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Product design: A conceptual development of product remanufacturing index

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Product Design: A Conceptual Development of Product Remanufacturing Index

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PRODUCT DESIGN: A CONCEPTUAL DEVELOPMENT OF PRODUCT REMANUFACTURING INDEX

Swapnil B. Dixit

ABSTRACT

In light of increasing pressure from environmental safety advocate groups and governments for eco-friendly manufacturing, safe after life product & waste disposal has had strong emphasizes in the past several years. Industrial manufacturers are becoming more and more responsive towards environment safety concerns. These efforts are being reflected by concepts such as green design or environmentally responsible design and manufacturing (ERDM). The key research areas in the 21st century for reducing the toll on the environment will be material recycling, controlled waste disposal (including fluids and gases) and remanufacturing.

Remanufacturing offers a dual advantage over material recycling. First the geometrical form of the product and the functional capabilities are restored with fairly low costs. Second, it reduces the need for dumping or disposal, making it better for the environment Remanufacturing is also an avenue to enforce product take back which has become important for the integrating environmental considerations. Remanufacturing can be lucrative and thus a motivating factor for the profit oriented industrial community.

The work in this research is based on making remanufacturing more distinctive in terms of product design. An approach that incorporates remanufacturing principles at the product design inception phase can be highly beneficial in the context of after life processing of product. The approach used in this research is one of determining a suitable method of calculating the remanufacturing index (RI). The remanufacturing index of a product serves as a beforehand indication of the degree of the efforts return a product to

its original geometrical shape and functional capabilities. This index will provide an insight at the time of initial design of a particular product for understanding afterlife scenarios, which might help to reduce waste, save energy, virgin material, and other resources.

The remanufacturing index formulation devised in this research considers all the major aspects of product after life, including disassembly, recycling and other damage correction efforts. This research offers modular analyses of a product for the purpose of remanufacturing. The index is a collection of interfacing elements such as inspection, damage correction and environmental impact. It considers all possible after life aspects of a product and combines them in a systematic manner to give a fair outlook of efforts to remanufacture.

CHAPTER 1

INTRODUCTION

A key challenge for designers and process engineers is the impact of environmental pollution due to rapid industrialization. A lot of research is being focused on developing environmentally friendly technologies. Product designers and manufacturers are rigorously working towards reducing environmental pollution. In most of the developed countries industrial organizations, specifically manufacturers, are taking actions to prevent damage to the eco-system. Many countries are working on stricter legislation in order to prevent future damage to the eco-system brought about by negligence during designs, manufacturing and process development. Consumer awareness created by environmental protection advocates has also played a major role in putting pressure on manufacturing organizations to reduce pollution. In the wake of environmental concerns, consumer preferences have shifted towards more environmentally friendly products and the companies that design and manufacture them. Thus it is important that designers meet important parameters of product design such as cost effectiveness, reliability and environmental safety. There is continued emphasis to examine the environmental impacts at both the product and process design stages by both designers and manufacturers.

1.1 Major Environmental Problems

In the early 1980s the environment protection movement won major support in the United States and the rest of the industrialized world. Initially, problems such as high lead content due to automobile emissions, mercury levels in the air and water, were of major concern .Since that time studies conducted by various environmental groups have discovered major problems in the following areas;

1) Landfill: By definition, a landfill is place where waste is disposed off. About 80% of America's waste goes to landfills (ERDM, John Sutherland, 2000). In 1996 the Environment Protection Agency (EPA) reported that 17 states in the United States would reach their landfill capacity in less than a decade. Five states including New York and Massachusetts have less than 5 years to reach capacity. Increasing demand of land for habitation along with increasing rate of waste generation has reduced land availability in the US. Problems with landfill have become graver due to increased generation of methane gas from landfills, with the attendant hazard of explosion. (EPA, 2001)
2) Air and water contamination: Discharge of greenhouse gases such as Carbon dioxide (CO_2), methane and CFCs into the air is considered as one of the leading causes of global warming. These gases are believed to have damaging effect on the ozone layer resulting in a constant rise in earth's temperature. This has contributed to melting of glaciers and increase in ocean water levels. The smog results from photochemical reaction under sunlight between nitrogen oxide (NO_2) and hydrocarbon emissions from automobiles and chemical plants lead to respiratory problems. At the same time industrial waste dumped in rivers and water reservoirs is believed to cause higher levels of lead and mercury in fish and other edible aquatic creatures.
3) Industrial mishaps: Accidents like Union Carbide in India and Chernobyl in the former U.S.S.R. resulted in casualties and grave environmental impact which served as a warning for serious side effects of unchecked rapid industrialization.

Damage to the environment due to industrial growth differs as per topography and level of development. Every region around the world has confronted at least one environmentally related problem such as loss of bio-diversity, acid rain, mining discharge, crude petroleum spills, etc.

Prudence on the part of process and product designers has the potential to prevent some of environmental pollution problems, if these problems are anticipated at the time of design inception.

Nowadays progressive thinking about environmental safety is leading to efforts towards safe and less polluting product and processes design. Environmental safety has become one of the important competitive factors for global organizations. Some organizations are finding it difficult to accommodate eco-design principles because of the huge investment necessary to achieve it. It is a difficult task to balance profit and investment cost for eco-design. The problem is more acute for small and medium scale industries in view of big investments in environmental safety and the monetary returns. Government bodies and certification agencies like International Organizations for Standardization (ISO) and Quality Systems Requirements (QS) are promoting responsible manufacturing practices that are encouraging companies to consider the benefits of eco-design.

1.2 Environment Protection Legislation in the United States

Lobbying for environmental safety legislation was started in the 1960s. Governments can help promote environmental safety through enforced regulations. Government regulations and mandates have considerable influence on operation of industries. Such lobbying has successfully encouraged government and its branches to consider for the environment safety issues in its policies. The need to create awareness for environment at every level was well articulated. The biggest breakthrough achieved was the establishment of government agencies such as Environmental Protection Agency (EPA) in 1970. EPA started working on the principle of voluntary measures which often achieves more environmental improvements at lesser cost than enforced regulation and mandates. The following are some prominent examples where major environmental issues were tackled with legislation:

1. Clean Air Act (CAA) (1990)
2. Federal Insecticide, Fungicide And Rodenticide Act (FIFRA) (1996)
3. Toxic Substances Control Act (TSCA) (1976)
4. Occupational Safety And Health Hazard (OSHA) (1971)
5. Pollution Prevention Act (PPA) (1990)
6. Resource Conservation and Recovery Act. (RCRA)

7. Clean Water Act (CWA) (1977)
8. Comprehensive Environmental Response, Compensation And Liability Act (CERCLA) (1980)
9. Energy Policy Act (EPA) (1992) (ERDM, John Sutherland, 2001)

1.3 Eco-Design

Eco-design focuses on the environmental aspects of all stages of the product development process in order to design a product that creates the lowest environmental impact throughout its life cycle. It combines ecological and economic goals for new product and process development. Eco-design has become a necessity rather than an option for industries. In 1993, former President Bill Clinton signed an executive order mandating federal preferential purchasing policies for products that benefits the environment. The EPA publishes a list of preferred products on a regular basis, which are manufactured in conjunction with eco-design principles (Berko-Boateng, Azar, Jong, Yander 1993).

The world business council for sustainable development (WBCSD) has pioneered the effort to assist industries to understand the principles of eco-design. It has produced with practical guidelines for incorporating eco-design principles into the designs in order to achieve maximum profit based on the following principles (WBCSD, 2002)

1. Reducing material intensity of goods and services
2. Reducing energy intensity of goods and services
3. Reducing toxic dispersion
4. Enhancing material recyclability
5. Maximizing the use of renewable sources
6. Extending durability of product
7. Increasing the service intensity of goods and services

Eco-design has different names including Recycling, Remanufacturing, Environmentally Responsible Design & Manufacturing (ERDM), Eco-Efficiency and

Green Design. All these terms imply reduced waste generation and savings on waste disposal costs as well as take-back obligations of products. Two major eco-design practices namely recycling and remanufacturing are discussed in next sections 1.4 and 1.5.

1.4. Recycling

Recycling is a process of altering the physical form of a used product to make the same or different product and to achieve minimal waste dump. It is one of the best methods for reducing the consumption of finite natural resources, and it also prevents disposal or dumping to a significant extent. The used product is collected, cleaned, sorted and transformed into useful product. Products with homogenous material composition are best suited for recycling. Plastics, paper, aluminum cans, and automobile tires are few prominent examples of recyclable products. Recycling has become a norm in plastic, paper, aluminum products, and vulcanized rubber industries. It has shown distinct advantages in terms of saving virgin materials. For example recycling of paper saves trees used for paper manufacturing and recycling aluminum cans saves ore extraction and the costs associated with it.(Maxwell, Wenzel 2002)

1.5 Remanufacturing

In simple terms, “Remanufacturing” can be described as an activity in which products that are known to be worn, defective, or discarded are brought to a (re)manufacturing facility, where they are disassembled. All the components are cleaned and inspected. The components, which could be reused, are brought up to specification. Those are not usable are replaced with new or refurbished components.

When the product is reassembled, inspected and tested, it is ready for a second life. Remanufacturing thus potentially reduces the costs of purchased parts and waste disposal. The cost of remanufactured product could be as much as 45% to 65 % of a new product. A study by Rolf Steinhilper (October 1995), shows that disposal costs are 3% of direct production costs for cars, 12.5% for refrigerators and freezers, 2% for ink cartridges. According to Robert Lund's study in Remanufacturing (2003) remanufacturing should include following principles:

1. Technology to restore products
2. Interchangeability of parts
3. Technology is stable for more than one life cycle of the product
4. Sufficient market to sustain enterprise

The concept of remanufacturing started in the early 1980s and became quite popular as opposed to material recycling. Some industrial giants like Rank-Xerox, HP, and Arrow Automotive started adopting the principles of remanufacturing in the form of environmentally friendly designs for manufacturing products and processes. Remanufacturing yields two very distinct advantages. The first is that it is eco-friendly, and the second is that it preserves much of the value added to the product. It also saves significant time, energy, and resources by reducing virgin material extraction rates. It reduces waste generated from raw material separation, processing, and energy usage associated with manufacturing. Copper is a good example that illustrates this fact. 1 ton of recycled copper can avoid mining of 200 tons of copper ore. This saves one ton of nitrate explosive used for removing the material from the ground, one ton of coke or other hydrocarbon fuel for smelting. Another advantage is that it results in a reduction of about two tons of sulfur dioxide and three tons of carbon monoxide being released into the atmosphere. (Argument, Lettice, Bhamara 1998)

1.6 Economic Impact of Remanufacturing

Remanufacturing requires facilities similar to a regular manufacturing facility. The input for the remanufacturing facility will be products whose intended life is over. The products which are brought to remanufacturing facility after their life is over are called 'after life take back' products. Remanufacturing is economically viable if high volume processes similar to new product manufacturing are available. There are other factors like range of products, and degrees of wear and tear of the product components. Products with little change in shape and material over long periods of time are best suitable for remanufacturing. This might result in products that were manufactured in different years coming to the remanufacturing facility. This makes the process of remanufacturing more complex. For example in computer and cellular phone manufacturing it is difficult to use remanufactured component because of the rapid rate of product change. This makes the recovery of high value parts difficult as in some case when products become obsolete within three to four years.

Rank-Xerox, which manufactures cartridges and toners, has successfully connected itself to remanufacturing through 'after life take back', resulting overwhelming profits for that company. Studies performed by Rank Xerox have shown that eco-efficient product development policies combined with take back incentives have made returns increase up to 70%. Total material savings was $64.9 millions in 1995 and demand for remanufactured copiers exceeded supply by 50%. The percentage of total manufacturing waste sent to landfills has been reduced from 41% in 1993 to 21% in 1995. This was achieved through redesigning of the products. The design engineers have reduced the different types of plastics used for cartridges from 27 to only 6 types of recycle friendly plastics. This made the process of take back and recycles easy. This has made Rank-Xerox program profitable without compromising quality.(Allocca, 2000)

1.7 Purpose of the Current Research

The focus of this research is to develop a formulation that provides a systematic measure of remanufacturing at the time of design inception. The research proposes the development of a remanufacturing index (RI). The remanufacturing index is an effort to incorporate remanufacturing principles at the time of product design making it highly beneficial in the context of after life processing of the product.

This research is directed towards a developing a suitable method of formulating the remanufacturing index (RI). The RI of a product serves as a beforehand indication of the degree of efforts required to bring that product back to its original geometrical shape and functioning capabilities. The remanufacturing index formulation devised in this work would consider major aspects of product after life, such as disassembly and damage correction efforts. The remanufacturing index is a collection of interfacing, quality assurance, damage correction and toxicity indices that are combined in a systematic manner in order to provide a measure of the efforts required to remanufacture.

The RI serves as a guide post at the time of the design of a particular product for understanding its after life scenario, that helps reduce waste, save energy, virgin material and other resources. The idea is to provide design engineers an investiture for consider design factors such as material selection and process selection, that yield environmentally friendly product in terms of take back and recycling while yielding economic benefits at the same time. The proposed formulation reflects the remanufacturability of the product being designed.

CHAPTER 2

LITERATURE REVIEW

Environmental pollution can be controlled with prudent design practices. Foreseeing afterlife hazards of products can lead to safe environment. In developing the remanufacturing index (RI), considerable materials in environmental issues, environmental legislation, and safe eco-design were reviewed. The main focus was on developing an understanding of product lifecycle, product end of life strategies, methods to quantify impact of product life phases on the environment and product and process design methods for remanufacturing. A deliberate effort was made to study and understand contemporary methods of assessing remanufacturability as well as the costs associated with it.

2.1 Product Life Cycle

Product life cycle is an important aspect to be studied from remanufacturing and recycling perspective. Material, energy and manpower consumption along with environmental impact aspects were subjects of interests. Product life cycle could be best summarized in the Figure 2.1 (ERDAM, John Sutherland, 2002).

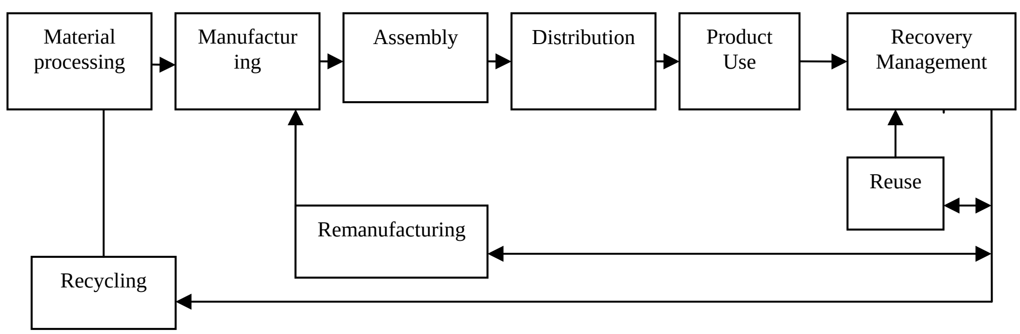

Figure 2.1 Product Life Cycle

1. Material processing involves extracting ores and raw materials. Extraction is done from earth's crust for ores and liquid petroleum, from woods for paper and rubber based products. Material extraction consumes energy and creates wastes in processing and resulting in diminishing resources. Recycling is always preferable to avoid environmental disruption that virgin material extraction requires. Recycling takes less energy than extraction and reduces the amount of landfills.
2. Manufacturing involves processing raw material into parts. These parts and processing techniques are quite diverse based on product performance characteristics. Manufacturing process consumes considerable amount of energy and manpower. In many cases toxic wastes and harmful bi-products are generated.
3. The assembly process involves putting different manufactured parts together manually or by automated means. The assembly process can be a very complex especially where large numbers of parts are involved e.g. automobile, computers. Assembly of the product consumes energy and manpower.
4. Product-use is putting product to its intended use which might involve energy consumption, wear and tear of product and its component. In some cases products use might result into generation of pollutants e.g. automobiles, refrigeration units.

2.2 Life Cycle Analysis (LCA)

As per the definition by EPA (1993)

"Life-cycle analysis is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material sage and environmental releases, to assess the impacts of those energy and materials uses and releases to the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life-cycle of the product, process or activity, encompassing extracting and processing raw materials, manufacturing, transportation, and distribution; use/reuse/ maintenance; recycling; and final disposal."

LCA is potentially identifying aspects such as energy, material consumption and waste generation during product life stages. LCA enables manufacturers and designers to quantify how much energy and material were used and how much solid, liquid and gaseous waste were generated at each stage of product's life. LCA is a major tool to investigate material and energy flow along the product life cycle. LCA is potentially a powerful tool used by regulators for formulating environmental legislation. (Senthil, Ong, Nee and Tan 2002).

2.2.1 LCA Advantages

LCA is a broad scientific validation technique for assessing environmental impact. It enables the identification of key areas in product manufacturing to product usage to locate improvements through environmental perspective. Use of resources for product varies by degree of complexity of design; every product poses different environmental impact. LCA helps to identify those stages, which have material or energy demand, and stages, which have potential to cause pollution. LCA study is performed at a micro level. It helps to identify the use of scarce recourses, showing where a more sustainable product could be substituted.

