<tr>
<td>Upgradeability</td>
<td>Ease of installation</td>
<td>Level of installation</td>
</tr>
<tr>
<td></td>
<td>Option for upgrade</td>
<td>Option to install upgrades such as USB port, memory slot.</td>
</tr>
</tbody>
</table>
**Energy efficiency:** measured by the use of power consumption of the printer and the average value is set to be 80Wh. The power consumption function was assumed to be linear and the following equation can be formulated, where the power used is $use_{ergy}$ and the index for the sub-element is $index_{use_{ergy}}$.

\[ index_{use_{ergy}} = (-1/40) * use_{ergy} + 2.5 \] (4.1)

**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 from the used materials. A list of commonly used materials at Lexmark and their corresponding eco-indicator 95 values are shown in Table 4.2.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Eco-indicator 95 (mPt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plastics:</strong></td>
<td></td>
</tr>
<tr>
<td>Noryl</td>
<td>N/A</td>
</tr>
<tr>
<td>High Impact Polystyrene</td>
<td>7.35</td>
</tr>
<tr>
<td>(HIPS)</td>
<td></td>
</tr>
<tr>
<td>Polypropylene</td>
<td>2.81</td>
</tr>
<tr>
<td>Polyethylene LDPE</td>
<td>3.3</td>
</tr>
<tr>
<td>HDPE</td>
<td>2.78</td>
</tr>
<tr>
<td>ABS</td>
<td>5.41</td>
</tr>
<tr>
<td><strong>Metals:</strong></td>
<td></td>
</tr>
<tr>
<td>Zinc plated sheet steel</td>
<td>12.2</td>
</tr>
<tr>
<td>304 Steel</td>
<td>23</td>
</tr>
<tr>
<td>316 Steel</td>
<td>24.6</td>
</tr>
<tr>
<td>Aluminum 6060</td>
<td>20.7</td>
</tr>
</tbody>
</table>

\[ index_{mat_utilization} = \sum (weight * eco-indicator 95value) \] (4.2)
**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. The maximum number of functional years for a printer denoted by $life_{ptl}$ is set at 5 years, and the recovery cost denoted by $rcvyr_{cst}$ is set at $1.00 per kg of material.

\[
rcvry_{cst} = \frac{\text{weight} \times 1}{\text{prod}_{\text{prc}}}
\]  \hspace{1cm} (4.3)

\[
index\_life\_cycle\_factor = \frac{(1/6)\times life_{ptl} + rcvry_{cst}}{2}
\]  \hspace{1cm} (4.4)

**Environmental effects:** considers only the direct environmental effects by the use of printer, such as emissions which is measured by CO$_2$ output of the printer. The CO$_2$ emissions are calculated in comparison to the values in 1995 (HP compares with 1995, Canon compares with 1990), and is denoted by $ems$ which is the reduction of CO$_2$ emissions since 1995. Also this sub-element includes the evaluation for restricted hazardous material as required by the RoHS directive.

\[
enviro\_effects = ems + \text{inclusion of hazardous material}
\]  \hspace{1cm} (4.5)

**Recyclability:** measures all aspects related with recycling the printer at the end-of-life. This includes the cost, separability ($sprb$) 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 denoted by $cst_{rcymat}$ is measured against the non-recycled virgin material ($cst_{mat}$) for comparison of lost value. The index for recycled material is calculated by the sum of all lost value of materials, used in the product.
\[ \text{index}_\text{sprb} = (-1/8) \times \text{sprb} + 1 \quad (4.6) \]

\[ \text{index}_\text{val}_\text{rcymat} = \sum \frac{\text{cst}_\text{rcymat}}{\text{cst}_\text{mat}} \quad (4.7) \]

\[ \text{index}_\text{recyclability} = \frac{\text{index}_\text{sprb} + \text{val}_\text{rcymat}}{2} \quad (4.8) \]

**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 toner cartridge change, the input is simply reduced to a yes/no attribute criterion.

\[ \text{index}_\text{reliability} = \frac{\text{mtnce} + \text{index}_\text{mat}_\text{utilization}}{2} \quad (4.9) \]

**Service life/ Durability:** includes maintenance schedule.

\[ \text{index}_\text{service}_\text{life} = \text{mtnce} \quad (4.10) \]

**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 price where it is compared with the current market price of a similar product.

