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Overview of Prospects in Adopting Remanufacturing of End-of-Life Electronic Products in the Developing Countries

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***Abstract*—The useful life of consumer electronic products appears to be relatively short because of rapid changes in equipment features and capabilities, thereby leading to an increase in the generation of end-of-life electronics or electronic waste (e-waste). The present e-waste management practices have been unsustainable while posing environmental challenges. Large quantities collected in developed countries are also moved across frontiers into developing countries. Consequently, new management strategies are required to divert e-waste from landfills, check the trans-boundary movement of e-waste, and halt the adoption of inappropriate management practices in developing countries. This can be achieved by the global application of product reuse and recovery strategies. These strategies reduce the requirements for virgin materials, energy consumption, and landfill space. In this paper, we discussed the influence of product design on product end-of-life scenario and review the recovery options available for end-of-life electronics. Remanufacturing is a viable option in electronic waste management: reducing e-waste generation and increasing reuse of equipment and components. The remanufacturing operation for mobile phone was used as illustration. The prospects, challenges, and opportunities in adopting remanufacturing in developing countries were also discussed. The problems of product design and product obsolescence issues need to be addressed if a global solution to e-waste generation and management is to be found soonest. The globalization of producer responsibility is critical in achieving this.**

***Index Terms*—Electronic waste, Product recovery, remanufacturing, Sustainable development, Waste management.**

I. INTRODUCTION

The global demand for consumer electric and electronic products has been phenomenal in the last two decades. Consumer electric and electronic equipment (EEE) are of particular concern due to high production volumes and characteristically short time scales of technological or stylistic obsolescence leading to the generation of large quantities of obsolete and discarded products otherwise refereed to as waste electrical electronic equipment (WEEE) or electronic waste (e-waste) [1] [2]. The negative environmental effects of the growing consumption of electronic hardware are most visible in the end-of-life (EoL) stage. The escalating growth in consumer waste in recent years has started to threaten the environment and is posing significant challenge to waste management experts. Product recovery is mainly driven by the escalating deterioration of the environment and aims to minimize the amount of waste sent to landfills by recovering materials and parts from products at their EoL [3]. Product recovery options include remanufacturing, material recovery (recycling), and energy recovery through waste-to-energy facilities. Product recovery reduces the requirement of virgin materials, energy consumption, landfill space and environmental pollution. The recovery of products can lead to profitable business opportunities. The most dramatic reduction in environmental impact of a product can be made by product re-use and re-manufacture in which the geometrical form of the product is retained and the product is re- used for the same purpose as during its original life cycle or for secondary purposes.

Africa, especially sub-Saharan Africa and some countries in the Asia Pacific have been at the bottom of the information and communication technologies (ICT) ladder both in the acquisition of the basic electronic goods (Figure 1) and in the expenditure in ICT infrastructure (Figure 2).

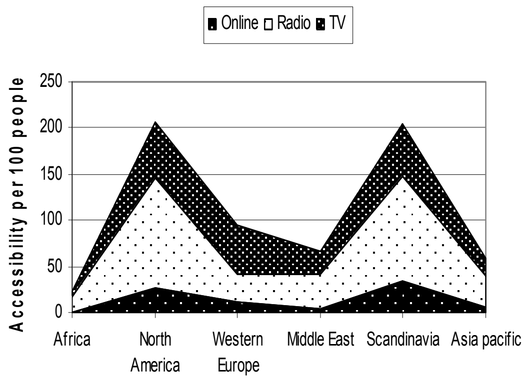

Figure 1. Proportion of people having access to various technologies. Data adapted from [4].

Africa accounts for almost zero percent of global ICT production and virtually imports all its ICT needs [4]. In fact, a significant proportion of ICT wares in use in Africa are either hand-me down goods or imported secondhand devices.

In the light of large-scale generation of e-waste at global and regional levels, and the increasing trans-boundary movement of large quantities of EoL devices into developing countries, we review the role of product recovery as a viable strategy in electronic waste management. The primary focus

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of this paper is to review the role of remanufacturing as a tool in electronic waste management: reducing e-waste generation and increasing reuse of equipment and components.

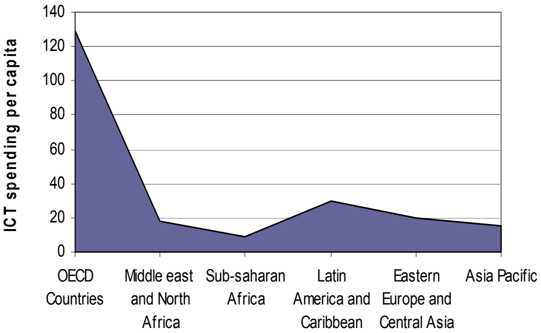

Figure 2. ICT spending per capita according to region
Data adapted from [4].