2.2.2 LCA Limitations

The development of LCA requires extensive data collection and calculations. LCA though highly desirable cannot be implemented for every product design. This is due to lack of standard databases of all kinds of environmental impacts. Results are voluminous and sometimes difficult to understand and interpret. Ideas generated from results go beyond the scope on influence of designers. Comparison of dissimilar products in most respect can only be made by judgments and assumptions. Reliable methods for aggregating figures generated by LCA and using them to compare the life cycle impact of the products have not been developed. LCA does not adequately describe product end of life issues because of difficulties in defining boundaries, embedded toxicity, emissions and environmental impact of end of life treatment systems. LCA refers to existing products, and do not offer guidelines for future product design or recommendations to do so. (Ulrich, 19995)

2.3 Designs for Environment (DFE)

"Design for Environment aims to bridge the gap between two traditionally separate functions: product development and environmental management. The goal of DFE is to bring these two functions into closer contact and address product life-cycle issues that are often ignored." – Implementing Design for Environment: A Primer

Design is a set of decisions taken to solve a particular set of product requirements issues. Design is a crucial phase for product and its life, as 80% of the product's life cycle costs are committed through design choices (Chandra1993). DFE is defined as the systematic way of incorporating environmental attributes and costs into the design of product. DFE is making suitable choices during design process, which will result in less environmental impact throughout product life cycle and after life. A product's environmental impact ranges from release of toxic substances into the environment to consumption of material and energy resources.

DFE occurs early in the design stage to ensure that environmental consequences are taken in to account before any manufacturing decisions are committed. Following are some examples of how choices made can make product design in line with DFE requirements. (EPA 1992)

1. Using alternative joining technologies such as snaps, darts and screws instead of adhesives and welding.
2. Minimizing or eliminating embedded metal threads in plastics.
3. Using screws of similar head technology.
4. Minimizing the variety of materials used (including fillers, colors and additives).
5. Marking plastics clearly with resin type identifiers.
6. Using components made of known materials.
7. Avoiding painting and putting labels on recyclable parts.
8. Using modular architecture, so that modules can be replaced to upgrade or repair equipment.
9. Using ceramics instead of plastics with flame-retardants.
10. Leasing of products for "take-back" and reuse.
11. Using "power down or sleep modes" for electronic devices to cut energy use during inactivity. 2.3.1 DFE Approach

Ideal product design approach as described, by Ulrich Nissen (1995) is shown in table 2.1

Table 2.1 DFE Approach

Primary Criteria the product should support	Examples of sub criteria	General effect (during waste management)	Environmental effect
Environmentally sound incineration / disposal	1. Centralizations of hazardous substances 2. Marking of hazardous substances 3. separable connections between hazardous and other substances	Easy separation of hazardous substances	Reduces the amount of hazardous waste and toxic emissions; no contamination of other substances
Recycling reprocessing of the material	1. Low material variety 2. avoidance of compound material 3. material markings 4. low number of connections	Easy separation of materials in to constituent fractions in order to approach horizontal recycling	Reduces material consumption, reduces waste generation
Remanufacturing reuse of the product	1. Connections to be separated non destructively 2. Easy to clean 3. simple design structure	Increase longevity, long use of product	

2.4 Product End of Life Strategies

Product end of life is defined as a stage when product no longer satisfies its intended basic work function to the expected degree for the first user (Allocca 2002). The other definition can be a point at which the product no longer performs the intended functions due to failure or wear out. Product end of life is an important aspect for designers through eco-design perspective. The take back or disposal responsibility and its economic implications are much dependent on how product end of life takes place. Product end of life is the first stage for remanufacturing. For a product to be remanufactured it is important to have all know how of how to incorporate resources to rebuild the product. 2.4.1 Product End of Life Hierarchy

Product end of life hierarchy in Allocca, (2002) is categorized in six broad categories.

1. Reuse: Reuse is the secondhand trading of the product for use as originally designed. Automobiles and its spare components are the best examples of reuse. The products those are build for longer life span like 10 to 20 years or more are feasible for reuse. Lengthened product life is one of the suitable alternatives to eco-design but it is not a solution. Rapid change in consumer’s taste makes it more difficult to build such products. Rate of growth of technology constantly triggers feasibility of obsolesce. Computers are examples of obsolescence due faster growth in model design changes.
2. Service: Servicing is increasing product life by replacing worn out parts or rebuilding some product’s part in order to make it functional for longer duration. Servicing is preferred for products those are huge in size and shape. Earthmovers and houses are the products where servicing is suitable through economic perspective and is widely used. It is profitable practice for both consumers and industries.
3. Recycling with disassembly: Recycling reclaims material streams useful for applications in same or different products. Disassembly in to material fraction increases the value of the materials recycled by removing material contaminants, hazardous material or highly valuable components. Recycling with disassembly is feasible for products with homogeneous materials as discussed in chapter one. Products designed for recycling with disassembly are becoming widely popular.

Paper and aluminum products are now fully recycled. This is economically feasible and profitable option.

4. Recycling without disassembly: This can be sated as shredding in simple terms. Products with composite material structure are suitable for this option. Automobile tires can be cited as an example for recycling without disassembly. The shredded material is separated with chemical processes or simply using magnetic density or other properties of the materials
5. Remanufacturing: As stated in definition in chapter 1 it is a process in which reasonably large quantities of product are brought back in to facility and disassembled. Parts from a specific product are not kept with the product but instead they are collected by part type, cleaned and inspected for possible repair and reuse. Remanufactured products are then reassembled on assembly line using those recovered parts and new parts wherever necessary. Remanufacturing is feasible solution for complex assemblies. Products designed through remanufacturing perspective will have much longer lives and will be giving economic advantage for manufacturers.
6. Disposal: This end of life strategy is transferring product to landfill or incinerating the product with out without much energy recovery. This is the last option to be practiced for eco-design.

To consistently perform an environmental impact analysis across all possible end of life strategies it is necessary to determine a reference point. The reference point can be product in resalable condition or product requires recycling or product requires to be remanufactured.

2.4.2 Phillips Eco-scan System

Lot of research has been done on quantifying impact of product end of life on environment. Phillips' Environmental competence center has done pioneering work in assessing environmental impact with the technique called Eco-scan technique. Eco-scan technique is type of LCA, which examines entire life cycle of a product, and analysis from the Eco-scan gives valuable quantified information about environmental impact. This technique can be effectively used for feedback to designers. (Allocca 2000).Eco-scan from Phillips is one of the best methods to quantify impact of product end of life which can be later become a substantial tool for design. This method study gives a wider picture of every state in product life with impact on environment. Eco-scan technique considers Environmental impact (EI) of manufacturing, packaging, usage, disposal of the product. EI stands for environmental impact and LCA represents values directly derived from eco-scan values from Phillips Eco-indicator database.

$$EI_{life\ cycle} = EI_{manufacture} + EI_{transportation} + EI_{packaging} + EI_{disposal} + EB_{bonus} \quad \ldots (2.1)$$

$$EI_{manufacture} = (1+x)\ LCA_{manufacture} \quad \ldots (2.2)$$

The value x in equation 2.2 is percentage of the product that must be manufactured for second life. The values range from 0% (for reuse), 10% (for service) 40% (remanufacture), 100% (for recycle and disposal)

In the similar fashion $EI_{packaging}$, $EI_{transportation}$, EI_{energy} are calculated. Finally Environmental bonus is determined.

$$EI_{packaging} = LCA_{packaging} \quad \ldots (2.3)$$

$$EI_{transport} = (1.131\ y)\ w \quad \ldots (2.4)$$

y = distance between end user and recycling facility

w = weight of the products in kilograms (kg)

Figure 1.131 is in unit milli-points per mile kg from Phillips database

$$EI_{energy} = LCA_{energy\ (1st\ life)} + LCA_{energy\ (2nd\ life)} \quad \ldots (2.5)$$

$$EI_{disposal} = 2.1\ (w_{electronics}) + 2.0\ (w_{metals}) + 0.8\ (w_{misc.\ glass}) + 0.1\ (w_{wood}) \quad \ldots (2.6)$$

$$EB_{bonus} = -\{0.8\,(LCA_{electronics}) + 1.0\,(LCA_{metals}) + 0.8\,(LCA_{plastics}) + 0.8\,LCA_{misc.\ glass}) \quad \ldots (2.7)$$

Assumptions combined with LCA collected on Phillips products yields environmental impact estimates for end of life strategies. Phillips has performed analysis for its electronic goods like television, VCR, cell phone, CRT monitors, and CD players.

Table 2.2 Environmental Impact Results for Philips' Product

PRODUCT	REUSE	SERVICE	REMANUFACTURE	RECYCLE WITH DISASSEBMLY	RECYCLE WITHOUT DISASSEMBLY	DISPOSAL
Cell phone	88 (63)	93(66)	95(68)	105(75)	122(87)	140(100)
VCR	613(76)	631(78)	639(79)	666(82)	698(86)	812(100)
CRT monitor	1877(70)	1950(73)	2035(76)	2186(82)	2463(92)	2679(100)
LCD monitor	1942(57)	2083(62)	2473(73)	3223(95)	3260(96)	3384(100)
CD player	2590(98)	2596(98)	2609(98)	2632(99)	2636(99)	2652(100)
Audio product	3321(85)	3375(87)	3357(86)	3393(87)	3474(89)	3892(100)
Mainstream television	3168(89)	3658(90)	3674(91)	3740(92)	3954(98)	4045(100)

The units in the table are milli-points. Numbers in parenthesis are percentage of disposal. Cell phone has low environmental impact for end of life as compared monitors, which have high environmental impact.

2.6 Designs for Remanufacturing

Decisions have to be made after products take back for economic viability of their use in a product to be remanufactured. It is an important phase as it affects the entire remanufacturing operation to be performed. The main purpose of this section is to understand how design can affect recovery potential of the product to be remanufactured. Certain characteristics are vital for design for remanufacturing. (Ferrer 2000), (Ayers, Ferrer, Leynseele 1997)

1. Serviceability: Modules subjected to wear should be easily disassembled. The parts should be easily repaired and substituted.
2. Infrequent design changes: High value added components and assemblies should have stable designs. Hence when product is back after its first life serve may not be obsolete.
3. Design flexibility: It facilitates interchanging of modules. There is significant commonality of modules and part product lines across the generations.
4. Material recovery: It is process of recovering material value in the product. It could be a destructive process or picking out components after cleaning.
5. Value recovery: It is the process of recovering usable components or subassemblies from the product. The aim is to save material value and value added in the production or individual component.
6. Recyclability: It is the measure of efficiency with which material recycling is profitable. It is termed as ratio net gain from recycling to recycling cost.
7. Disassemblability: It is the measure of effectiveness of disassembling a component instead of recycling it. It is determined from comparison of marginal revenue if the component is recycled to if the component is disassembling costs.
8. Reusability: It is measure of how economically efficient is it to renovate a component for immediate reuse.

2.7 Assessing Remanufacturability

Assessing remanufacturabiltiy is relative process. Assessment depends on the stage on which one prefers to do it. Many industries have started it after their products have established in market but the serious effort to establish remanufacturing characteristics in to design of product is basic contention this research stands for. The process of establishing remanufacturing metrics as described by in Towards Design for Remanufacturing – Metrics for Assessing Remanufacturability by Bras and Hammond 1996 is one of the basic cornerstones for establishing remanufacturing index.

The paper identifies eight basic remanufacturing processes assembly, disassembly, testing, repair, cleaning, inspection, refurbishing and replacement. The overlap between these processes is eliminated, such that each can be assessed independently of each other. The metric is developed after combining and partitioning independent criteria. Major four categories were identified and sets of metric were developed:

1. Cleaning
2. Damage correction, composed of repair, refurbishment and replacement metrics
3. Quality assurance, composed of testing and inspection metrics
4. Part interfacing, composed of disassembly and assembly metrics

2.7.1 Remanufacturing Index Calculation

Remanufacturing index calculation begins with eight key criteria identification viz. replacement (key), disassembly, reassembly, testing, inspection, replacement (basic), refurbishing, cleaning. Four categories which are independent of each other are determined those are interfacing, quality assurance, damage correction and cleaning. Indices for metric are calculated using the formulas as given below. The formulas are based on Boothroyed and Dewhurst’s DFA metric. (Hammond & Bras 1996)

$$\mu_{disassembly} = \left(\frac{(\#Ideal)(t)}{time_D} \right) \quad \text{… (2.8)}$$

$$\mu_{assembly} = \left(\frac{(\#Ideal)(t)}{time_A} \right) \quad \text{… (2.9)}$$

The assembly and disassembly matrices are defined using the number of ideal parts times an ideal part (dis)assembly time score divided over the actual total time for (dis) assembly.

$$\mu_{inspection} = \left(\frac{(\#\,Idealinspection}{\#\,parts - \#\,\mathrm{Re}\,plcement} \right) \quad \ldots (2.10)$$

The inspection metrics is defined by number of inspections over theoretical minimum number of parts which do not need to be replaced during refurbishing.

$$\mu_{Testing} = \left(\frac{(\#Tests)(t)}{time_T} \right) \quad \ldots (2.11)$$

Metric for testing is defined by total idealized time for testing multiplying the total number of tests by time duration for the test divided by actual time required to perform all the tests.

$$\mu_{cleaning} = \left(\frac{(\#\,Ideal)(\min CleaningScore)}{CleaningScore} \right) \quad \ldots (2.12)$$

The metric for cleaning is comparison of total cleaning score of each parts and ideal number of parts multiplied by minimum cleaning score. Cleaning scores are to be determined by product design and prioritizing cleaning process which will differ product to product.

$$\mu_{\mathrm{Re}\,furbish} = \left(1 - \frac{(\#\,\mathrm{Re}\,furbish)}{\#(parts)} \right) \quad \ldots (2.13)$$

Metric for refurbishing is calculated based on the fact that number of parts which do not require refurbishing is equivalent to the total number of parts less the number of parts which do require refurbishing.

$$\mu_{Key\,\mathrm{Re}\,pl} = \left(1 - \frac{(\#\,Key\,\mathrm{Re}\,plced)}{\#(Key)} \right) \quad \ldots (2.14)$$

$$\mu_{Basic\,\mathrm{Re}\,plce} = \left(1 - \frac{(\#\,\mathrm{Re}\,pl - \#\,Key\,\mathrm{Re}\,plce)}{\#(Parts)} \right) \quad \ldots (2.15)$$

Replacement metrics are constructed in the same manner refurbishing metrics are constructed. Remanufacturing index is calculated by combining the matrices satisfying weighting criteria and inverse weighting criteria. The weights have to be determined by designers as per the product characteristics. This research by Bras and Hammond (1996) gives effective technique to formulate remanufacturing index. However this research does not give environmental impact in process of remanufacturing and does not take in to account costs and probabilities of the product components and its economic implications on remanufacturing.

2.8 Summary

In this chapter considerable literature pertinent to the objectives of this research was reviewed. The components reviewed were product life cycle, life cycle analysis (LCA), design for environment (DFE), product end of life strategies, design for remanufacturing and assessing remanufacturability. The next chapter states and explains the research problem and assumptions made for developing remanufacturing index.

CHAPTER 3

STATEMENT OF THE PROBLEM

Remanufacturing is an effective method for prevention of environmental hazards, material wastage and excessive energy consumption. A sound method of measuring the remanufacturability of a product is by developing a reliable Remanufacturing Index (RI). As seen in chapter 2, several approaches have been used by researchers and industrial organizations to measure remanufacturability for specific product types. As yet there is no general method for measurement of remanufacturability. In consideration of these limitations of existing methodologies, this research addresses a method of developing a remanufacturing index for wide range of products. The RI developed considers product after life scenarios, recyclability, disassemblibility, damage correction, and environmental impact during product remanufacturing process.

The RI would serve as a measure of efficiency with which a product could be remanufactured. The RI of the product would also give a detailed insight of costs involved and its relation to design parameters of the product and its components considered for remanufacturing. The maximum value of the RI is 1 and denotes 100% remanufacturability of the product. Conversely the minimum value is 0, and indicates that the product can not be efficiently remanufactured.

In this chapter the research problem was defined and the uniqueness of the research was explained. In chapter 4 the methodology for developing the RI, components or RI and expected results are explained in detail.

CHAPTER 4

RI MODEL DEVELOPMENT

In this chapter, method of formulating the Remanufacturing Index (RI) and its components are stated. All major assumptions made are discussed aw well as the objectives of the research are included.

4.1 Approach to Problem

As discussed in chapter two, the major components of the product after life assessment and formulation of remanufacturing in terms of numeral are stated. The main objective of the research is to form guidelines for designers to make the products more remanufacture friendly through an economic perspective. In this research an effort has been made to introduce new methods to calculate components of remanufacturing index, in order to give a balanced outlook to examine remanufacturing of wide range of products. This research takes into consideration the economics of remanufacturing as a basis of remanufacturing a product. The two methods of formulation of remanufacturing index reviewed in chapter 2 are helpful in devising the method in this research. The first method is by Bras and Hammond (1995), its approach to assess remanufacturability is based on Design for Assembly (DFA) Index by Boothroyd and Dewhurst (1991). This paper considers the basis of actual versus theoretical minimum parts needed and time parameters in the product to assess to goodness of remanufacturability. The second approach is by Ferrar (1991), which considers the limited economic sustainability of a remanufacturing process and recovery potential of assemblies.