\[ \text{index}_\text{tkbk}_\text{opt} = \text{tkbk}_\text{opt} \quad (4.11) \]

\[ \text{index}_\text{prod}_\text{prc} = \frac{\text{mkt}_\text{prc}}{\text{prod}_\text{prc}} \quad (4.12) \]
\[ \text{index_ethical_responsibility} = \frac{\text{index_tkbk_opt} + \text{index_prod_prc}}{2} \]

(4.13)

**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.

\[ \text{index_pkg_mat} = \frac{\text{pkg_mat}}{100} \]

(4.14)

**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.

\[ \text{index_upgd_opt} = \frac{\text{instl*upgd_mtd}}{100} \]

(4.15)

The influencing factor’s and sub-element’s relationships for high and medium importance are shown in Figures 4.2 and 4.3. These figures are a good representation to show that influencing factors contribute to more than one sub-element.
Figure 4.2: High importance sub-elements and influencing factors
Figure 4.3: Medium importance sub-elements and influencing factors
After the relevant product’s sustainability data is collected, compiled and used, the influencing factors are calculated, and then appropriate weighting had to be applied to formulate the product’s sustainability level. There are two stages where weighing is applied to the model (Figure 4.1), once at the sub-element level, and after reaching the importance category selection level. The weighting for the sub-element level was determined by the design and environment teams’ relative importance, largely reflecting their extensive practical product design experience (see Table 4.3, Figures 4.4 and 4.5). As seen in these figures, 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.

Table 4.3: OEM survey results on weighting for high and medium categories

<table>
<thead>
<tr>
<th>High Importance</th>
<th>Weighting (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency</td>
<td>29</td>
</tr>
<tr>
<td>Material utilization</td>
<td>20</td>
</tr>
<tr>
<td>Life-cycle factor</td>
<td>13</td>
</tr>
<tr>
<td>Environmental effects</td>
<td>19</td>
</tr>
<tr>
<td>Recyclability</td>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Medium Importance</th>
<th>Weighting (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>27</td>
</tr>
<tr>
<td>Service life/ Durability</td>
<td>22</td>
</tr>
<tr>
<td>Ethical responsibility</td>
<td>16</td>
</tr>
<tr>
<td>Packaging</td>
<td>21</td>
</tr>
<tr>
<td>Upgradeability</td>
<td>14</td>
</tr>
</tbody>
</table>
By using the weighing 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 \times 29) + (material Utilization Index \times 20) + (Life-cycle Factor Index \times 13) + (Environmental Effects \times 19) + (Recyclability \times 19) 

(4.16)

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

(4.17)

The next level of the flow chart includes the weighing criteria for the ‘high’ and ‘medium’ categories by the relative importance as provided to us by our industry partners. Therefore the final evaluation will be evaluated as:

Total Product Score = (High Importance Category Index \times 70\%) + (Medium Importance Category Index \times 30\%) 

(4.18)

The achieved results can be considered acceptable in that it shows that the Lexmark laser printers in general are well within the sustainable product scoring range and that with a few changes, the product could achieve a better index.

The calculations were formulated using Visual Basic on Microsoft Excel and is shown below. The input table is shown in figure 4.6 and Figures 4.7, 4.8 are the calculations for the index for two different products.
### Sustainable Product Index

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Product 1</th>
<th>Product 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy for use (Wh)</td>
<td>70</td>
<td>75</td>
</tr>
<tr>
<td>Quantity of material (kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Impact Polystyrene</td>
<td>2.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1.00</td>
<td>0.20</td>
</tr>
<tr>
<td>Polyethylene LDPE</td>
<td>2.00</td>
<td>3.00</td>
</tr>
<tr>
<td>HDPE</td>
<td>2.00</td>
<td>5.00</td>
</tr>
<tr>
<td>AES</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Noryl</td>
<td>0.00</td>
<td>0.20</td>
</tr>
<tr>
<td>Sheet Metal</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Zinc plated sheet steel</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Steel 304</td>
<td>1.40</td>
<td>0.50</td>
</tr>
<tr>
<td>Steel 314</td>
<td>2.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Aluminum 6060</td>
<td>0.40</td>
<td>0.30</td>
</tr>
<tr>
<td>Number of potential functional years</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Weight of printer (kg)</td>
<td>6.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Reduction in emission since 1995 (CO2) (%)</td>
<td>56</td>
<td>45</td>
</tr>
<tr>
<td>Time taken to separate material (hrs)</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Percentage of separation before shredding</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>Does it have a maintenance schedule (Y/N)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Take back options (Who pays for it)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Estimated printer price ($)</td>
<td>189</td>
<td>200</td>
</tr>
<tr>
<td>Market price of similar printer ($)</td>
<td>166</td>
<td>160</td>
</tr>
<tr>
<td>Time printer will be in the market</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Percentage of recycled material in packaging</td>
<td>56</td>
<td>66</td>
</tr>
<tr>
<td>Number USB, Connectors, memory slots etc.</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Ease of installation (0-difficult, 1-easy)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Amount of hazardous material containing:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mercury</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cadmium</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hexavalent chromium</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Polybrominated biphenyls (PBB)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Polybrominated diphenyl ethers (PBDE)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4.6: Input values for the comparison of two products
The calculations in Figures 4.7, 4.8 shows that comparisons can be made between two products of the same family, or even with products from a competitor. The code used to generate the program is given in Appendix A.