In doing this, we present an overview of options in material recovery from e-waste and the role of product design in determining recovery options applicable at the EoL of an EEE. Also discussed is the role of remanufacturing in achieving sustainability in the ICT sector. In the second part of the paper, we review remanufacturing operation, using mobile phone remanufacturing for illustration. The later sections outline the challenges, prospects, and limitations of remanufacturing EoL EEE especially in the developing countries. Finally, we draw the conclusions.

II. THE GLOBAL E-WASTE CRISIS

Large quantities of e-wastes are generated and managed at the global level as a consequence of the fast expanding global market for electronic goods, and the rapid reduction in the lifespan of electronic products (Figure 3). Figure 3 show that TVs have the highest life span of about thirteen years and mobile phones the least, with a life span of two years. The second rapidly scrapped devices are computers whose life span has decreased to about three years [5].

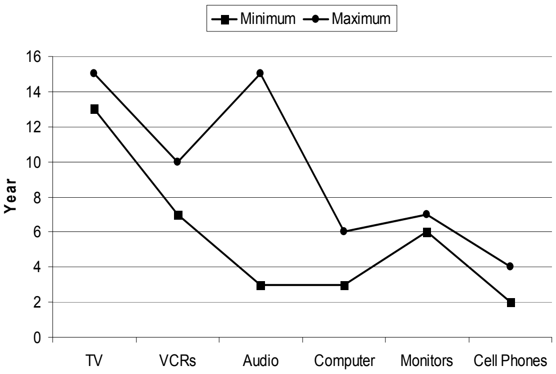

Figure 3 Life span of selected electronic devices
Data from [5].

In fact, the growth of the electronics sector and the rapid changes in technology mean that more consumers are replacing more equipment more often than ever before. E-wastes have garnered significant interest among policymakers and waste management experts because they are a waste stream with a unique combination of characteristics [6]:

1) Large quantities are generated and this is expected to continue to increase
2) They contain potentially toxic materials including mercury, lead and cadmium
3) They contain valuable scarce materials such as gold, palladium etc.
4) In many cases, the recycling is not economical, and,
5) Recycled materials compete unfavorably in some circumstances with virgin materials due to variations in composition and contamination. For instance, effective reuse of recycled cathode ray tube (CRT) glass (CRTs used in TVs and monitors) is hampered by uncertainty in the composition of recycled glass as well as contamination with lead [7].

The problem with the present management system for e-waste as identified in a study by The University of Illinois include market issues, obsolescence issues, feedstock collection, feedstock management, and product-design [8]. Consequently, the key issues in dealing with the global e-waste crises include:

1) *Reducing the volume generated*: The most critical issue in e-waste as is generally applicable in waste management is to reduce the volume. Reuse in the form of repair, refurbishment and remanufacturing are the potential options to reduce e-waste.
2) *Design of electronics*: the application of design for environment (DfE) should see that toxic materials are designed out of electronics in line with the RoHs Directive and similar regulations elsewhere. The designs should ensure that electronic products are built for re-use, repair, refurbishment and/remanufacturing (including software upgradeability). The design of electronics should also make the recovery of materials from EEE at EoL easy.
3) *Technology*: technology for repair, refurbishment and remanufacturing as well as recycling should be made available to developing countries especially those countries that have emerged as ‘e-waste hot spots’.

III. RECOVERING END-OF-LIFE ELECTRONIC PRODUCTS

Product recovery aims at recovering materials and parts from used or obsolete products by means of repair, reconditioning, remanufacturing, and recycling, including reuse of parts and components. There are two common ways of electronic product recovery, namely, remanufacturing and demanufacturing [9]. Remanufacturing focuses on rebuilding product cores whereas demanufacturing focuses on disassembling products and recovering materials to reduce waste and extract economic value wherever practicable [10] [11]. Wolfington and Maranto, [12] observed that the resolution, or mitigation of the e-waste problem has dual objectives: 1) to optimize the proper disposal of the toxic elements of electronic waste, and 2) to optimize the recycling of the valuable elements of electronic waste. They observed that the optimal approach to fulfilling these objectives will unlikely be resolved by legislation alone, but rather, will require a combination of policy parameters, private sector initiative, and consumer education [12].