The method adopted in this research basically draws parallel with approaches by Bras and Hammond (1995) and Ferrar (2001). The approach used in this research tries to combine economic sustainability combined with DFA approach along with other economic factors in formulation of RI. This model proposed in the thesis is based on the costs of disassembly, inspection, cleaning, refurbishing, and dumping. The cost of the mentioned operations in remanufacturing reflects all the recourses such as time required for particular operation, man hours and machine hours invested etc. This would result into more realistic approach to calculate remanufacturability of a product.

4.1.1 Product Tree Approach to Decouple Product

The approach considered in the effort is to break the product down to its basic components (Kulkarni 2005). This is referred as the product tree approach. In this approach the product is classified in to three levels. Product is examined from the high level which represents the product itself to the lowest level which is component the basic part. The intermediate level represents the module consists of one or more components. The product is defined as a set of modules which have different functional applications. Modules are simply different sub-assemblies of the product. The modules are assembled from different components. The components are the basic elements of the product tree shown in fig 4.1.

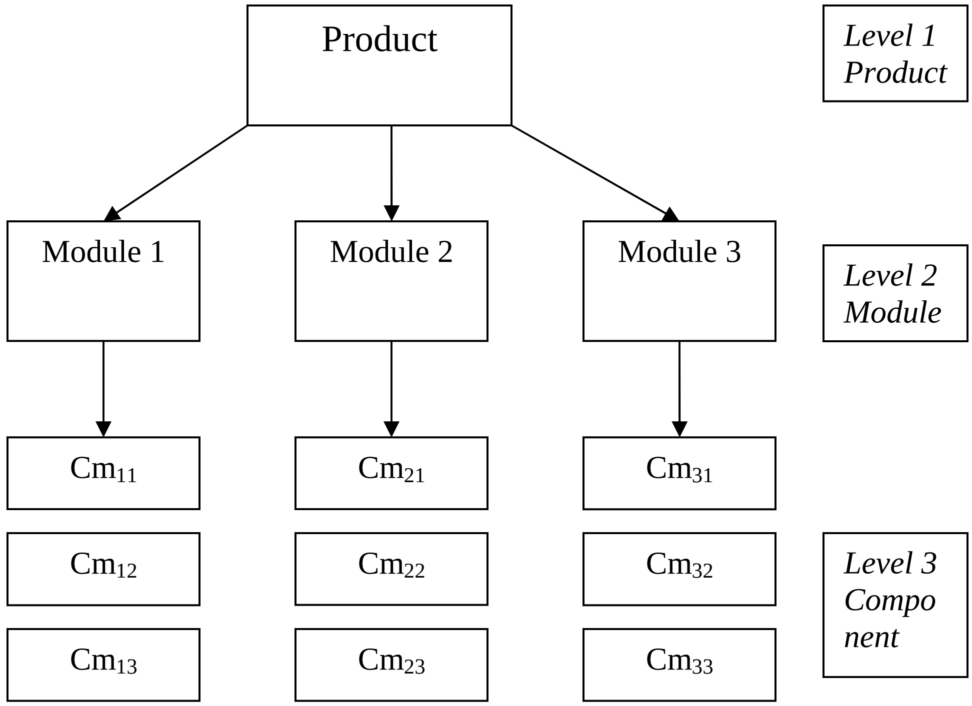

Figure 4.1 Product Tree

Once the product has been identified, the next step is to develop the formulation structure for RI of the product. The formulation begins with the formulations RI of components. The RI of the modules is formulated as combination of the RI of its components. The RI of the product is combination of RI of its constituent modules.

The process begins with disassembling the product. The product is disassembled into modules and subsequently into components. As stated in chapter 3, RI is collection of indices. The indices for the components are categorized in two categories first one being basic indices and second being state indices. Basic indices are necessary for every component. State indices are which denotes the state of the component as explained below.

A. Base indices:

1. Disassembly index
2. Inspection index

B. State indices:

1. Reusability index
2. Refurbishing index
3. Recycling index
4. Environmental index

The components are disassembled, cleaned and inspected and their state is determined. The state of the components can be classified in to following categories.

1. Reusable: The components which can be reused as they are after disassembly.
2. Refurbishable: The components which can be used after minor rework to restore their functional ability and aesthetics.
3. Recyclable: The components which are to be recycled
4. Scrap and dump: The components which cannot be recycled and need to be land-filled.

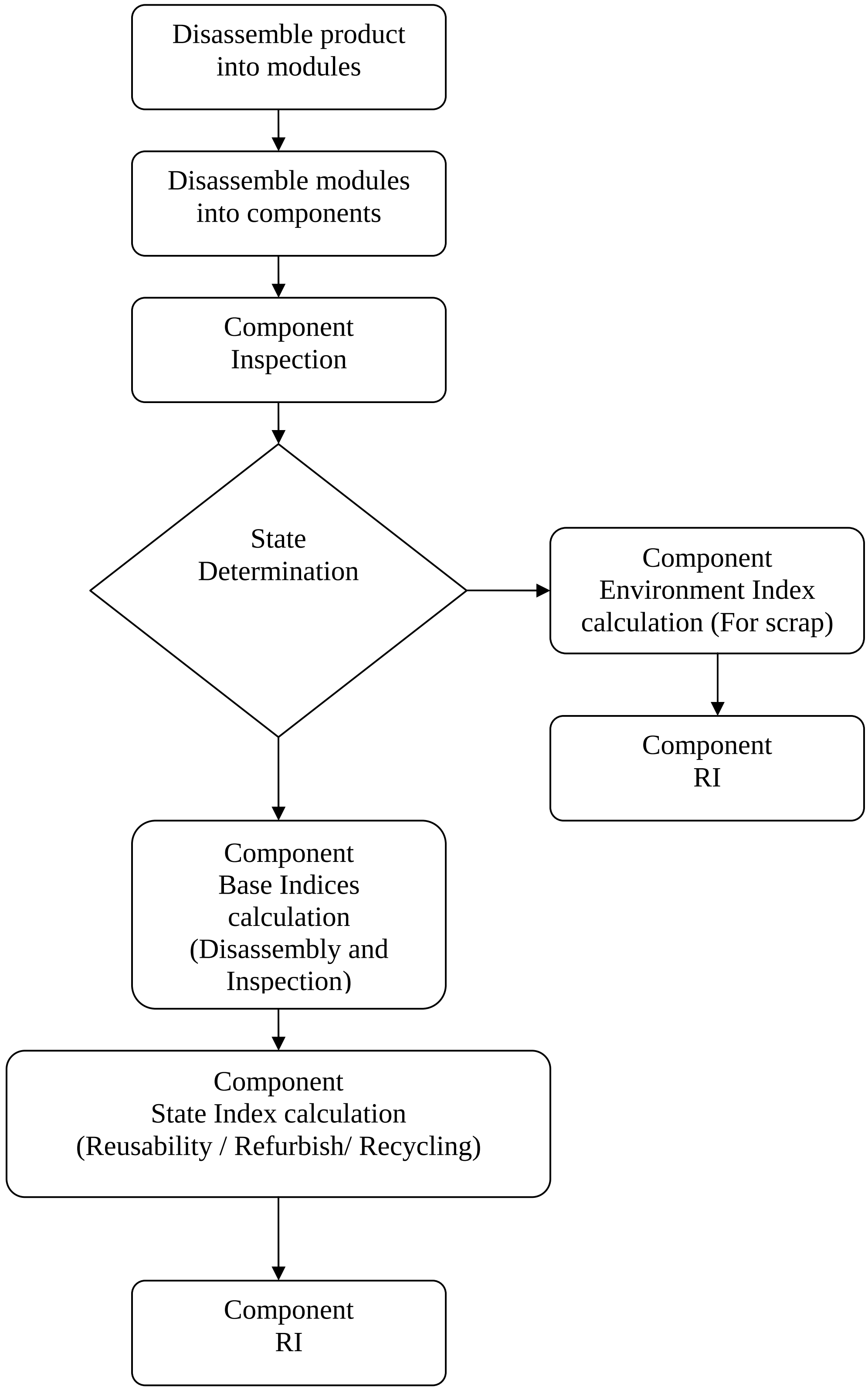

Figure 4.2 Product RI Flow Chart

4.2 Components of RI

4.2.1 Disassembly Index

The disassembling operation is the first step on the remanufacturing floor. There are two major types of disassembly operation. Reversible disassembling operation, in which module can be disassembled to recover the most of the components as against the irreversible disassembling operation or destructive disassembly. The disassembilibility of a component from its parent module is economical efficiency of disassembling it. The focus of the work will be the disassembly a component from its parent module at minimum cost. The cost assessment of the component after disassembly will provide a good feedback on the amount of the depreciation that has occurred over the period of time.

The formulation of the disassembly index will provide an important insight to the designers regarding the work product and components. There are several considerations or the points of view associated with disassembling of a product in a remanufacturing shop. An outlook to disassembling process through remanufacturing perspective will result in to faster disassembling methods. The fastening methods like snap fit design or threaded joints wherever possible over welding joints would result into faster disassembly with minimum damage to the module and its components. Development of non-destructive tools for disassembly would improve the economic efficiency of disassembly. Automated disassembly would result in to minimizing the cost.

It is important to find a balance between the resources invested in the disassembly process and returns from it. The method this research suggests is to consider the ratio of current estimated cost of the component and original cost of the component.

Disassembly Index (DI) = $\dfrac{DCC}{OCC} = \dfrac{Disassembly\,Cost\,of\,Component}{Original\,Cost\,of\,Component}$ … (4.1)

Module M has components c_1, c_2, c_3 ….c_n

C_i = the cost of component c_i of the module.

D_{ci}= Cost of disassembling the component

OCC = Original cost of the component obtained from previous bill of material.

Number of components in the module = $C = \sum_{i=1}^{n} c_i$ … (4.2)

Disassembly cost = D_{ci} … (4.3)

$$DI = \frac{D_{ci}}{OCC} \quad \text{… (4.4)}$$

From equation 4.3 it is evident that the value of DI will be always less than one. The DI of component is the best way to judge losses occurred due to usage of component over the period of time. Comparing current worth of the component with its original cost gives an idea of the depreciation occurred over the period of time. It also considers the costs involved in the process of disassembling.

The assumptions in the formulating disassembly index as a part of RI are

1. A part in case is damaged during disassembly rendering it useless, is recycled or scraped and its recycling return-revenue is calculated.
2. Wear rate of the components in assemblies are predictable

For example an electric motor assembly is brought back to remanufacturing shop. The electric motor is as whole considered as a product. Stator assembly, rotor assembly and power board are the modules. Rotor, shaft and bearings are classified as the components. The factors in which designers will be interested is examining what is current monetary worth of the motor, the degree of wear and tear of the parts.(Bovea, Vidal, 2004)

4.2.2 Inspection and Cleaning Index

Inspection refers to the process of qualitatively examining the components for assessing their condition. The inspection method could be visual inspection or laboratory inspection performed after disassembling operation. This is an important step in remanufacturing; the major consideration would be focused on cost of inspection and condition of the components of the module during the time of inspection processes. The next step is to segregate the components of module in order to dispatch them to respective future processes locations. The segregation is done to determine the future treatment needed by the component of the module. The major categories of treatment of parts can be classified as parts needing refurbishing, parts those can be used as it is; parts those need to be scrapped or recycled.

Inspection also helps to understand the damage which is as a result of misuse by the user, abusive environments and corrosion. In this phase consideration of cleaning costs are inevitable. Sometimes a large portion of the recourses can be consumed in cleaning operations.

The inspection index for component will provide feedback on cost of inspection and cleaning of the components for example sometimes it’s not feasible to inspect a component coastwise compared to use a new one. The components with high intrinsic value are worth inspecting in monitory perspective as compared to less valued parts. It is a major step in decision making on fate of the components of the module. The inspection index could be formulated as shown below.

$$\text{Inspection index (ICI)} = \frac{TCIC}{OCM} = \frac{Total\,Cost\,of\,Inspection\,\&\,Cleaning\,of\,Component}{Original\,Cost\,of\,Component} \ldots (4.5)$$

TCIC= Total cost of inspection and cleaning
TCI= Total cost of inspection
Ic_i = cost of inspection of component i

TCI = $\sum_{i=1}^{n} Ic_i$ … (4.6)

TCL = Total cost of cleaning
TCL_i= cost of cleaning of component i

TCI= $\sum_{i=1}^{n} CL_i$ … (4.7)

Total cost of Inspection and cleaning = TCIC = TCI+ TCL … (4.8)

TCIC = $\sum_{i=1}^{n} Ic_i + \sum_{i=1}^{n} CL_i$ … (4.9)

Cost of Component = OCC

ICI= $\frac{TCIC}{OCC} = \frac{\sum_{i=1}^{n} Ic_i + \sum_{i=1}^{n} CL_i}{OCC}$ … (4.10)

The IIN will be less than one. If the cost of inspection and cleaning exceeds cost of the component then is not in economic interest to inspect and clean the components. Inspection index gives the comparison of inspection and cleaning costs compared to the original cost of the component.

4.2.3 Recycling Index

Recycling of a component refers to economic viability of a unit through material recovery perspective. Recycling is one of the disposing alternatives for the components which are rendered unusable due to wear tear occurred during previous usage or in the disassembly process. The recycling is in this research is always referred as material recovery. The material recovery refers to the recovering of material value from the component. The process involves destruction of component and loss of all functions. The value recovery is done by the shredding and electromagnetic separation. The metallic components are perfect candidate for recycling operations.

The facilities are already established for metal recycling as the value is retained and recovered purity from the smelting operations is equivalent of newly extract metals. The plastic component recycling is still in its infancy stage as desired quality, which is of the virgin material, of plastic fraction is not easily obtained.

The best measure of recyclability of a component is to compare recycling cost to net monetary recovery from recycling the component. Recycling done for material recovery results in to destruction of component and loss of all functions of module. If recycling index is less than one it means that recycling is a profitable operation.

$$\text{Recycling Index (RCI)} = \frac{TCY}{PRRCY} \quad \ldots (4.11)$$

$$RCI = \frac{Total\ Cost\ of\ \mathrm{Re}cycling\ of\ Component}{\mathrm{Pr}ojected\ \mathrm{Re}venue\ Obtained\ by\ \mathrm{Re}cycling\ Component\ in\ Module} \quad \ldots (4.12)$$

TCY = Total cost of recycling

PRRCY=Projected revenue obtained by recycling component in the module

RY_i = Revenue obtained by recycling component i

$$TCY = \sum_{i=1}^{n} C_{REi} \quad \ldots (4.13)$$

$$PRRCY = \sum_{i=1}^{n} RY_i \quad \ldots (4.14)$$

C_{RYi} = cost of recycling component i

$$RCI = \frac{PRRCY}{TCY} = \frac{\sum_{i=1}^{n} RY_i}{\sum_{i=1}^{n} C_{RYi}} \quad \ldots (4.15)$$

The assumption in calculating the recycling index is that if the component classified as recyclable then it can be recycled totally. Total recycling means the revenue obtained is deterministic. The recycling index is always desired to be less than one. The revenue obtained by recycling will be high where recycling yields more pure material. As described in previous part of this section metals will yield high returns as compared to plastics and other non metal components. (Nielsen, Wenzel 2002)

In case of plastic it requires particle by particle by sorting in order to have enrichments leading to 99% purity, which in terms is very costly process. The recycling of a component can be implemented through different perspective in case it can not be recycled to get virgin material. For example nickel cadmium batteries can be recycled to recover both nickel and cadmium used for different purposes. Recycling of component is not necessarily done by the remanufacturing unit. The components which are to be recycled can be sold to specializing recycling agencies. The monitory returns can be summed up as revenue obtained by recycling the component.

4.2.4 Refurbishing Index

Refurbishing refers to repair of damaged parts and application of protective / aesthetic coating. It is unimportant that the damage inflicted to module was during product’s service life or during disassembly process. The important consideration while considering refurbishing would be whether the damage inflicted to the component in its previous use can be undone easily. The ease of the refurbishing will determine a significant portion of resources put on the component overhaul. The refurbishing could be one of the most important factors in cost reduction on remanufacturing floor. It is more helpful when remanufacturing of one of the mass manufactured product component is done. Standardized component used in wide variety of designs helps to reduce the cost of the refurbishing operation. Refurbishing operation becomes eco-friendly when component under consideration contains environmentally controlled substances as one of its constituent, for example electronic circuit boards. Electronic circuit boards are perfect candidate for refurbishing. Refurbishing the boards when one or two elements are dysfunctional will save a considerable amount of material and energy resources.