<table>
<thead>
<tr>
<th>Calculations Product 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Importance Sub Elements</strong></td>
</tr>
<tr>
<td>Energy efficiency</td>
</tr>
<tr>
<td>Material utilization</td>
</tr>
<tr>
<td>Life-cycle factor</td>
</tr>
<tr>
<td>Environmental effects</td>
</tr>
<tr>
<td>Recyclability</td>
</tr>
<tr>
<td><strong>Total for high importance sub-elements</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Medium Importance Sub Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
</tr>
<tr>
<td>Service life/ Durability</td>
</tr>
<tr>
<td>Ethical responsibility</td>
</tr>
<tr>
<td>Packaging</td>
</tr>
<tr>
<td>Upgradeability</td>
</tr>
<tr>
<td><strong>Total for med importance sub-elements</strong></td>
</tr>
</tbody>
</table>

| Product 1 Sustainability Index | 0.66 |

Figure 4.7: Calculated product sustainability score for product 1
Finally by using the data above a “label” can be created as a pie chart to show the level of each sustainability element present in the product (see Figures 4.9 and 4.10). The sub-elements were grouped according to their respective elements. The final comparison of the two products is shown in Figure 4.11.

Environmental Impact = index_life_cycle_factor + index_ems

Societal Impact = index_tkbk_opt + index_prod_prc

Functionality = index_upgd_opt + index_reliability + index_service_life

Resource Utilization & Economy = index_use_egy + index_mat_utilization

Manufacturability = index_pkg_mat

Recyclability = index_recyclability
Figure 4.9: Elements of Product 1

Figure 4.10: Elements of Product 2
4.2 Discussion

When the Lexmark results were compared to the consumer model in Chapter 3.4, it shows that consumers were not as interested in the same sustainability factors as the electronics manufacturers (see Table 4.4 and Figure 4.12). 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 and resource utilization and product’s cost closely following. The manufacturability aspect was excluded from the consumer survey as the average consumer is unlikely to be knowledgeable about manufacturing processes.
The successful production and marketing of a sustainable product solely depends on how well the manufacturers’ and consumers’ ideologies 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 consumer’s interest for their preferences in product choices in the market. As seen in Figure 4.13, there is a broad gap that needs to be bridged between 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 OEM’s will be forced to focus significantly on concurrent engineering along with this proposed model to access consumer preferences and demands through marketing and sales groups.

![Diagram of OEM and Consumer Expectations](image)

**Figure 4.13: The correlation between OEM and consumer expectations**

The ideal situation or product is determined by the effects products has on the six elements. This ideal product is believed to be between the OEM and consumer expectations and the gap between the OEM and consumer needs to be bridged first to achieve these optimum conditions. In reality, there may not be an ‘ideal’ product, but an approximate product can be achieved by the following conditions.
Table 4.5: Optimum levels of sustainability elements

<table>
<thead>
<tr>
<th>Sustainability Elements</th>
<th>Level needs to achieve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Impact</td>
<td>Minimum</td>
</tr>
<tr>
<td>Societal Impact</td>
<td>Minimum</td>
</tr>
<tr>
<td>Functionality</td>
<td>Maximum</td>
</tr>
<tr>
<td>Resource Utilization and Economy</td>
<td>Minimum</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>Maximum</td>
</tr>
<tr>
<td>Recyclability/Remanufacturability</td>
<td>Maximum</td>
</tr>
</tbody>
</table>

Both consumers and OEMs need to contribute to closing this gap between the expectations for sustainable products to exist and survive. OEMs need to increase awareness among consumers by targeting at more NGOs and other organizations to increase public awareness on adverse environmental effects and also need to assure the consumers that sustainable products are safe and do not cause any health risks and are easy to use with the best functional options available. Consumers need to help the growth of sustainable products by purchasing them, and also research products before purchasing.