A. The Electronic Industry

The increasing demand for ICT innovations, the ever-shortening technology cycle, and the increased depreciation rates of electronics are forcing the early "retirement" of ICT products [13]. This is especially evident in the most dynamic consumer products such as computers and mobile telephones. This has been attributed to the increasing tendency for consumers to discard or return products in lieu of better products long before the old products reach the end of their useful final life [1]. This is compounded by the fact that in recent years, EEE has increased in technological complexity, with new product innovations and ever shortening product life expectancy. However, the consumer electronic industry in general have accomplished a greater deal to reduce its impact on the environment by focusing on efficient use of its products, reducing products energy consumption and implementing environmental management systems to make the manufacturing processes increasingly resource efficient [14]. However, much still needs to be done in finding short-to-long term solutions to e-waste management especially in the developing countries.

E-waste is a generic term embracing various types of electronic equipment. According to the definition in the Directive of Parliament and European Union Council on waste electrical and electronic equipment, e-waste can be subdivided into ten different categories**.** E-waste is posing a significant management problem to waste management experts even in the developed countries. This is because the necessary infrastructures to manage e-waste in a sustainable manner have not been developed or have not been appropriately commercialized. For instance, the Creasolv® process has been developed as a sound management option for e-waste plastics containing brominated flame-retardants, (BFRs). It is a solvent-based method of removing BFRs and presently offers the best commercial and environmental option in the sound management of waste BFR-containing plastics. This process removes the flame-retardants and other by-products such as dioxins and furans, and permits the recovery of polymer products that have properties similar to virgin polymers. Unfortunately, this process is yet to be replicated at industrial scale or commercialized.

The developing countries are facing a fast increasing load of e-waste originating from local consumption and from illegal importations [12] [15]. The challenges facing waste management in the developing countries are enormous [16]. There is therefore a need for an urgent intervention through waste reduction and reuse strategies in order to mitigate the negative environmental impacts of the present management practices for EoL EEE.

B. Product design and product EoL scenario

End-of-life strategies are particularly important for electronic products where product lives depend on technological obsolescence rather than wear-out life. However, the EoL strategy chosen depends on the characteristics of the product. A good EoL strategy for any product is to choose the alternative that causes minimal damage to the environment while maximizing the reusability of the products and components. As the sustainability debate progresses, there is an urgent need to control the consumerism issues and the increasing waste generation by the EEE sector by extending the lifetime of electronic products [17]. The development of products that cause a minimum of negative effects in their EoL phase requires that the manufacturers set the right design priorities. The design of a product should take into consideration what the appropriate EoL scenario of the product should be:

1) will a product be reused?
2) will a product be disassembled for components reuse?
3) will a product be shredded for material recovery?
4) will a product be incinerated (with energy recovery)? or
5) will the product be dumped to landfill?

These issues should be considered at the design stage in order to have products that meet with the tenets of sustainable development. Consequently, the design of any electronic equipment should clearly define the EoL strategy of a product before considering product recovery, recyclability or remanufacturability [18]. Reuse options available at the EoL of a product are illustrated in Figure 4.

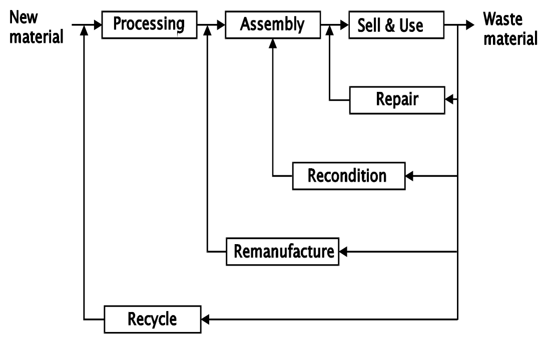

Figure 4. Reuse option available for end-of-life electronic products.
Source: King et al, [18].

Designing products for remanufacturing is required to assure their adaptability to remanufacturing operation. For example, designing products with high level of modularity would be required if the products are to be remanufactured at their EoL. Xerox has been cited severally in literature as a typical leader in the remanufacturing of their copiers. Xerox concurrently designs manufacturing and remanufacturing facilities for new models of their copiers, and in steady state, most of their products are actually "newly remanufactured" copiers [19]. Xerox has saved hundreds of millions of dollars through asset recovery and remanufacturing programs, while having a significant positive effect on the environmental bottom line [20].

Similarly, the manufacturers of EEE have advanced research into design for environment (DfE) and significant progress had been made in the past two decades. For instance, IBM has established a research arm called Design for Environment and has established a worldwide asset recovery service organization. This has been providing a global remanufacturing and refurbishment focus for corporate and institutional accounts.