The main assumption in formulating refurbishing index is the component is repairable and major part of the component has considerable value built in and little rework will yield a high savings. The probabilities of survival are considered very high for refurbished modules. The refurbishing index would be comparison of cost of refurbishing to the expected performance of the module in future in case monetary terms. The other feedback it would give is on wear and tear tendencies of components of the module over the period of time. The simple design of parts against the complex will reduce the value lost over the period of time. The parts with bigger in size are certainly preferable over smaller size. The parts designed with less mating contacts and relative stress levels are more lasting. Design changes incorporated to make the parts sturdier to withstand wear and tear or reduction of factors leading to wear and tear will be enormously helpful if stated in advance.

Refurbishing Index RFI= $\frac{TCRF}{RRF} = \frac{Total\ Cost\ of\ \mathrm{Re}\ furbishing\ Component}{Total\ \mathrm{Re}venue\ Saved\ by\ \mathrm{Re}\ furbishing}$ … (4.16)

CRF_i = Cost of refurbishing of component i

C_{Ci} = Cost of component i of the module.

Total current cost of the components to be refurbished = C_{Ci} … (4.17)

Total cost of refurbishing of components = TCRF= CRF_i … (4.18)

Total cost of Revenue saved by refurbishing components in module = cost of new components – cost refurbishing of the same component

RRF= C_{Ci} - CRF_i … (4.19)

RFI = $\frac{CRF_i}{Cc_i - CRF_i}$ … (4.20)

Refurbishing is very important factor in remanufacturing. Refurbishing cost of component is a major factor in refurbishing index. Less the cost of refurbishing higher the value of refurbishing index. The refurbishing method used for the component should be less recourse consuming which will yield more productivity in refurbishing.

4.2.5 Reusability Index (RUI)

Reusability of a component refers to the ability to use a component after minor cleaning operation. This would take into consideration that reusing a component should be less costly than manufacturing it from scratch. The reusability is can be termed as value recovery. Value recovery can be referred as recovering value embedded in the component and value added in the production of the component at the time of manufacturing (Roger 2003). One of the main goals in remanufacturing is to reuse as many parts as possible. (Czaplika 2003)

The main assumptions are the probability of failure of a component is low. The reusability of component is also important because it is an indicator of economical feasibility of saving the virgin material and energy. The parts which can be used as it after their first use can be termed as rotational parts. The mechanical components which are simple in design to reduce the stress induce are suppose to have more rotational ability than parts with complex design and relatively high stress induction. For example parts used in automotive jacks are simpler in design as compared to cordless drill. This becomes evident from that fact that 80% parts from automotive jack are rotational against 60% in cordless drill. The reusability index is defined as ratio of worth of reusable component to original cost of the component.

$$RUI = \frac{Estimated\ Worth\ of\ Components}{Original\ \cos t\ of\ Component} = \frac{EWC}{OCC} \qquad \ldots (4.21)$$

OCC = original cost of the component

Estimated Worth of the component =EWC = C_{Ci}

$$RUI = \frac{EWC}{OCC} = \frac{C_{Ci}}{OCC} \qquad \ldots (4.22)$$

The reusability index is a strong indicator of well design of component and its durability. It reflects that the component was designed to isolate wear and other anticipated service damage. The reusability index for high intrinsic value components would have a considerable interest on designer's part.

4.2.6 Environment Index (EVI)

Environmental impact of the product after its use is the main reason to implement remanufacturing. The environmental impact in some cases is more crucial for example products using Freon or certain types of polymers or components containing traces of environmentally controlled substances. The environment index is formulated in order to determine the economical impact of the component disposal in case it needs to be dumped in the landfill. Environmental index is measure of the economic impact of component rendered unusable after onetime use and needs to be dumped. The environmental index is formulated by comparing the dumping cost of the component to its original cost. The dumping costs may involve some of the regulatory fees paid to government.

$$EVI = \frac{Total\ Amount\ spent\ for\ Dumping\ an\ Unusable\ Component}{Cost\ of\ Orignal\ Component} = \frac{CLF}{OCC} \qquad \ldots (4.23)$$

CLF_i = cost of land filling component i

OCC = Original cost of component i

$$EVI = \frac{CLF}{OCC} = \frac{CLF_i}{OCC} \qquad \ldots (4.24)$$

The environment index is critical through both designer and organizational management perspective. It is an indicator of pollution created by the component and subsequently the product. The index would also reflect the environmental costs incurred to the organization. To reduce environmental impact designers can follow few guidelines while selecting the material (Michelini, Razzoli 2004)

1. Selecting natural material over synthetic material
2. Use of the same material for different component wherever possible
3. Avoiding complex material, surface coating, surface treatment
4. Use of recyclable material wherever possible

It is desirable that environment index should be as low as possible. In case it exceeds one would reflect on the environmental characteristics of the design. In this case one should not consider the product involving radioactive materials.

4.3 Component Index Weight Criteria

In remanufacturing all the indices do not influence the RI with equal magnitude. Some indices carry relatively high importance compared to others. The magnitude of the influence of the individual index needs to be determined. This can be accomplished by considering the influence of some important factors on indices. These factors are decided by the designer or other decision-maker on the remanufacturing floor. These factors are described in details in the next sections.

The approach used to determine weight carried by individual index is accomplished with metrics approach explained in coming sections. The first step in determining the individual weight is to identify the factors influencing the particular index. The second step is to convert the influence of the factor into number. This can be accomplished by assessing the influence of factors and rating them on the number scale. There could be several methods to achieve numbering the weights. In this research following approach is considered.

1. The three basic factors (BF) for every index were identified. These factors are time, cost involved and other resources consumed by the process. The other resources could be man hour or machine hour etc. The basic factors could be different for different products or different situations.
2. Each of the above factors is rated against the three other set of influencing factors (IF) for the index. The influencing factors are again are defined by situation and design requirements for that particular product.
3. The basic factors (BF) are weighted against other index influencing factors (IF) and is accomplished with the help of questionnaire.
4. The number rating is assigned for standing of influencing factor against basic factor on the scale of 0 to 3. The value obtained after comparing basic factor to influencing factor will be written in the matrix. The value could be decided with the help of questionnaires as explained in next sections.
5. The total in the bottom right corner gives weight for the index.

Table 4.1 Component Index Weight

Basic Factors(BF) / Influence Factors(IF)	Cost(BF1)	Time(BF2)	Other Resources(BF3)	Total
IF1	A1	A2	A3	
IF2	B1	B2	B3	
IF3	C1	C2	C3	
Total				Weight

6. Each value from A1 to C3 will be put by assessing the IF against BF. The values are based on the assessing questionnaire described in the next section.
7. Add the scores in the each column and write the total in corresponding cell in the total row. Add the scores in the each row and write the total in the corresponding cell in the total column.

The weight scheme described above enables the flexibility. This is done to accommodate the different industrial scenarios and product design conditions. The weight values are to be determined by designer depending upon objectives to be achieved for particular product.

4.3.1 Other Resources

The basic factor other resources introduced in the weight criteria for components is for element of flexibility to different industrial scenarios for remanufacturing products. A designer has to determine the factors pertaining to certain situations which have to be considered for remanufacturing. This could be best explained in with the help of example of plastics. In the E.U. certain types of plastics softeners like phthalates are banned for industrial application. In the US that is permitted for industrial use. This type of situation could be a problem in remanufacturing of specific components. The additional resources required to solve the problem could be incorporated.

4.4 Disassembly Index Weight Criteria

Disassembly of the component will have three influencing factors those are ease of disconnection, design complexity, and functional complexity of the component. These factors will be weighted against base factors.

Table 4.2 Disassembly Index Weight

Basic Factors(BF) → / Influence Factors(IF) ↓	Cost (BF1)	Time (BF2)	Other Resources (BF3)	Total
Ease of Disconnection (IF1)	A1	A2	A3	
Design complexity (IF2)	B1	B2	B3	
Functional complexity (IF3)	C1	C2	C3	
Total				

Comparing ease of disconnection compared against time, cost, and other resources.

A1: Ease of disconnection, cost

Disconnection of component cost low = 3

Disconnection of component cost moderate = 2

Disconnection of component cost high = 1

A2: Ease of disconnection, Time

Component disconnection consumes less time = 3

Component disconnection consumes moderate time = 2

Component disconnection consumes lot of time = 1

A3: Ease of disconnection, other recourses

Component disconnection consumes less resources = 3

Component disconnection consumes moderate resources = 2

Component disconnection consumes high resources = 1

Comparing design complexity against time, cost, and other resource consumption

B1: Design complexity, cost

Design complexity making disassembly less costly =3

Design complexity making disassembly moderately costly =2

Design complexity making disassembly more costly = 1

B2: Design complexity, time

Design complexity making disassembly less time consuming =3

Design complexity making disassembly moderately time consuming =2

Design complexity making disassembly more time consuming = 1

B3: Design complexity, other resources

Design complexity leading to less resource consumption =3

Design complexity leading to moderate resource consumption =2

Design complexity leading to high resource consumption =1

Comparing functional complexity against time, cost, and other resource consumption

C1: Functional complexity, cost

Functional complexity making disassembly less costly =3

Functional complexity making disassembly moderately costly =2

Functional complexity making disassembly more costly = 1

C2: Functional complexity, time

Functional complexity making disassembly less time consuming =3

Functional complexity making disassembly moderately time consuming =2

Functional complexity making disassembly more time consuming = 1

C3: Functional complexity, other resources

Functional complexity leading to less resource consumption =3

Functional complexity leading to moderate resource consumption =2

Functional complexity leading to high resource consumption =1

4.5 Inspection Index Weight Criteria

Inspection index will have three influencing factors weighted against the basic factors. Inspection method, cleaning method, an estimate of loss in case inspected component fails.

Table 4.3 Inspection Index Weight

Basic Factors(BF) / Influence Factors(IF)	Cost (BF1)	Time (BF2)	Other Resources (BF3)	Total
Inspection method (IF1)	A1	A2	A3	
Cleaning Method (IF2)	B1	B2	B3	
Loss in case inspected component fails (IF3)	C1	C2	C3	
Total				

Comparing Inspection method with coast, time, and other resources

A1: Inspection method and cost

Inspection method less costly =3

Inspection method moderately costly =2

Inspection method more costly = 1

A2: Inspection method and time

Inspection method less time consuming =3

Inspection method moderately time consuming =2

Inspection method highly time consuming =1

A3: Inspection Method other resources

Inspection method less resource consuming = 3

Inspection method moderately resource consuming = 2

Inspection method highly resource consuming = 1

Comparing cleaning method against time, cost, and other resources

B1: Cleaning Method and cost

Cleaning Method less costly =3

Cleaning Method moderately costly =2

Cleaning Method more costly = 1

B2: Cleaning Method and time

Cleaning Method less time consuming =3

Cleaning Method moderately time consuming =2

Cleaning Method highly time consuming =1

B3: Cleaning Method other resources

Cleaning Method less resource consuming = 3

Cleaning Method moderately resource consuming = 2

Cleaning Method highly resource consuming = 1

Comparing Loss in case inspected component fails against time, cost, and other resources

C1: Loss if component fails and cost

Loss if component fails less costly =3

Loss if component fails moderately costly =2

Loss if component fails more costly = 1

C2: Loss if component fails and time

Loss if component fails less time consuming =3

Loss if component fails moderately time consuming =2

Loss if component fails highly time consuming =1

C3: Loss if component fails and other resources

Loss if component fails less resource consuming = 3

Loss if component fails moderately resource consuming = 2

Loss if component fails highly resource consuming = 1

4.6 Recycling Index Weight Criteria

Three influencing factors for recycling Index are recycling process, component material composition i.e. if the component is made from single material or composite material and Material recovery.

Table 4.4 Recycling Index Weight

Basic Factors(BF) / Influence Factors(IF)	Cost (BF1)	Time (BF2)	Other Resources (BF3)	Total
Recycling process (IF1)	A1	A2	A3	
Material composition (IF2)	B1	B2	B3	
Material recovery (IF3)	C1	C2	C3	
Total				

Comparing Recycling process against Cost, time, and other resources

A1: Recycling process and cost

Recycling process is less costly =3

Recycling process moderately costly =2

Recycling process highly costly = 1

A2: Recycling process and time

Recycling process less time consuming =3

Recycling process moderately time consuming =2

Recycling process highly time consuming = 1

A3: Recycling process and other resources

Recycling process leading to less resource consuming =3

Recycling process leading to moderate resource consuming =2

Recycling process leading to high resource consuming =1

Comparing Material composition with cost, time, and other resources

B1: Material composition and cost

Material composition leading affecting recycling is less costly =3

Material composition leading affecting recycling is moderately costly =2

Material composition leading affecting recycling is highly costly = 1

B2: Material composition and time

Material composition affecting recycling is less time consuming =3

Material composition affecting recycling is moderately time consuming =2

Material composition affecting recycling is highly time consuming = 1

B3: Material composition and other resource consumption

Material composition affecting recycling less resource consuming =3

Material composition affecting recycling is moderate resource consuming =2

Material composition affecting recycling high resource consuming =1

Comparing Material recovery with cost, time, and other resources

C1: Material recovery and cost

Material recovery affecting recycling is less costly =3

Material recovery affecting recycling is moderately costly =2

Material recovery affecting recycling is highly costly = 1

C2: Material recovery and time

Material recovery affecting recycling is less time consuming =3

Material recovery affecting recycling is moderately time consuming =2

Material recovery affecting recycling is highly time consuming = 1

C3: Material recovery and other resource consumption

Material recovery affecting recycling less resource consuming =3

Material recovery affecting recycling is moderate resource consuming =2

Material recovery affecting recycling high resource consuming =1

4.7 Refurbishing Index Weight Criteria

Three influencing factors for refurbishing index are special set up required for refurbishing, design complexity, functional complexity.

Table 4.5 Refurbishing Index Weight

Basic Factors(BF) / Influence Factors(IF)	Cost (BF1)	Time (BF2)	Other Resources (BF3)	Total
Special Set up required (IF1)	A1	A2	A3	
Design complexity (IF2)	B1	B2	B3	
Functional complexity (IF3)	C1	C2	C3	
Total				

Comparing Special set up requirements against time, cost, and other resource consumption

A1: Special set up requirements, cost

Low cost for special set up for refurbishing =3

Moderate cost for special set up for refurbishing =2

High cost for special set up for refurbishing =1

A2: Special set up requirements, time

Low time required for special set up =3

Moderate time required for special set up =2

High time required for special set up =1

A3: Special set up, other resources consumption

Special set up requiring less other resources =3

Special set up requiring moderate other resources =2

Special set up requiring high other resources =1

Comparing design complexity against time, cost, and other resource consumption

B1: Design complexity, cost

Design complexity making disassembly less costly =3

Design complexity making disassembly moderately costly =2

Design complexity making disassembly more costly = 1

B2: Design complexity, time

Design complexity making disassembly less time consuming =3

Design complexity making disassembly moderately time consuming =2

Design complexity making disassembly more time consuming = 1

B3: Design complexity, other resources

Design complexity leading to less resource consumption =3

Design complexity leading to moderate resource consumption =2

Design complexity leading to high resource consumption =1

Comparing functional complexity against time, cost, and other resource consumption

C1: Functional complexity, cost

Functional complexity making disassembly less costly =3

Functional complexity making disassembly moderately costly =2

Functional complexity making disassembly more costly = 1

C2: Functional complexity, time

Functional complexity making disassembly less time consuming =3

Functional complexity making disassembly moderately time consuming =2

Functional complexity making disassembly more time consuming = 1

C3: Functional complexity, other resources

Functional complexity leading to less resource consumption =3

Functional complexity leading to moderate resource consumption =2

Functional complexity leading to high resource consumption =1

4.8 Reusability Index Weight Criteria

Three influencing factors for reusability index are Technology cycle, Wear rate, and obsolescence factor.