A set of guidelines can be used to help OEMs understand consumers better. Similar research has been done by Ottman [41] in 1993 but with emphasis on the environmental sustainability.
Guidelines for manufacturers:

- Educate yourself as well as other employees in the corporation
- Encourage continuous improvement in learning, teaching and research
- Take action when necessary to focus and keep goal in sight
- Enforce concurrent engineering
- Conduct surveys regularly to learn the changing trends
- Invest in research in sustainability—it’s never too late
- Create benchmarks (even if it’s within the company)

Guidelines for consumers:

- Research products before purchasing
- Look out for long-term benefits
- Give preference to corporations that practice global sustainability
- Read sustainability reports
- Always think of your own safety first
CHAPTER 5
CONCLUSIONS

This chapter will summarize and conclude the findings of this thesis and discuss future work in this area at the University of Kentucky.

5.1 Concluding Remarks

The main objective of this research was to design a model to evaluate and compare the product’s sustainability levels of different product models at the design stage of product development. The model was created by considering six major sustainability elements, twenty-four sub-elements and forty-four corresponding influencing factors.

A generic product sustainability scoring method was developed for consumer electronics products using science-based sustainability principles.

For verification, the model was adjusted accordingly to suit the case study on a Lexmark printer, and was used with ten sub-elements and the corresponding influencing factors. Methods were formulated for each sub-element to be measured and used, with data and information made available by Lexmark and other sources such as the EPA. Weighting for each sub-element and importance categories were provided by Lexmark’s design and environmental team.
Based on the information 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 products, with sufficient data, it could be customized to other products.

A consumer survey was also conducted to understand their expectations and views on sustainable elements. The results show that the consumer and OEM have different views and expectations. It is a clear indication that OEMs need to work together to minimize this difference and consumers also need to be educated on sustainability related topics.

Sustainability may not be well defined, quantified or even identified, but there lies a clear idea that this concept needs to turn into practice and then into reality before too long. The efforts put forth by corporations, governments, academic institutions need to continue and grow in the coming years and the aim must be for developing science of sustainability to be an accepted element. The ‘ideal’ sustainable product may not exist now, but a near perfect condition may be achieved with these efforts and continued research and development.

In conclusion, it is evident that the efforts extended by the electronics manufacturers are making good contribution towards to manufacturing sustainable products. There still exists some concepts that needs to be included into business
strategies of sustainable development. One of the main realizations is that concurrent engineering need to be emphasized and practiced throughout the full life-cycle of the product from manufacture to the recycling of the product. As shown in Chapter 4.2, there is a clear distinction between the OEMs’ and consumers’ expectation and this gap needs to be bridged. In the hierarchy of design and manufacturing elements, concurrent engineering has to be a priority for engineers to work together with consultants on market research and consumer ideologies.

Educating consumers of proper sustainable values is a key target for this interest and it will be necessary for OEMs to invest heavily on public relations for their products. But this does not mean they should influence consumers to purchase their products portrayed as “green” products and consumers should be warned of such misconduct of practices. Consumers are willing to believe facts or information, if it comes from a reliable source, and that also may not necessarily be OEMs, since consumers believe that OEMs promote sustainability to market their products. The best practice is for OEMs to establish connections with organizations such as NGOs whom consumers are more likely to believe. Also, public media such as advertisements in television programs, radio broadcasts and newspapers should be targeted to convey this important message.

Next, OEMs need to be sure of the direction of their research and developments in the area of sustainability, and benchmarking plays a vital role in this aspect. In trying to compete in a hard-hitting market OEMs have to be sure of their current practices and future practices need to survive and shine in this area.
Everyone involved needs to realize that the current views on sustainability have to change, and it always takes effort and practice. In the book “Cradle to Cradle”, one of the five guiding principles that needs to take place to practice eco-effectiveness is explained as “understand and prepare for the learning curve” and it is essential to understand that change takes time, extra material and is difficult and messy [46].

5.2 Future work at UK

A consumer-oriented approach will be considered in the successful implementation of this proposed model in the future. Future work in this area includes 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.