An important issue in dealing with e-wastes is to reduce the volume generated and the design of electronics is critical in achieving this. Consequently, the foregoing shows that designers should adhere to the tenets of design for environment (DfE) or design for recycling (DfR) to ensure that products are built for re-use, repair, and/or upgradeability. Emphasis should be laid to the use of less toxic, easily recoverable, and recyclable materials, which could be taken back for refurbishment, remanufacturing, disassembly, and reuse.

C. Product recovery

Today, the material disposition is been driven primarily by design and economics, and products or components that do not have effective reverse logistics networks or are designed such that they cannot be economically re-manufactured or re-cycled are disposed into the solid waste stream. Efforts at developing products with an improved environmental performance should not be seen as a threat by electronics manufacturers, but rather as an opportunity to increase business venture and sales, and to create awareness to consumers that the enterprise is 'environmentally conscious'.

White et al [9] described product recovery as the broad set of activities designed to reclaim value from a product at end-of-life. An analog to production, this set of activities includes both reuse and recycling. In addition to reclaiming materials for recycling, recovery also extracts information, refurbishes parts, or remanufactures whole products for reuse [9]. The term "*Reverse Manufacturing*' has also been used to describe product recovery. It is used to describe activities designed to reuse, recover, refurbish, remanufacture, demanufacture, or recycle durable product assets at the end of a product life-cycle. Reverse manufacturing is a complementary term to 'forward manufacturing', which describes the activities traditionally used to bring a product to market [9]. Product recovery plays three main roles:

1) it lessens the environmental and economic costs of waste disposal,
2) it reduces the economic cost of purchasing and processing of new materials. This is because reusing components from used products ensures that their embodied value is retained, and,
3) it could be used as an environmental marketing tool by companies to differentiate their products and services.

Several authors have reviewed the complexity of developing an integrated recovery process for e-waste, with case studies been more on waste computers [9] [21] [22]. End-of-life costs are dependent on reverse logistics costs, product disassembly costs, the net value of materials to be recycled or processed, and the likelihood and revenue from component reuse or remanufacturing [23].The five common options for material recovery from EoL products are repair, refurbish, remanufacturing, cannibalization and recycling [24] (Table 1). These activities have been extensively discussed in literature (Table 1). Reuse and recycling of EoL electronics are very demanding but advantageous alternative to incineration or landfill of electronic scrap [25]. Factors such as cost, labor availability, return flow volume, and optimal disassembly level, determine which recovery process is feasible [26]. Recovery of EoL products are constrained by the large variety of product models available in the market, size changes, and compatibility issues [27]. There are three scenarios for the reuse of EoL products. These are the complete reuse of the devices after repair/reconditioning, the reuse of modules such as printed circuit board as spare parts, and, lastly, the reuse of components diodes, resistors, etc. Meanwhile the decision to remanufacture, disassemble and then recycle, recycle without prior disassembly, or simply dispose of an EoL product is based on product durability, rate of technological obsolescence, product complexity, duration of a design cycle, and reason for redesigns (among other factors) [28].

Product recovery would be required in controlling the various inappropriate management practices for EoL electronics in the developing countries, (such as disposal with solid waste, into surface water bodies and crude backyard recycling practices), save resources and ensure environmental protection.

TABLE 1. OPTIONS AVAILABLE FOR MATERIAL RECOVERY FROM END-OF-LIFE ELECTRONICS

Option	Aim and Operation
Repair	Original product used after fixing or replacing broken or faulty parts.
Refurbishing	Original product quality restored after disassembly to a certain level and repairing/replacing the faulty or broken components/parts.
Remanufacturing	'New' product is manufactured from old (recovered from disassembly of old devices) and new components. Technological (software) upgrading may also be carried out.
Cannibalization	Reusable parts and modules are recovered from used products, to be used in any of the three operations mentioned above. Others scraped
Recycling	Materials recovered from used products and parts by vigorous separation processes (without conserving any product structure).
Energy recovery	High calorific value components (e.g. plastics) could be incinerated in modern waste-to-energy plants for electricity generation or in smelters and cement kilns as source of energy.

D. Achieving sustainability through remanufacturing

The phenomenal rate at which the ICT sector is developing poses threats to sustainable development- large amounts of natural resources are involved in the life cycle of ICT products and hazardous wastes are generated [13]. The present rate of material extraction from the earths crust is not sustainable. This 'un-sustainability' is not only due to the depletion of resources, but also to the waste problems that are related to material extraction and the management of EoL products [29].