Table 4.6 Weight Criteria Reusability Index

Basic Factors(BF) / Influence Factors(IF)	Cost (BF1)	Time (BF2)	Other Resources (BF3)	Total
Technology Cycle (IF1)	A1	A2	A3	
Wear rate (IF2)	B1	B2	B3	
Obsolescence factor (IF3)	C1	C2	C3	
Total				

Comparing Technology cycle against time, cost, and other resources

A1: Technology cycle and cost

Technology cycle influence is less costly =3

Technology cycle influence is moderately costly =2

Technology cycle influence is highly costly = 1

A2: Technology cycle and time

Technology cycle influence is less time consuming =3

Technology cycle influence is moderately time consuming =2

Technology cycle influence is highly time consuming = 1

A3: Technology cycle and other resources

Technology cycle leading to less resource consuming =3

Technology cycle leading to moderate resource consuming =2

Technology cycle leading to high resource consuming =1

Comparing Wear rate with cost, time, and other resources

B1: Wear rate and cost

Wear rate leading affecting reusability is less costly =3

Wear rate leading affecting reusability is moderately costly =2

Wear rate leading affecting reusability is highly costly = 1

B2: Wear rate and time

Wear rate affecting reusability is less time consuming =3

Wear rate affecting reusability is moderately time consuming =2

Wear rate affecting reusability is highly time consuming = 1

B3: Wear rate and other resource consumption

Wear rate affecting reusability less resource consuming =3

Wear rate affecting reusability is moderate resource consuming =2

Wear rate affecting reusability high resource consuming =1

Comparing Obsolescence factor with cost, time, and other resources

C1: Obsolescence factor and cost

Obsolescence factor affecting reusability is less costly =3

Obsolescence factor affecting reusability is moderately costly =2

Obsolescence factor affecting reusability is highly costly = 1

C2: Obsolescence factor and time

Obsolescence factor affecting reusability is less time consuming =3

Obsolescence factor affecting reusability is moderately time consuming =2

Obsolescence factor affecting reusability is highly time consuming = 1

C3: Obsolescence factor and other resource consumption

Obsolescence factor affecting reusability less resource consuming =3

Obsolescence factor affecting reusability is moderate resource consuming =2

Obsolescence factor affecting reusability high resource consuming =1

4.9 Environmental Index Weight Criteria

Three influencing factors for environment index are Technology cycle, Legal complexity, and material sensitivity

Table 4.7 Weight Criteria Environmental Index

Basic Factors(BF) / Influence Factors(IF)	Cost (BF1)	Time (BF2)	Other Resources (BF3)	Total
Technology cycle (IF1)	A1	A2	A3	
Legal complexity (IF2)	B1	B2	B3	
Material sensitivity (IF3)	C1	C2	C3	
Total				

Comparing Technology cycle against time, cost, and other resources

A1: Technology cycle and cost

Technology cycle is less costly =3

Technology cycle moderately costly =2

Technology cycle highly costly = 1

A2: Technology cycle and time

Technology cycle less time consuming =3

Technology cycle moderately time consuming =2

Technology cycle highly time consuming = 1

A3: Technology cycle and other resources

Technology cycle leading to less resource consuming =3

Technology cycle leading to moderate resource consuming =2

Technology cycle leading to high resource consuming =1

Comparing Legal complexity with cost, time, and other resources

B1: Legal complexity and cost

Legal complexity leading affecting recycling is less costly =3

Legal complexity leading affecting recycling is moderately costly =2

Legal complexity leading affecting recycling is highly costly = 1

B2: Legal complexity and time

Legal complexity affecting recycling is less time consuming =3

Legal complexity affecting recycling is moderately time consuming =2

Legal complexity affecting recycling is highly time consuming = 1

B3: Legal complexity and other resource consumption

Legal complexity affecting recycling less resource consuming =3

Legal complexity affecting recycling is moderate resource consuming =2

Legal complexity affecting recycling high resource consuming =1

Comparing Material sensitivity with cost, time, and other resources

C1: Material sensitivity and cost

Material sensitivity affecting recycling is less costly =3

Material sensitivity affecting recycling is moderately costly =2

Material sensitivity affecting recycling is highly costly = 1

C2: Material sensitivity and time

Material sensitivity affecting recycling is less time consuming =3

Material sensitivity affecting recycling is moderately time consuming =2

Material sensitivity affecting recycling is highly time consuming = 1

C3: Material sensitivity and other resource consumption

Material sensitivity affecting recycling less resource consuming =3

Material sensitivity affecting recycling is moderate resource consuming =2

Material sensitivity affecting recycling high resource consuming =1

4.10 Component RI Calculation

This is the third step in formulation of remanufacturing index for a component. After calculating individual indices for the components and the weights the next step would be combining them in to remanufacturing index for component. The component RI will have total three indices to be combined. The disassembly and inspection indices are the basic indices of the equation. The third equation will be decided after the Recycling, Refurbishing, Reusability and Environmental Indices are calculated. The index which will have maximum value will be used to combine it with Disassembly and Inspection Index.

4.10.1 Effective Index

The index equations as stated in the sections 4.2.1 to 4.2.6 can not be used as they are for the purpose of computation of RI of the component. The values of equations like DI, ICI, RCI, RFI and EVI are desired low as far as possible and the value of RUI is always desired high as possible. In order to combine the equations with their respective weights, those need to be brought on the same level of desirability. This can be achieved by computing effective indices in case they need to be used. The effective indices DI, ICI, RCI, RFI and EVI can be simply calculated by subtracting the index from 1.

4.10.2 Relative Weight Establishment for Components

The weights as established in the section 4.4 previously are transformed into relative weights. The concept of relative weight could be easily stated as relative standing of weights for DI, ICI and STI to each other. The relative index can be computed with following formula.

$$\mathrm{Re}\,lativeWeight\ DI = \frac{WeightDI}{Weight\ DI + Weight\ ICI + WeightSTI} \quad \ldots (4.25)$$

$$\mathrm{Re}\,lativeWeight\ ICI = \frac{Weight\ ICI}{Weight\ DI + Weight\ ICI + WeightSTI} \quad \ldots (4.26)$$

$$\mathrm{Re}\,lativeWeight\ STI = \frac{Weight\ STI}{Weight\ DI + Weight\ ICI + WeightSTI} \quad \ldots (4.27)$$

4.10.3 Weight Determination Guidelines

Table 4.8 Weight Determination Guidelines

Index	Weight Selection factors
Disassembly	1. Special tools required 2. Special handling considerations required 3. Special instructions / supervision needed
Inspection & Cleaning	1. Special testing equipment required 2. special material testing required 3. Type of testing and inspection required 4. Type of cleaning agent used 5. Safety of cleaning agents 6. Extra testing techniques required because of aging considerations
Recycling	1. Type of material composition: homogenous, heterogeneous 2. Recycling techniques 3. Material recovery and quality of material recovered 4. Legal issues for recycling of particular materials
Reusability	1. Deprecation cycle 2. Life of component in its existing stage 3. Material availability
Refurbishing	1. Special set or processes required other than manufacturing 2. reliability of refurbishing process 3. Design complexity affecting refurbishing 4. Availability of refurbishing process
Environmental	1. Hazard of dumping component 2. Degree of safety for surrounding people 3. Legal expenses for dumping components 4. Design requirements for the particular material 5. Life cycle of the material

4.11 Combining Individual Indices

Combining the module indices into RI can be accomplished in several ways. The combine index should satisfy four major criterions Hammond (1996).

1. The magnitude criterion which ensures that resulting remanufacturing index should not be significantly larger or smaller than individual indices. The index should not be more than 1 and less than 0
2. The idealization criterion which stipulates that in case all the indices are 1 then RI should come to 1 and index of the component / module / product will be 1.
3. The Annihilation criterion which ensures that in case one index approaches to zero – regardless of the performance of the other indices. This will ensure that a significant problem which would make a product would not be overshadowed by out standing performances in other areas.
4. The weighting criterion which stipulates since every index dose not contributes equally to the total outcome each must be weighted according to its contribution.
5. Inverse weighted addition criterion is a non linear additive approach and is widely used. It satisfies all the above criterions.

For the purpose of calculation of RI of the component the two base indices and one state index of component are combined using inverse weight addition method. Inverse weighted addition criterion is a non linear additive approach and is widely used in electric circuit resistance calculations. The equation 4.24 will illustrate the concept.

$$RI_{COMPONENT} = \frac{1}{\frac{\mathrm{Re}\,lative\ Weight\ DI}{Effective\ DI} + \frac{\mathrm{Re}\,lative\ Weight\ ICI}{Effective\ ICI} + \frac{\mathrm{Re}\,lative\ Weight\ (State\ Index)}{Effective\ (State\ Index)}} \quad \ldots (4.28)$$

4.12 Module RI Determination

The next step after the RI of the component has determined is to calculate RI of module. The RI of module will be obtained by combining RI of individual components. In this case RI of the module can be simply taken as average of the RI of the components of the module.

$$RI_{MODULE} = \frac{RI_{Component1} + RI_{Component2} + RI_{Component...n}}{Total\ Number\ of\ Components\ in\ Module} \quad \text{…. (4.29)}$$

4.13 RI of Product

RI of the product is calculated by combining the RI of individual modules. All the modules don’t carry the same importance in a product as a total. So a weighting scheme indicating relative importance of module; has been designed. The individual modules carry different magnitude of weights in the product. The magnitude of the weight carried by a module can be determined by comparing the remanufacturing cost of the module to each other. The comparative basis can be explained with the help of tables 4.8 and 4.9. The comparison weights can be chosen by designer with desecration.

Table 4.9 Weights for Modules (I)

Weight determination	Values
Row has more Remanufacturing cost than column	1.25
Row has same Remanufacturing cost than column	1
Row has less Remanufacturing cost than column	0.75

The values selected in second column of table 4.9 for weight determination for modules are based on based feedback from design department of the product ETFX-50. The major considerations are costs of individual modules. The values suggested were range of 0.25, 0.50, and 0.75. The more the difference between cost of modules higher would be the range selected. In this case range of 0.25 was selected based on the feedback.

Table 4.10 Weight Determination for Modules (II)

	Module 1	Module 2	Module 3	Module...n	Score	Approximate Weight (%)
Module 1	1					
Module 2		1				
Module 3			1			
Module…n				1		
				Total		

The weights and RI of the individual modules are combined with inverse weight addition criteria to obtain the RI for the product.

$$RI_{PRODUCT} = \frac{1}{\frac{Weight\ Module1}{RI_{MODULE1}} + \frac{Weight\ Module2}{RI_{MODULE2}} + \frac{Weight\ Module_n}{RI_{MODULE..n}}} \quad \ldots (4.30)$$

4.14 Summary

In this chapter method of formulating the RI of a product was explained. The relevant parameters in each index formation were stated in details. The method of calculating remanufacturing index of components, modules and the product was explained along with weighing scheme guidelines. In the next chapter 5 a case study is performed using the RI formulation explained in this chapter.

CHAPTER 5

RI MODEL TESTING

5.1 Formulation Application to Case Study

In this chapter the Remanufacturing Index (RI) formulation as stated in the chapter 4, was used to determine the RI of electric stapler, ETF X 50. The product is manufactured by Arrow Fasteners, a company based in Chicago Illinois as shown in the fig. 5.1.

Figure 5.1 ETFX-50 Electric Staple Gun
(Source: Arrow Fasteners, Chicago IL)

5.2 Product Components

Table 5.1 below lists all the parts of the electric staple gun, For each part listed is its corresponding material, manufacturing method and the function each part performs in the overall function of the electric staple gun.

Table 5.1 ETFX-50 Parts Description

Part Number	Part Name	Materials	Method of Manufacture	Function
1	Plastic Housing	Polypropylene	Injection Molding	• Encases internal mechanisms • Part of Handle built into housing • Cools Coils
2	Black Grip	Polypropylene	Injection Molding	• Comfortable Grip • Non Slip Surface
3	Trigger	Polypropylene	Injection Molding	• Actuates Staple Gun by Pushing Switch on Control Circuit
4	Trigger Spring	Aluminum Alloy	Extrusion	• Provides resistance to trigger • Resets trigger to original position
5	(5) 1” Housing Screws	Steel	Metal Stamping	• Holds plastic housing together
6	Safety Clip	Polypropylene	Injection Molding	• Disables or allows function of staple gun depending on position

Table 5.1 (Continued)

7	Staple Housing (Sub-assembly)			• Houses and feeds staples
7.1	Exterior Shell	Steel	Stamped, Bent, Welded	• Houses staple feeder mechanism
7.2	Staple Cartridge	Steel	Stamped, Bent, Welded	• Houses staples
7.3	Feeder Mechanism (Spring, feeder, latch)	Steel	Stamped, Bent, Welded	• Pushes staples to position to be fired from staple gun • Allows staples to be loaded
7.4	(3) 1” Bolts	Aluminum Alloy	Casting	• Fastens staple housing to plastic housing • Provides grounding from plastic housing electrical circuit
7.5	(3) Nuts (Nylock)	Aluminum Alloy	Casting	• Fastens to the end of the bolts which hold staple housing to plastic housing
7.6	Prime guard Screw	Aluminum Alloy	Casting	• Fastens staple cartridge to exterior shell
7.7	Nut (Nylock)	Aluminum Alloy	Casting	• Fastens to the end of the bolt which holds staple cartridge to exterior shell

Table 5.1 (Continued)

8	Electro Magnet (Sub-assembly)			• Fires staples when actuated by trigger and circuit sub-assembly
8.1	Stop-Plate	Steel	Stamping, Welding	• Keeps firing mechanism from damaging housing
8.2	Padding	Reinforced fiber resin	Fibers	• Dampens firing mechanism force and reduces sound produced by firing mechanism
8.3	Locating Pin	Steel	Extrusion	• Keeps firing mechanism in proper position
8.4	Firing Plate	Steel	Stamping	• The part used to force staples out of staple gun
8.5	Spring (1" diameter)	Steel	Extrusion	• Resists firing mechanism • Resets firing mechanism
8.6	Hollow rod	Steel	Extrusion	• Moved by the electro-magnet and creates firing force • Moves firing plate
9	Circuit and Cord (Sub-assembly)			• Provides power to staple gun • The control for the firing mechanism
9.1	Circuit Board	Several materials including tin	Soldering	• Control mechanism for staple gun • Contains a switch for activation
9.2	Wiring	Copper alloy with plastic coating	Drawn	• Transfers power to circuit and grounds staple gun
9.3	Cord	Copper alloy with plastic coating	Drawn	• Connects circuit board to power source

5.3 Product Tree Approach Application

As stated in chapter 4, the product tree approach is applied to the Electrical staple and nail gun. The first level identified is the product as whole shown in fig. 5.2. The modules identified as second level items. Then the components identified as third level.

Figure 5.2 ETFX-50 Assembled
(Source: Prof. Sridhar Kota**,** University of Michigan, Ann Arbor, MI)

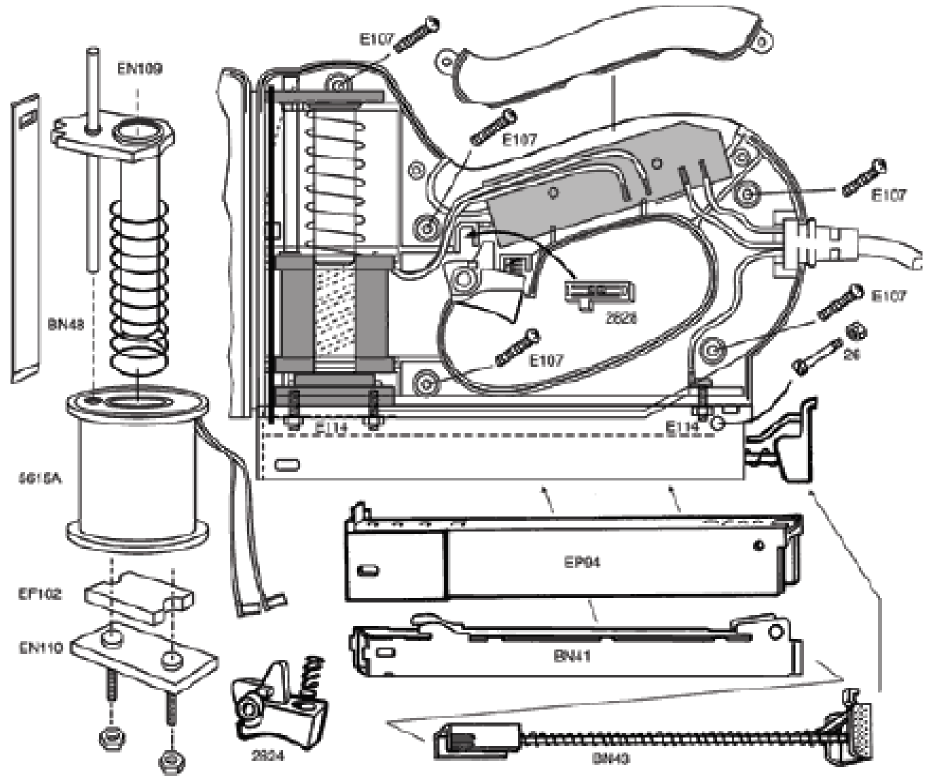

Figure 5.3 Product Assembly and Sub-Systems
(Source: Arrow Fasteners, Chicago IL)

5.4 Module Classification

The product was classified in to three different modules as listed in tables 5.1-5.3.