The proposed model will also be expanded for a range of products and include “design for sustainability” principles. This work will be continued at the University of Kentucky to refine the model to a wider range of products.
APPENDIX A
Product Sustainability Calculations

Sub indexcalc()
Set CurrentSheet = Application.ActiveSheet
'product 1
'energy efficiency index
[c43] = ([-0.025] * [B5]) + [2.5]

'material utilization index
[c44] = (0.00735) * [B7] + (0.00281) * [B8] + (0.0033) * [B9] + (0.0028) * [B10] +
(0.00541) * [B11] + (0) * [B12] + (0) * [B13] + (0.0122) * [B14] + (0.023) * [B15] +
(0.0246) * [B16] + (0.0207) * [B17]

'lifecycle factor
[c45] = (((0.1667) * [B18] + [B19] / [B25])) / 2

'environmental effects
[c46] = (([B20] / 100) + (Application.Sum([B32:B37]) / 6))

'recyclability
[C47] = (((-0.125) * [B21] + 1) + [B22] / 100) / 2
'reliability
[c51] = ([B23] + [c44]) / 2
'service life
[c52] = [B23]
'ethical responsibility
[c53] = ([B26] / [B25] + [B24]) / 2
'packaging
[c54] = [B28] / 100
'upgradeability
[c55] = [B30] * [B29] / 100

[D43] = [B43] * [c43]
[D44] = [B44] * [c44]
[D45] = [B45] * [c45]
[D46] = [B46] * [c46]
[D47] = [B47] * [C47]
[D51] = [B51] * [c51]
[D52] = [B52] * [c52]
[D53] = [B53] * [c53]
[D54] = [B54] * [c54]
[D55] = [B55] * [c55]
\[ D48 \]. Value = Application.Sum([D43:D47])
\[ D56 \]. Value = Application.Sum([D51:D55])

\[ E48 \] = \[ B48 \] * \[ D48 \]
\[ E56 \] = \[ B56 \] * \[ D56 \]
\[ E58 \] = \[ E48 \] + \[ E56 \]

'product 2
'energy efficiency index
\[ C65 \] = ((-0.025) * \[ C5 \]) + [2.5]

'material utilization index
\[ C66 \] = (0.00735) * \[ C7 \] + (0.00281) * \[ C8 \] + (0.0033) * \[ C9 \] + (0.0028) * \[ C10 \] +
(0.00541) * \[ C11 \] + (0) * \[ B12 \] + (0) * \[ C13 \] + (0.0122) * \[ C14 \] + (0.023) * \[ C15 \] +
(0.0246) * \[ C16 \] + (0.0207) * \[ C17 \]

'lifetime cycle factor
\[ C67 \] = (((0.1667) * \[ C18 \] + \[ C19 \] / \[ C25 \])) / 2

'environmental effects
\[ C68 \] = (((\[C20\] / 100) + (Application.Sum([C32:C37]) / 6))

'recyclability
\[ C69 \] = (((-0.125) * \[ C21 \] + 1) + \[ C22 \] / 100) / 2
'reliability
\[ C73 \] = ([C23] + [c44]) / 2
'service life
\[ C74 \] = [C23]
'ethical responsibility
\[ C75 \] = ([C26] / [C25] + [C24]) / 2
'packaging
\[ C76 \] = [C28] / 100
'upgradeability
\[ C77 \] = [C30] * [C29] / 100

\[ D65 \] = \[ B65 \] * \[ C65 \]
\[ D66 \] = \[ B66 \] * \[ C66 \]
\[ D67 \] = \[ B67 \] * \[ C67 \]
\[ D68 \] = \[ B68 \] * \[ C68 \]
\[ D69 \] = \[ B69 \] * \[ C69 \]
\[ D73 \] = \[ B73 \] * \[ C73 \]
\[ D74 \] = \[ B74 \] * \[ C74 \]
\[ D75 \] = \[ B75 \] * \[ C75 \]
\[ D76 \] = \[ B76 \] * \[ C76 \]
[D77] = [B77] * [C77]

[D70].Value = Application.Sum([D65:D69])
[D78].Value = Application.Sum([D73:D77])

[E70] = [B70] * [D70]
[E78] = [B78] * [D78]
[E80] = [E70] + [E78]

'End Sub

End Sub

Private Sub CommandButton1_Click()
  indexcalc
End Sub

Private Sub Label1_Click()

End Sub

Private Sub Label2_Click()

End Sub
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VITA

The author was born in Hamamatsu, Japan in 1978. She completed her Bachelors in Electrical Engineering in 2002 at the University of Kentucky. While in her undergraduate career she was an active member of the Society of Women Engineers and the International Microelectronics and Packaging Society (IMAPS). She was also initiated into Phi Eta Sigma, National Honor Society and was an associate member of Eta Kappa Nu.

Niranjali de Silva
05-04-2005