The disposal practices for electronics even in the developed countries gives short shrift to reuse and remanufacturing opportunities, and instead settles for partial recycling, landfilling and export [12] [30]. In fact, a study by University of Illinois in 2009 observed that the present global e-waste management system is generally not sustainable because mechanisms for collecting, sorting, reuse, refurbishing, repairing, and remanufacturing are not well developed and/or implemented [8].

The adoption of sustainable management strategies for end-of-life electronics is critical in averting the loss of precious scarce resources and the environmental consequences of adopting inappropriate management practice. It is important to adopt 'sustainable design' – a tool in achieving sustainable development – in the production of EEE. Sustainable design aims at conceiving products, processes, and services that meet the needs of society while striking a balance between economic and environmental interests. The European Union Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHs) Directives are typical examples of using legislation to influence product design in order to achieve sustainable development and environmental protection. Sustainable design requires the consideration and integration of engineering, economics, societal and environmental science models. The EU WEEE and RoHS Directives are of particular significance to e-waste management. Electronic producers are presently adopting remanufacturing as a preferred option in meeting with recovery targets set by the WEEE Directive. The EU has become a central driving force on European hazardous substance and waste management and, in some respect, a regional and global leader in sustainable development [31].

Remanufacturing of EEE is becoming increasingly necessary and important in ensuring that future economic and manufacturing growth is sustainable. The life cycle of EEE begins with development and production, followed by use and maintenance, and leads right up to the reuse and recycling of the entire product, or at least part of it. If reuse is not possible, recycling should be given preference; only as a last resort should a product be incinerated or dumped in a landfill. To avoid negative environmental impacts by today's practice in demand markets with slack environmental regulations, clean remanufacturing activities must be initiated at the returned product's origin [32].

The reuse of EoL EEE conserves resources and feedstock that supply steel, glass, plastics and precious metals. Such reuse activities also avoid air, and water pollution as well as greenhouse gas emissions associated with material production and manufacturing. The reused resources in a remanufacturing operation consist of the material in the product, energy, machine time, labor and other costs that have been accumulated in the new production process [33].

IV. Product Remanufacturing

Re-manufacturing for re-use is becoming a reasonable alternative when considering the possible EoL treatment options for electronics [34]. This is especially critical for electronic products where the EoL issues emerge quickly due to short life spans [26]. A strong business venture could emerge in product remanufacturing if product design permits and if there is an adequate supply of used products [35]. This is because an electronic product may be disposed of prior to the completion of its functional life, for reasons such as technological obsolescence or may be disposed of well after its functional life. This timing uncertainty has been identified as the major complicating factor that makes remanufacturing different from conventional forward flow manufacturing [36].

The residual value of a product depends on various quantity parameters such as the age, functional age (working or not working), physical condition, functional life (as a measure or obsoleteness), remaining useful life etc. Most often, the value of these parameters, which define the current state of the product, can be determined through inspection or estimated from knowledge gathered from experience [1].

A. Re-manufacturing: an overview

Remanufacturing comprises any action necessary to build up as-new products using components taken from previously used EEE as well as new components, if applicable. The output product meets the original equipment manufacturer (OEM) functionality and reliability specifications. To remanufacture a product requires the complete disassembly of the unit, thorough testing, and replacement or reprocessing of all components not meeting these specifications [6].

Remanufacturing is the term given to the process of re-inventing products and returning them to their "as new" standard and form by performing necessary operations such as disassembly, overhaul, and replacement [37]. It involves locating end-of-life equipment, refurbishing their cores, and reselling the intact products [9]. This has become increasingly necessary and important given the need to ensure that future economic and manufacturing growth is sustainable [38]. During the last few decades, the concept of remanufacturing has spread from the automotive industry to other sectors, such as those involving various types of electrical apparatus, toner cartridge, and household appliances [39].

Many definitions for remanufacturing are found in literature but most are variations of the same basic idea – product rebuilding. In most definitions, the used/worn-out/broken products that enter the remanufacturing process are referred to as 'cores'. A combination of these definitions useful for the meaning of remanufacturing was presented by Lindahl et al [40] – "*remanufacturing is an industrial process whereby products referred to as cores are restored to useful life*". During this process, the core passes through a number of remanufacturing steps for example inspection, disassembly, part replacement/refurbishment, cleaning, reassembling, and testing to ensure it meets the desired product standards.