Module 1: Casing and fastening accessories

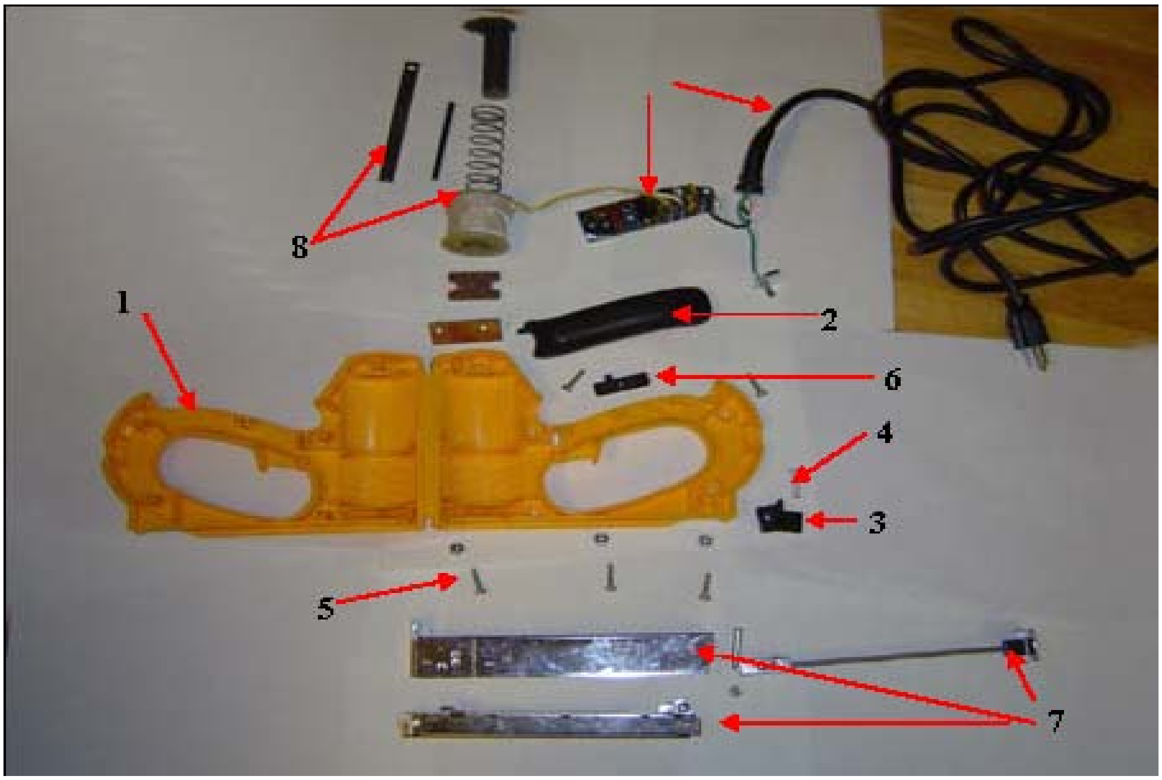

Figure 5.4 Exploded View of Staple Housing Sub-Assembly (Module 1 & 2)

Table 5.2 Module 1 Analysis

Part	Part Name	Function	Material	Cost	Problem	Action
1	Plastic Housing	Encases internal mechanisms Part of Handle built into housing Cools Coils	Polypropylene	$2.50	Cracked	Recycle
2	Black Grip	Comfortable Grip Non Slip Surface	Polypropylene	$1.25	-	Reuse
3	Trigger	Actuates Staple Gun by Pushing Switch on Control Circuit	Polypropylene	$0.50	-	Reuse
4	Trigger Spring	Provides resistance to trigger Resets trigger to original position	Aluminum Alloy	$0.10	-	Reuse
5	(5) 1” Housing Screws	Holds plastic housing together	Steel	$0.65	-	Reuse
6	Safety Clip	Disables or allows function of staple gun depending on position	Polypropylene	$0.55	-	Reuse

(Source: Prof. Sridhar Kota**,** University of Michigan, Ann Arbor, MI)

Table 5.3 Module 2 Analysis

Part	Part Name	Function	Material	Cost	Problem	Action
7	Staple Housing (Sub-assembly)	Houses and feeds staples		$4.50		
7.1	Exterior Shell	Houses staple feeder mechanism	Steel	$3.25	Needs coating	Coating
7.2	Staple Cartridge	Houses staples	Steel	$4.50	-	Reuse
7.3	Feeder Mechanism (Spring, feeder, latch)	Pushes staples to position to be fired from staple gun Allows staples to be loaded	Steel	$3.50	Spring broken	Recycle spring
7.4	(3) 1" Bolts	Fastens staple housing to plastic housing Provides grounding from plastic housing electrical circuit	Aluminum Alloy	$0.50	-	Reuse
7.5	(3) Nuts (Nylock)	Fastens to the end of the bolts which hold staple housing to plastic housing	Aluminum Alloy	$0.30	-	Reuse
7.6	Prime guard Screw	Fastens staple cartridge to exterior shell	Aluminum Alloy	$0.50	-	Reuse
7.7	Nut (Nylock)	Fastens to the end of the bolt which holds staple cartridge to exterior shell	Aluminum Alloy	$0.30	Threads out	Recycle

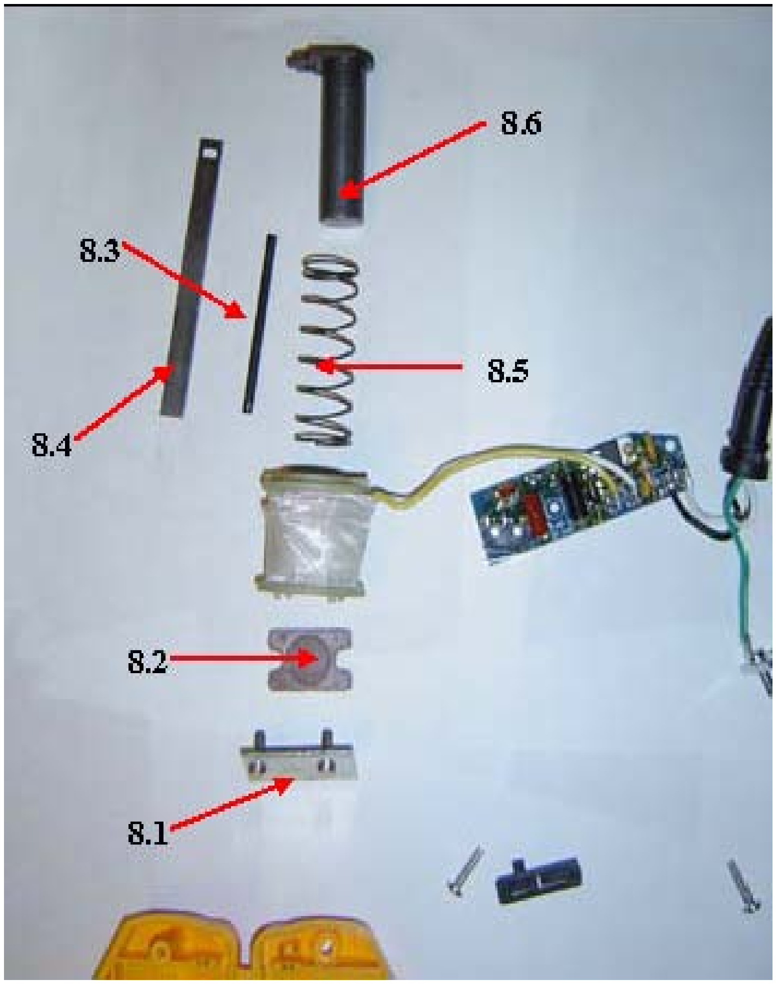

Figure 5.5 Exploded View of Electro Magnet Sub Assembly (Module 3)
(Source Prof. Sridhar Kota**,** University of Michigan, Ann Arbor, MI)

Table 5.4 Module 3 Analysis

Part	Part Name	Function	Material	Cost	Problem	Action
8.0	Electro Magnet (Sub-assembly)	Fires staples when actuated by trigger and circuit sub-assembly				
8.1	Stop-Plate	Keeps firing mechanism from damaging housing	Steel	$1.30	Bend	Refurbish
8.2	Padding	Dampens firing mechanism force and reduces sound produced by firing mechanism	Reinforced fiber resin	$0.65	Cracks	Recycle
8.3	Locating Pin	Keeps firing mechanism in proper position	Steel	$0.75	Bent	Refurbish (straighten out Pin)
8.4	Firing Plate	The part used to force staples out of staple gun	Steel	$0.75	Needs coating	Refurbish (Coating)
8.5	Spring (1" diameter)	Resists firing mechanism Resets firing mechanism	Steel	$0.65	-	Reuse
8.6	Hollow rod	Moved by the electro-magnet and creates firing force Moves firing plate	Steel	$1.25	-	Reuse
8.7	Coil	Induces electromagnetic induction	Copper	$4.50		Reuse

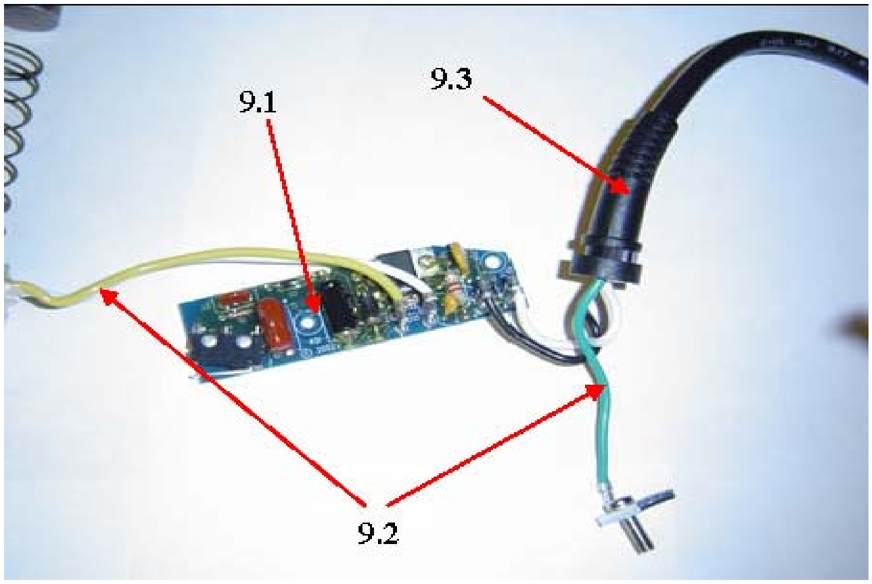

Figure 5.6 Exploded View of Circuit and Cord Sub Assembly (Module 4)
(Source: Prof. Sridhar Kota**,** University of Michigan, Ann Arbor, MI)

Table 5.5 Module 4 Analysis

Part	Part Name	Function	Material	Cost	Problem	Action
9.0	Circuit and Cord (Sub-assembly)	Provides power to staple gun The control for the firing mechanism				
9.1	Circuit Board	Control mechanism for staple gun Contains a switch for activation	Several materials including tin	$1.15	-	Reuse
9.2	Wiring	Transfers power to circuit and grounds staple gun	Copper alloy with plastic coating	$0.50	-	Reuse
9.3	Cord	Connects circuit board to power source	Copper alloy with plastic coating	$3.00	Damaged (Cuts / burn marks)	Recycle

5.5 Remanufacturing Index Calculations ETFX-50: Model 1

5.5.1 Model 1 Base and State Index

Table 5.6 Index Table for Module 1

No.	Component Name	Base Indices		State Index
1	Plastic Housing	Disassembly	Inspection and Cleaning	Recycling
2	Black grip	Disassembly	Inspection and Cleaning	Reusability
3	Trigger	Disassembly	Inspection and Cleaning	Reusability
4	Trigger Spring	Disassembly	Inspection and Cleaning	Reusability
5	Housing Screws (5)	Disassembly	Inspection and Cleaning	Reusability
6	Safety clip	Disassembly	Inspection and Cleaning	Reusability

OCC = Original cost of the component
DCC =Disassembly cost of the component
DI = Disassembly index of the component
EDI = Effective disassembly index of the component
TCIC = Inspection and cleaning cost of the component
CLI = Cleaning Cost of the component
INC = Inspection Cost of the component
ICI =Inspection & Cleaning index of the component

Table 5.7 Module 1 Base Index Computation

No.	Component Name	OCC	DCC	DI	EDI	TCIC		ICI	EICI
						CLI	INC		
1	Plastic Housing	$2.00	$0.20	0.10	0.90	$0.00	$0.01	0.01	0.99
2	Black grip	$1.00	$0.06	0.06	0.94	$0.04	$0.01	0.05	0.95
3	Trigger	$0.40	$0.01	0.03	0.98	$0.01	$0.01	0.05	0.95
4	Trigger Spring	$0.08	$0.01	0.13	0.88	$0.00	$0.03	0.38	0.63
5	Housing Screws (5)	$0.52	$0.04	0.08	0.92	$0.02	$0.02	0.08	0.92
6	Safety clip	$0.44	$0.02	0.05	0.95	$0.02	$0.01	0.07	0.93

OCC = Original cost of the component

TCY = Recycling cost of the component

PRRCY = Projected recycling revenue of the component

RCI = Recycling index of the component

ERCI = Effective recycling index of the component

Table 5.8 Component 1 State Index Computation (I)

No.	Component Name	Index	OCC	TCY	PRRCY	RCI	ERCI
1	Plastic Housing	Recycling	$2.00	$0.40	$0.70	0.57	0.43

OCC = Original cost of the component

EWC = Estimated worth of the component

RUI = Reusability of the component

ERUI = Effective reusability index of the component

Table 5.9 Module 1 State Index Computation (II)

No.	Component Name	Index	OCC	EWC	RUI	ERUI
2	Black grip	Reusability	$1.00	$0.80	0.80	0.80
3	Trigger	Reusability	$0.40	$0.32	0.80	0.80
4	Trigger spring	Reusability	$0.08	$0.06	0.75	0.75
5	Housing screws (5)	Reusability	$0.52	$0.42	0.81	0.81
6	Safety clip	Reusability	$0.44	$0.35	0.80	0.80

5.5.2 Module 1 Index Weight Computations

As described in chapter 4, the weight selection for individual indices is based on degree of resources consumption as shown in the table 4.8. The weight was assigned on the scale of 1 to 3. These weights are particular to this case study.

Disassembly Index Weight

Module1 Component 1: Plastic Housing

Comparing ease of disconnection compared against time, cost, and other resources for plastic housing. Other resources for plastic housing were identified as special tools requirement for disassembly, inspection and cleaning, extra handling of the components during course of disassembly, inspection and cleaning.

Table 5.10 Disassembly Index Weight Plastic Housing

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Inspection and cleaning index weight computation

Module1 Component 1: Plastic Housing

Table 5.11 Inspection and Cleaning Index Weight Plastic Housing

Factor	Value	Comments
A1	2	Needs Inspection critical due to high aesthetic requirements
A2	2	Inspection for cracks in shell
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Recycling Index weight
Module 1 Component 1: Plastic Housing

Table 5.12 Recycling Index Weight: Plastic Housing

Factor	Value	Comments
A1	1	Recycling of polypropylene
A2	1	Recycling
A3	3	
B1	1	Plastic resin
B2	2	
B3	3	
C1	1	
C2	3	
C3	3	
Total	18	

Disassembly Index Weight: Black Grip
Module 1 Component 2

Table 5.13 Disassembly Index Weight: Black Grip

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Inspection and Cleaning Index Weight: Black Grip
Module 1 Component 2

Table 5.14 Inspection and Cleaning Index Weight: Black Grip

Factor	Value	Comments
A1	2	Aesthetic requirements
A2	2	Aesthetic requirements
A3	3	
B1	2	Aesthetic requirements
B2	2	
B3	3	
C1	3	
C2	3	
C3	3	
Total	23	

Refurbishing Index Weight: Black Grip
Module 1 Component 2

Table 5.15 Refurbishing Index Weight: Black Grip

Factor	Value	Comments
A1	3	
A2	3	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	27	

Disassembly Index Weight: Trigger
Module 1 Component 3: Trigger

Table 5.16 Disassembly Index Weight: Trigger

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	26	

Module 1 Component 3
Inspection and Cleaning Index Weight: Trigger

Table 5.17 Inspection and Cleaning Index Weight: Trigger

Factor	Value	Comments
A1	2	Aesthetic requirements
A2	2	Aesthetic requirements
A3	3	
B1	2	Aesthetic requirements, Inspected for cracks
B2	2	
B3	2	Ridges cleaning/ dirt
C1	2	Ridges
C2	3	
C3	3	
Total	21	

Module 1 Component 3
Reusability Index Weight: Trigger

Table 5.18 Reusability Index Weight: Trigger

Factor	Value	Comments
A1	3	
A2	3	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	27	

Module 1 Component 4
Disassembly Index Weight: Trigger Spring

Table 5.19 Disassembly Index Weight: Trigger Spring

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Module 1 Component 4:
Inspection and Cleaning Index Weight: Trigger Spring

Table 5.20 Inspection and Cleaning Index Weight: Trigger Spring

Factor	Value	Comments
A1	2	Oil, dirt cleaned
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	Spring testing for fatigue cycles
C3	3	
Total	20	

Module 1 Component 4:
Reusability Index Weigh: Trigger Spring

Table 5.21 Reusability Index Weight: Trigger Spring

Factor	Value	Comments
A1	3	
A2	3	
A3	3	
B1	2	Simple design but life cycle is limited to two.
B2	2	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Module 1 Component 5
Disassembly Index Weight: Housing Screws

Table 5.22 Disassembly Index Weight: Housing Screws

Factor	Value	Comments
A1	3	
A2	3	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	27	

Module 1 Component 5
Inspection and Cleaning Index Weight: Housing Screws

Table 5.23 Inspection and Cleaning Index Weight: Housing Screws

Factor	Value	Comments
A1	2	Solvents used for cleaning
A2	2	
A3	2	
B1	2	Solvents used for cleaning
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Module 1 Component 5
Reusability Index: Housing Screws

Table 5.24 Reusability Index: Housing Screws

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	Deform due to stresses in use
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Module 1 Component 6
Disassembly Index Weight: Safety Clip

Table 5.25 Disassembly Index Weight: Safety Clip

Factor	Value	Comments
A1	3	
A2	3	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	27	

Module 1 Component 6
Inspection and Cleaning Index Weight: Safety Clip

5.26 Inspection and Cleaning Index Weight: Safety Clip

Factor	Value	Comments
A1	2	Aesthetic requirements
A2	3	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	26	

Module 1 Component 6: Safety clip
Reusability Index: Safety clip

Table 5.27 Reusability Index: Safety Clip

Factor	Value	Comments
A1	3	
A2	2	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	26	

5.5.3 Module 1 Indices And Indices Weight Summary

Table 5.28 Module 1 Indices and Indices Weight

No.	Name	EDI	ECI	ESTI	RWDI	RWICI	RWSTI	RI
1	Plastic Housing	0.90	0.99	0.43	0.32	0.40	0.29	0.71
2	Black Grip	0.94	0.95	0.80	0.29	0.33	0.39	0.88
3	Trigger	0.98	0.95	0.80	0.35	0.28	0.36	0.90
4	Trigger Spring	0.88	0.63	0.75	0.36	0.29	0.36	0.75
5	Housing Screws	0.92	0.92	0.81	0.38	0.28	0.34	0.88
6	Safety Clip	0.95	0.93	0.80	0.34	0.33	0.33	0.89
								0.83

Remanufacturing Index of module 1 = 0.830

The computations for module 2 to 4 are listed in appendices A, B and C.

5.6 Module Remanufacturing Costs

Table 5.29 Remanufacturing Cost of Modules

Module no.	Remanufacturing Cost
Module 1 (M1)	$2.22
Module 2 (M2)	$1.84
Module 3 (M3)	$1.05
Module 4 (M4)	$2.83

5.7 Module Weight Determination

Table 5.30 Module Weight Determination

	M1	M2	M3	M4		% Weight
M1	1	1.25	1.25	0.75	4.25	0.27
M2	0.75	1	1.25	0.75	3.75	0.23
M3	0.75	0.75	1	0.75	3.25	0.20
M4	1.25	1.25	1.25	1	4.75	0.30
					16	1.00

5.8 RI of ETFX-50

$$= \frac{1}{\frac{Weight\ for\ Module1}{RI\ of\ Module1} + \frac{Weight\ for\ Module2}{RI\ of\ Module2} + \frac{Weight\ for\ Module3}{RI\ of\ Module3} + \frac{Weight\ for\ Module4}{RI\ of\ Module4}}$$

$$= \frac{1}{\frac{0.27}{0.83} + \frac{0.23}{0.69} + \frac{0.20}{0.67} + \frac{0.30}{0.71}}$$

=0.72

CHAPTER 6

RESULTS INTERPRETATIONS AND FUTURE RESEARCH

The RI computation model was constructed in this research with the motive of getting an insight of product after-life. The major goal was to study the conditions of the product and its components after its intended life-cycle is over. This research will give some valuable guidelines for material selection and physical part-design or change deign of physical part to make it last longer in terms of life-cycle. The second important point in the model was inducing environmental considerations in RI computations. The environmental factors play a major role in case component is discarded and categorized as harmful for environment. The best way to understand the product RI is to get into details of individual component RI. The component RI would reflect the quality of design and impact of operating condition of the same.

The value of Remanufacturing Index (RI) should fall within range of 0 to 1 as stated in the chapter 3. The ideal RI is 1, which is reflection of no costs for refurbishing, recycling are involved and relative weights are equal for every index of components. In addition to that there is no depreciation of the components. This is a very ideal situation which can hardly be achieved.

The second important thing to achieve is equal relative weights, which can not be attained as not all the processes involved could have same weights. The goodness of remanufacturing process on basis of RI computed can be assessed with value of RI as shown in the table

Table 6.1 RI Desirability

RI Value	Remanufacturing Desirability
Between 1 to 0.75	High
Between 0.75 to 0.60	Moderate
Between 0.60 to 0.30	Low
Between 0.30 to 0.0	Poor

6.1 Results and Interpretation of the RI of ETFX-50

The RI of the ETFX-50 came out to be 0.72. The value indicates that the product sample has good remanufacturability. This could be interpreted as the remanufacturability of specific sample studied was 72% in terms of costs. The index was on the higher side, which could be reasoned on the fact that small number of high cost parts were either refurbished or replaced. The costs of replacement and refurbishing were minimal. In this case study 21% components were recycled, 61% components were reused and 17% components were refurbished. The various costs of remanufacturing are listed in the table.

Table 6.2 ETFX-50 Remanufacturing Summary

	Cost	% Components
Reusability Value	$13.76	61.00
Recycling Revenue	$1.49	21.00
Recycling Cost	$0.69	
Refurbishing cost	$0.86	17.00

The second important factor needs to be considered is the weight scheme for both components and modules. The weight scheme designed is the most important factor for flexibility. The model could be easily applied to wide range of products with different set of conditions. The conditions for remanufacturing for staple gun are very different than remanufacturing of automobile parts such as gear box or clutch. The focus is based on costs and availability of resources for remanufacturing.

6.2 Benchmarking of ETFX-50 with Bras and Hammond Model

The RI of the ETFX-50 staple gun was computed with Bras and Hammond method of RI computing. The computation was carried as per the guidelines as given in the research paper. The RI index of the staple gun turns out to be 0.33. The computations are as shown in the table 6.3 -6.6

Table 6.3 ETFX-50 Summary

# Parts	34
# Ideal Parts	19
#Refurbished Parts	4
# Replaced Parts	6
# Key Parts	11
# Key Replaced Parts	3
# Tests	4
# Ideal Inspection	18
Cleaning Score	99
Td	30.2
Ta	59.2
Tt	52.5

Table 6.4 ETFX-50 Questionnaire

Part #	Part Name	Number of Parts	Large Relative Motions	Different Material Properties required	Required to facilitate Assembly or disassembly	Required to Isolate wear	Significant intrinsic value (relative to Assembly)	Does Part Fatigue	Will parts require adjustment	If coated can coating be reapplied	If worn can worn surfaces be restored	If damaged during assembly Can damaged part be refurbished	Theoretical min Number of parts	Total number of refurbished parts	Total number of replaced parts	Number of Ideal inspections	Number of Key parts	Number of Key parts Replaces
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Plastic Housing	2	N	N	Y	N	Y	N	N			N	2	0	2	0	2	2
2	Black grip	1	N	N	Y	N	Y	N	N			N	1	0	0	1	1	
3	Trigger	1	N	N	Y	N	N	N	N			N	1	0	0	1	0	
4	Trigger Spring	1	Y	N	N	N	N	N	N	Y		Y	1	0	0	1	0	
5	Housing Screws (5)	5	N	N	N	N	N	N	N	Y		N	0	0	0	0	0	
6	Safety Clip	1	N	N	Y	N	N	N	N			N	1	0	0	1	0	
7	Exterior Shell	1	N	N	Y	N	Y	N	N	Y		Y	1	1	0	1	0	
8	Staple Cartridge	1	N	N	N	N	Y	Y	Y	Y	Y	Y	1	0	0	1	1	
9	Feeder Mechanis m	3	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	3	0	1	2	1	1
10	(3) 1” Bolts	3	N	N	N	N	N	N	N	Y		N	0	0	0	0	3	
11	(3) Nuts (Nylock)	3	N	N	N	N	N	N	N			N	0	0	0	1	0	
12	Prime guard Screw	1	N	N	N	N	N	N	N	Y		N	0	0	0	0	0	
13	Nut (Nylock)	1	N	N	N	N	N	N	N			Y	0	0	1	0	0	
14	Stop-Plate	1	Y	N	Y	Y	Y	Y	N	Y	Y	Y	1	0	0	1	1	
15	Padding	1	N	N	N	Y	N	Y	N			Y	1	0	1	1	0	
16	Locating Pin	1	Y	N	N	Y	N	Y	Y	Y	Y	Y	1	1	0	1	0	
17	Firing Plate	1	Y	N	Y	Y	N	N	Y			Y	1	1	0	1	0	
18	Spring (1” diameter)	1	Y	N	N	N	N	N	N	Y		Y	1	1	0	1	0	
19	Hollow rod	1	Y	N	Y	N	N	N	N	Y	Y	N	1	0	0	1	0	
20	Coil	1	N	N	Y	N	Y	N	N			Y	1	0	0	1	0	
21	Circuit Board	1	N	Y	Y	N	Y	N	N		Y	Y	0	0	0	1	1	
22	Wiring	1	N	Y	Y	N	Y	N	N		Y	N	0	0	0	1	1	
23	Cord	1	N	Y	Y	N	N	N	N		N	N	1	0	1	0	0	
		34											1 9	4	6	18	1 1	3

Table 6.5 ETFX-50 DFA Analysis

Part #	Part Name	Number of Parts A	If part can corrode –is part protectively coated B	Manual Removal time per part C	Manual Handling Time per part D	Disassembly Time (Seconds) E	Manual Handling time per part F	Manual Inspection Time G	Operating time H	Cleaning code I	Cleaning per part score J	Total cleaning score K
1	Plastic Housing	2	N	5.0	0.0	5.0	3.0	0.0	10.0	-		
2	Black grip	1	N	2.0	0.0	1.0	1.0	0.7	2.5	D	6	6
3	Trigger	1	N	1.2	0.0	1.2	0.6	0.5	3.0	D	6	6
4	Trigger Spring	1	Y	0.5	0.0	0.5	0.3	0.2	1.5	D	6	6
5	Housing Screws (5)	5	Y	0.0	0.0	0.0	0.0	2.0	0.0	B	3	3
6	Safety Clip	1	N	0.5	0.0	0.5	0.3	0.3	1.4	D	6	6
7	Exterior Shell	1	Y	3.6	0.0	3.0	1.5	1.3	1.8	D	6	6
8	Staple Cartridge	1	Y	1.0	1.5	1.0	0.5	0.5	1.5	D	6	6
9	Feeder Mechanism	3	Y	1.7	2.5	2.4	1.0	1.4	1.1	D	6	6
10	(3) 1” Bolts	3	Y	0.0	0.0	0.0	0.0	1.0	0.0	C	6	6
11	(3) Nuts (Nylock)	3	Y	0.0	0.0	0.0	0.0	1.0	0.0	C	6	6
12	Prime guard Screw	1	Y	0.0	0.0	0.0	0.0	1.0	0.0	C	6	6
13	(3)Nut (Nylock)	1	Y	0.0	0.0	0.0	0.0	1.0	0.0	C	6	6
14	Stop-Plate	1	Y	2.5	0.0	1.0	0.0	1.8	2.0	D	6	6
15	Padding	1	N	0.2	0.0	0.2	1.0	0.0	1.0	-		
16	Locating Pin	1	Y	0.1	0.0	0.1	0.1	0.1	0.2	B	3	3
17	Firing Plate	1	Y	1.0	0.0	1.0	0.1	1.0	1.1	D	6	6
18	Spring (1” diameter)	1	Y	0.1	0.0	0.1	0.1	0.2	0.3	D	6	6
19	Hollow rod	1	Y	0.1	0.0	0.1	0.1	0.2	0.3	C	6	6
20	Coil	1	N	2.0	2.5	4.0	1.0	3.0	8.0	A	1	1
21	Circuit Board	1	N	3.0	2.0	5.0	2.0	5.0	12.0	A	1	1
22	Wiring	1	N	2.0	1.0	3.0	0.8	3.0	6.5	A	1	1
23	Cord	1	N	1.0	1.0	1.8	1.0	0.0	5.0	-	0	0
						30.9			59.2			99

Table 6.6 ETFX-50 Matrices Values (I)

Metric Disassembly	0.943709	d
Metric Assembly	0.962838	a
Metric Inspection	0.642857	i
Metric Testing	0.761905	t
Metrics Cleaning	0.191919	C
Metrics Refurbishing	0.882353	f
Metrics Key Replaced	0.727273	k
Metrics Basic Replaced	0.941176	r

Table 6.7 ETFX-50 Matrices Values (II)

I	0.957018
Q	0.734694
D	0.893522

Table 6.7 RI of ETFX-50

100aCdfikrt	5.158641
21Cdfirt	1.547049
25adfirt	9.239738
9aCfirt	0.676461
32aCdirt	2.572442
aCdfrt	0.110338
8aCdfrt	0.882701
4aCdfir	0.372389
	15.40112

Remanufacturing Index	0.334952

The disparity between two indices can be easily explained with the help of differences between basic methodologies of research. The Bras and Hammond model is based on DFA (Design for Assembly) principle as explained in chapter 3. The major factors in DFA are time for assembly disassembly, inspection and cleaning and number of key parts replaced and refurbished. The case study of Kodak fun-saver camera in the same research yielded RI 0.83 as design was relatively simple. The products with simple designs tend to yield high remanufacturing indices. The products with complex design have low RI.

The analysis made after computations indicate that that cleaning score in case of ETFX-50 was high, which essentially made the RI sink to 0.33. This has an important revelation during this course of comparison. The different product of same make would give different cleaning score and hence the different index.

6.3 Result Interpretation of the Case Study

The RI of ETFX-50 electric staple gun indicates the even though all the indices are high the cleaning index pulls it down to low. The rational reasoning behind could be stated as the environment in which the staple gun is used. The other indices were fairly high as the assembly and disassembly procedure for these products are standardized.

6.4 Future Research

The future research for this model could be described in the following areas.

1. Incorporation of elements of manufacturability in terms of time of assembly disassembly, inspection and cleaning into the equation of RI of individual components.
2. Comprehensive study of design patterns for different types of products, which will enable the weight schemes as per the goal for remanufacturing easier.
3. Linking of LCA (Life Cycle Analysis) to RI. This would require choosing the elements of RI and interpreting them in terms of LCA factors.
4. Finally studying the viability of this model to existing design practices of wide range of products in wide range of geographical scenarios.

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APPENDICES

Appendix A Remanufacturing Index Calculations ETFX-50: Model 2

Table A.1 Index Table Module 2

No.	Component Name	Base Index		State Index
7.1	Exterior Shell	Disassembly	Inspection and Cleaning	Refurbishing
7.2	Staple Cartridge	Disassembly	Inspection and Cleaning	Reusability
7.3	Feeder Mechanism	Disassembly	Inspection and Cleaning	Reusability
7.4	Bolts	Disassembly	Inspection and Cleaning	Reusability
7.5	Nuts (Nylock)	Disassembly	Inspection and Cleaning	Reusability
7.6	Prime guard Screw	Disassembly	Inspection and Cleaning	Reusability
7.7	Nut (Nylock)	Disassembly	Inspection and Cleaning	Recyclablity

OCC = Original cost of the component
DCC =Disassembly cost of the component
DI = Disassembly index of the component
EDI = Effective disassembly index of the component
TCIC = Inspection and cleaning cost of the component
CLI = Cleaning Cost of the component
INC = Inspection Cost of the component
ICI =Inspection & Cleaning index of the component

Table A.2 Component1 Base Index Computation

No.	Component Name	OCC	DCC	DI	EDI	TCIC		ICI	EICI
						CLI	INC		
7.1	Exterior Shell	$2.60	$0.20	0.10	0.90	$0.00	$0.01	0.01	0.99
7.2	Staple Cartridge	$3.60	$0.06	0.06	0.94	$0.04	$0.01	0.05	0.95
7.3	Feeder Mechanism	$2.80	$0.01	0.03	0.98	$0.01	$0.01	0.05	0.95
7.4	Bolts	$0.40	$0.01	0.13	0.88	$0.00	$0.03	0.38	0.63
7.5	Nuts (Nylock)	$0.24	$0.04	0.08	0.92	$0.02	$0.02	0.08	0.92
7.6	Prime guard Screw	$0.40	$0.02	0.05	0.95	$0.02	$0.01	0.07	0.93
7.7	Nut (Nylock)	$0.24	$0.20	0.10	0.90	$0.00	$0.01	0.01	0.99

OCC = Original cost of the component
TCRF = Refurbishing cost of the component
RFI = Refurbishing index of the component
ERFI = Effective Refurbishing index of the component

Table A.3 Module 2 State Index Computation (I)

No.	Component Name	Index	OCC	TCRF	RFI	ERFI
7.1	Exterior Shell	Refurbishing	$2.60	$0.35	0.87	0.13

Appendix A (Continued)

OCC = Original cost of the component
EWC = Estimated worth of the component
RUI = Reusability of the component
ERUI = Effective reusability index of the component

Table A.4 Module 2 State Index Computation (II)

No.	Component Name	Index	OCC	EWC	RUI	ERUI
7.2	Staple Cartridge	Reusability	$3.60	$2.88	0.80	0.80
7.3	Feeder Mechanism	Reusability	$2.80	$2.24	0.80	0.80
7.4	Bolts	Reusability	$0.40	$0.32	0.80	0.80
7.5	Nuts (Nylock)	Reusability	$0.24	$0.96	0.80	0.80
7.6	Prime guard Screw	Reusability	$0.40	$0.32	0.80	0.80

OCC = Original cost of the component
TCY = Recycling cost of the component
PRRCY = Projected recycling revenue of the component
RCI = Recycling index of the component
ERCI = Effective recycling index of the component

Table A.5 Module 2 State Index Computation (III)

No.	Component Name	Index	OCC	TCY	PRRCY	RCI	ERCI
7.7	Nut (Nylock)	Recycling	$0.24	$0.01	$0.19	0.95	0.05

Appendix A (Continued)

Module 2 Component 7.1: Disassembly Index Weight: Exterior Shell

Table A.6 Disassembly Index Weight: Exterior Shell

Factor	Value	Comments
A1	3	
A2	3	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	27	

Module 2 Component 7.1: Inspection and Cleaning Index Weight: Exterior Shell

Table A.7 Inspection and Cleaning Index Weight: Exterior Shell

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	2	
B3	3	
C1	3	
C2	3	
C3	3	
Total	24	

Appendix A (Continued)

Module 2 Component 7.1: Refurbishing Index: Exterior Shell

Table A.8 Refurbishing Index: Exterior Shell

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

Module 2 Component 7.2: Disassembly Index Weight: Staple Cartridge

Table A.9 Disassembly Index Weight: Staple Cartridge

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	2	
B3	3	
C1	1	
C2	3	
C3	3	
Total	18	

Appendix A (Continued)

Module 2 Component 7.2: Inspection and Cleaning Index Weight: Staple Cartridge

Table A.10 Inspection and Cleaning Index Weight: Staple Cartridge

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

Module 2 Component 7.2: Reusability Index: Staple Cartridge

Table A.11 Reusability Index: Staple Cartridge

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Appendix A (Continued)

Module 2 Component 7.3: Disassembly Index Weight: Feeder Mechanism

Table A.12 Disassembly Index Weight: Feeder Mechanism

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

Module 2 Component 7.3: Inspection and Cleaning Index Weight: Feeder Mechanism

Table A.13 Inspection and Cleaning Index Weight: Feeder Mechanism

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

Appendix A (Continued)

Module 2 Component 7.3: Reusability Index Weight: Feeder Mechanism

Table A.14 Reusability Index Weight: Feeder Mechanism

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Module 2 Component 7.4: Disassembly Index Weight: Bolts

Table A.15 Disassembly Index Weight: Bolts

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Appendix A (Continued)

Module 2 Component 7.4: Inspection and Cleaning Index Weight: Bolts

Table A.16 Inspection and Cleaning Index Weight: Bolts

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Module 2 Component 7.4: Reusability Index Weight: Bolts

Table A.17 Reusability Index Weight: Bolts

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Appendix A (Continued)

Module 2 Component 7.5: Disassembly Index Weight: Nuts

Table A.18 Disassembly Index Weight: Nuts

Factor	Value	Comments
A1	3	
A2	3	
A3	3	
B1	3	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	27	

Module 2 Component 7.5: Inspection and Cleaning Index Weight: Nuts

Table A.19 Inspection and Cleaning Index Weight: Nuts

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Appendix A (Continued)

Module 2 Component 7.5: Reusability Index: Nuts

Table A.20 Reusability Index: Nuts

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Module 2 Component 7.6: Disassembly Index Weight: Prime Guard Screw

Table A.21 Disassembly Index Weight: Prime Guard Screw

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Appendix A (Continued)

Module 2 Component 7.6: Inspection and Cleaning Index Weight: Prime guard screw

Table A.22 Inspection and Cleaning Index Weight: Prime Guard Screw

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Module 2 Component 7.6: Reusability Index: Prime Guard Screw

Table A.23 Reusability Index: Prime Guard Screw

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Appendix A (Continued)

Module 2 Component 7.7: Disassembly Index Weight: Nut (Nylock)

Table A.24 Disassembly Index Weight: Nut (Nylock)

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Module 2 Component 7.7: Inspection and Cleaning Index Weight: Nut (Nylock)

Table A.25 Inspection and Cleaning Index Weight: Nut (Nylock)

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Appendix A (Continued)

Module 2 Component 7.7: Recycling Index Weight: Nut (Nylock)

Table A.26 Recycling Index Weight: Nut (Nylock)

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

Table A.27 RI Computation Module 2

No.	Name	EDI	ECI	ESTI	RWDI	RWICI	RWSTI	RI
7.1	Exterior Shell	0.92	0.96	0.87	0.41	0.36	0.23	0.39
7.2	Staple Cartridge	0.93	0.96	0.80	0.33	0.27	0.40	0.88
7.3	Feeder Mechanism	0.93	0.88	0.80	0.29	0.29	0.42	0.89
7.4	Bolts	0.93	0.95	0.80	0.35	0.35	0.31	0.75
7.5	Nuts (Nylock)	0.98	0.99	0.80	0.36	0.34	0.30	0.88
7.6	Prime guard Screw	0.98	0.93	0.80	0.36	0.32	0.32	0.89
7.7	Nut (Nylock)	0.88	0.96	0.95	0.40	0.35	0.24	0.18
								0.69

Appendix B Remanufacturing Index Calculations ETFX-50: Model 3

Table B.1 Module 3 Indices

No	Component Name	Base Index		State Index
8.1	Stop-Plate	Disassembly	Inspection and Cleaning	Refurbishing
8.2	Padding	Disassembly	Inspection and Cleaning	Recycling
8.3	Locating Pin	Disassembly	Inspection and Cleaning	Refurbishing
8.4	Firing Plate	Disassembly	Inspection and Cleaning	Refurbishing
8.5	Spring	Disassembly	Inspection and Cleaning	Reusability
8.6	Hollow rod	Disassembly	Inspection and Cleaning	Reusability
8.7	Coil	Disassembly	Inspection and Cleaning	Reusability

OCC = Original cost of the component
DCC =Disassembly cost of the component
DI = Disassembly index of the component
EDI = Effective disassembly index of the component
TCIC = Inspection and cleaning cost of the component
CLI = Cleaning Cost of the component
INC = Inspection Cost of the component
ICI =Inspection & Cleaning index of the component

Base Index Computation Table Module 3

Table B.2 Module 3 Base Index Computation Table

No.	Component Name	OCC	DCC	DI	EDI	TCIC		ICI	EICI
						CLI	INC		
8.1	Stop-Plate	$1.04	$0.10	0.10	0.90	$0.00	$0.04	0.04	0.96
8.2	Padding	$0.52	$0.10	0.19	0.81	$0.00	$0.02	0.04	0.96
8.3	Locating Pin	$0.60	$0.05	0.08	0.92	$0.01	$0.02	0.05	0.95
8.4	Firing Plate	$0.60	$0.06	0.10	0.90	$0.01	$0.02	0.05	0.95
8.5	Spring	$0.52	$0.01	0.02	0.98	$0.00	$0.01	0.02	0.98
8.6	Hollow rod	$1.00	$0.16	0.16	0.84	$0.00	$0.12	0.12	0.88
8.7	Coil	$3.60	$0.30	0.08	0.92	$0.20	$0.15	0.10	0.90

Appendix B (Continued)

OCC = Original cost of the component
TCRF = Refurbishing cost of the component
RFI = Refurbishing index of the component
ERFI = Effective Refurbishing index of the component

Table B.3 Module 3 State Index (I)

No.	Component Name	Index	OCC	TCRF	RFI	ERFI
8.1	Stop-Plate	Refurbishing	$1.04	$0.25	0.76	0.24
8.3	Locating Pin	Refurbishing	$0.60	$0.06	0.90	0.10
8.4	Firing Plate	Refurbishing	$0.60	$0.20	0.67	0.33

OCC = Original cost of the component
TCY = Recycling cost of the component
PRRCY = Projected recycling revenue of the component
RCI = Recycling index of the component
ERCI = Effective recycling index of the component

Table B.4 Module 3 State Index (II)

No.	Component Name	Index	OCC		EVI	EEVI
8.2	Padding	Dumping	$0.52	$0.20	0.19	0.81

OCC = Original cost of the component
EWC = Estimated worth of the component
RUI = Reusability of the component
ERUI = Effective reusability index of the component

Table B.5 Module 3 State Index (III)

No.	Component Name	Index	OCC	EWC	RUI	ERUI
8.5	Spring	Reusability	$0.52	$0.35	0.67	0.67
8.6	Hollow Rod	Reusability	$1.00	$0.80	0.80	0.80
8.7	Coil	Reusability	$3.60	$2.88	0.80	0.80

Appendix B (Continued)

Module 3 Component 8.1 Disassembly Index Weight: Stop-Plate

Table B.6 Disassembly Index Weight: Stop-Plate

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Module 3 Component 8.1: Inspection and Cleaning Index Weight: Stop-Plate

Table B.7 Inspection and Cleaning Index Weight: Stop-Plate

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Appendix B (Continued)

Module 3 Component 8.1: Refurbishing Index: Stop-Plate

Table B.8 Refurbishing Index: Stop-Plate

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Module 3 Component 8.2: Disassembly Index Weight: Padding

Table B.9 Disassembly Index Weight: Padding

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Appendix B (Continued)

Module 3 Component 8.2: Inspection and Cleaning Index Weight: Padding

Table B.10 Inspection and Cleaning Index Weight: Padding

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Module 3 Component 8.2: Recycling Index Weight: Padding

Table B.11 Recycling Index Weight: Padding

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	3	
C2	3	
C3	3	
Total	19	

Appendix B (Continued)

Module 3 Component 8.3: Disassembly Index Weight: Locating Pin

Table B.12 Disassembly Index Weight: Locating Pin

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Module 3 Component 8.3: Inspection and Cleaning Index Weight: Locating Pin

Table B.13 Inspection and Cleaning Index Weight: Locating Pin

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	19	

Appendix B (Continued)

Module 3 Component 8.3: Refurbishing Index: Locating Pin

Table B.14 Refurbishing Index: Locating Pin

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Module 3 Component 8.4: Disassembly Index Weight: Firing Plate

Table B.15 Disassembly Index Weight: Firing Plate

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	2	
C1	2	
C2	3	
C3	3	
Total	21	

Appendix B (Continued)

Module 3 Component 8.4: Inspection and Cleaning Index Weight: Firing Plate

Table B.16 Inspection and Cleaning Index Weight: Firing Plate

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Module 3 Component 8.4: Refurbishing Index: Firing Plate

Table B.17 Refurbishing Index: Firing Plate

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Appendix B (Continued)

Module 3 Component 8.5: Disassembly Index Weight: Spring (1” diameter)

Table B.18 Disassembly Index Weight: Spring (1” diameter)

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Module 3 Component 8.5
Inspection and Cleaning Index Weight: Spring (1” diameter)

Table B.19 Inspection and Cleaning Index Weight: Spring (1” diameter)

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Appendix B (Continued)

Module 3 Component 8.5: Reusability Index: Spring (1” diameter)

Table B.20 Reusability Index: Spring (1” diameter)

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Module 3 Component 8.6: Disassembly Index Weight: Hollow Rod

Table B.21 Disassembly Index Weight: Hollow Rod

Factor	Value	Comments
A1	2	
A2	3	
A3	3	
B1	2	
B2	3	
B3	3	
C1	3	
C2	3	
C3	3	
Total	25	

Appendix B (Continued)

Module 3 Component 8.6: Inspection and Cleaning Index Weight: Hollow Rod

Table B.22 Inspection and Cleaning Index Weight: Hollow Rod

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Module 3 Component 8.6: Reusability Index Weight: Hollow Rod

Table B.23 Reusability Index Weight: Hollow Rod

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	3	
C3	3	
Total	22	

Appendix B (Continued)

Module 3 Component 8.7: Disassembly Index Weight: Coil

Table B.24 Disassembly Index Weight: Coil

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	2	
B3	3	
C1	1	
C2	3	
C3	3	
Total	18	

Module 3 Component 8.7: Inspection and Cleaning Index Weight: Coil

Table B.25 Inspection and Cleaning Index Weight: Coil

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

Appendix B (Continued)

Module 3 Component 8.7: Reusability Index: Coil

Table B.26 Reusability Index: Coil

Factor	Value	Comments
A1	2	
A2	2	
A3	3	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	23	

Table B.27 RI Module 3

No.	Name	EDI	ECI	ESTI	RWDI	RWICI	RWSTI	RI
8.1	Stop-Plate	0.90	0.96	0.76	0.33	0.33	0.33	0.47
8.2	Padding	0.81	0.96	0.81	0.38	0.42	0.31	0.88
8.3	Locating Pin	0.92	0.95	0.90	0.36	0.31	0.33	0.24
8.4	Firing Plate	0.90	0.95	0.67	0.33	0.35	0.32	0.57
8.5	Spring	0.98	0.98	0.67	0.34	0.31	0.34	0.85
8.6	Hollow rod	0.84	0.88	0.80	0.37	0.30	0.33	0.84
8.7	Coil	0.92	0.90	0.80	0.33	0.25	0.42	0.86
								0.69

Appendix C Remanufacturing Index Calculations ETFX-50: Model 4

Table C.1 Base Indices Module 4

No.	Component Name	Base Index		State Index
9.1	Circuit Board	Disassembly	Inspection and Cleaning	Reusability
9.2	Wiring	Disassembly	Inspection and Cleaning	Reusability
9.3	Cord	Disassembly	Inspection and Cleaning	Recycling

OCC = Original cost of the component
DCC =Disassembly cost of the component
DI = Disassembly index of the component
EDI = Effective disassembly index of the component
TCIC = Inspection and cleaning cost of the component
CLI = Cleaning Cost of the component
INC = Inspection Cost of the component
ICI =Inspection & Cleaning index of the component

Table C.2 State Index Module 4 (I)

No.	Component Name	OCC	DCC	DI	EDI	TCIC		ICI	EICI
						CLI	INC		
9.1	Circuit Board	$0.92	$0.18	0.20	0.80	$0.12	$0.30	0.46	0.54
9.2	Wiring	$0.40	$0.03	0.08	0.93	$0.02	$0.10	0.30	0.70
9.3	Cord	$2.40	$0.07	0.03	0.97	$0.00	$0.01	0.00	1.00

OCC = Original cost of the component
EWC = Estimated worth of the component
RUI = Reusability of the component
ERUI = Effective reusability index of the component

Table C.3 State Index Module 4 (II)

No.	Component Name	Index	OCC	EWC	RUI	ERUI
9.1	Circuit Board	Reusability	$0.92	$0.74	0.80	0.80
9.2	Wiring	Reusability	$0.40	$0.32	0.80	0.80

Appendix C (Continued)

OCC = Original cost of the component
TCY = Recycling cost of the component
PRRCY = Projected recycling revenue of the component
RCI = Recycling index of the component
ERCI = Effective recycling index of the component

Table C.4 State Index Module 4 (III)

No.	Component Name	Index	OCC	TCY	PRRCY	RCI	ERCI
9.3	Cord	Recycling	$2.40	$0.20	$0.60	0.67	0.33

Appendix C (Continued)

Module 4 Component 9.1: Disassembly Index Weight: Circuit Board

Table C.5 Disassembly Index Weight: Circuit Board

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

Module 4 Component 9.1: Inspection and Cleaning Index Weight: Circuit Board

Table C.6 Inspection and Cleaning Index Weight: Circuit Board

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

Appendix C (Continued)

Module 4 Component 9.1: Reusability Index Weight: Circuit Board

Table C.7 Reusability Index Weight: Circuit Board

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Module 4 Component 9.2: Disassembly Index Weight: Wiring

Table C.8 Disassembly Index Weight: Wiring

Factor	Value	Comments
A1	2	
A2	2	
A3	2	
B1	2	
B2	2	
B3	3	
C1	2	
C2	2	
C3	3	
Total	20	

Appendix C (Continued)

Module 4 Component 9.2: Inspection and Cleaning Index Weight: Wiring

Table C.9 Inspection and Cleaning Index Weight: Wiring

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	2	
B3	3	
C1	1	
C2	3	
C3	3	
Total	18	

Module 4 Component 9.2: Reusability Index: Wiring

Table C.10 Reusability Index: Wiring

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	2	
B2	2	
B3	3	
C1	1	
C2	3	
C3	3	
Total	19	

Appendix C (Continued)

Module 4 Component 9.3: Disassembly Index Weight: Chord

Table C.11 Disassembly Index Weight: Chord

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	2	
B3	3	
C1	1	
C2	2	
C3	3	
Total	17	

Module 4 Component 9.3: Inspection and Cleaning Index Weight: Chord

Table C.12 Inspection and Cleaning Index Weight: Chord

Factor	Value	Comments
A1	1	
A2	1	
A3	3	
B1	1	
B2	2	
B3	3	
C1	1	
C2	3	
C3	3	
Total	18	

Appendix C (Continued)

Module 4 Component 9.3: Recycling Index: Chord

Table C.13 Recycling Index: Chord

Factor	Value	Comments
A1	1	Multiple material composition
A2	1	Multiple material composition
A3	3	
B1	1	Multiple material composition
B2	1	
B3	3	
C1	1	
C2	1	
C3	3	
Total	15	

RI Computation Module 4

Table C.14 RI Module 4

No.	Name	EDI	ECI	ESTI	WDI	WICI	WSTI	RI
9.1	Circuit Board	0.80	0.54	0.80	0.30	0.30	0.40	0.70
9.2	Wiring	0.93	0.70	0.80	0.35	0.32	0.33	0.80
9.3	Cord	0.97	1.00	0.67	0.34	0.36	0.30	0.62
								0.71