Remanufactured products typically have the same or similar performance characteristics and quality standards as new units. Ritchey et al [26] developed a framework to asses the technical and economical feasibility of remanufacturing electronic products. The framework identified factors critical to the success of a remanufacturing operation. These include return flow and collection costs; inventory costs; disassembly cost; technological feasibility; and labor and testing cost [26]. Remanufacturing operations requires small capital investments compared to manufacturing operations because no parts are produced and most of the work has already been done by the original equipment manufacturer (OEM). Consequently, a large untapped market exists for products remanufacturers. Michaud and Llerena, [41] observed that "*any product can be remanufactured if it can be disassembled and cleaned, if its components can be repaired or replaced so that the original function and performance level are kept, if there is enough demand for the product, and if the whole process is economically viable*".

Remanufacturing products incurs costs that are typically 40 to 65 percent less than those incurred in the delivery of new products [42]. This is because most of the raw materials already exist in their final form and thus require only a fraction of the material processing required of new products.

B. Collecting EoL products for remanufacturing

Product recovery starts with EoL product collection through reverse logistics. Reverse logistics is the movement of goods from a consumer towards a producer in a channel of distribution [43]. *It is the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods, EoL goods, and related information from the point of consumption to the point of origin for recapturing value or proper disposal* [43]. The key activities in reverse logistics include transportation, warehousing, distribution and inventory management. For remanufacturing be cost effective, it is important that the reverse flow of goods to be efficient with a minimal cost considering that if the total cost associated with the recovery of EoL products exceeds the total cost of new products, the remanufacturing firms would not have financial incentives to continue in the business.

The remanufacturing firm should be able to influence the quality, quantity, and timing of product returns by offering a quality-dependent price incentive for used products [44]. Issues relating to the reverse logistics for EEE have been discussed in literature [45] [46]. Ravi et al [43] observed that "*reverse logistics programs in addition to the various environmental benefits and the cost benefits can proactively minimize the threat of government regulation and can improve the cooperate image of the companies*". As a result reverse logistics is now perceived by organizations as an "investment recovery" as opposed to simply minimizing the cost of waste management.

Four primary sources through which remanufacturers can obtain products in the reverse logistics are:

1) *Supply chain return* – products that are returned by the different actors in the supply chain except the end-user. A typical example is unsold products returned by the retailer.
2) *Warranty returns* – products that are returned by end-users within the limited period as specified by the manufacturer, as failed products or due to customers being unsatisfied with the product.
3) *End-of-lease equipment returns* – products returned after the lease period. End-of-lease returns are the consequent of the move towards selling service (leasing) instead of selling products.
4) *End-of-life products* – products discarded by the users after the end of their useful life as perceived by the user. In some cases, the products may still be functioning. There is indication that about two-thirds of discarded electronics are still functional.

The characteristics of the waste flow depend on past and future sales, the product lifecycle, storage of product after its life has ended, and the likelihood that the e-waste will be recovered once it has been disposed [35] [47].

C. Remanufacturing operation

In a remanufacturing operation, devices collected through reverse logistics routes arrive at an overhaul centre and queue for maintenance. The returned products are dismantled into modules and the modules are further disassembled into component parts. The condition of the modules/parts is inspected to assess their condition and determine if overhauling is needed. The modules and parts without the need of service are organized and put aside for reassembling; usable parts are tested, cleaned, refurbished, upgraded and sent to the parts inventory. Repairable parts are moved to the repair shops according to their types. New parts are replenished by placing an order to meet the demand of the assembly. At the end of the repair activities, these parts and new parts where necessary, are assembled into a 'new' remanufactured product [48].

Literature indicates that a remanufacturing facility may be thought of as a three dependent subsystems: a disassembly shop, a remanufacturing shop, and an assembly shop [49]. The first subsystem is the disassembly shop where ***n*** types of units are disassembled into ***m*** base components and parts. The second subsystem is the remanufacturing shop area where operations required for bringing the parts and components back to 'like-new' condition are performed. The remanufacturing shop area also contains testing and evaluation operations where the parts are deemed useful and remanufactured or deemed useless and discarded. The last subsystem is the reassembly area, which reassembles remanufactured components and new parts (if required) into the final product. Sundin [29] analyzed remanufacturing in seven remanufacturing companies in order to explore how remanufacturing facilities can become leaner. The study observed that the three remanufacturing steps - inspection, cleaning and reprocessing - were crucial to most of the companies.

A typical operation in the remanufacturing of mobile phone starts with the arrival of the products. The phones are then registered, sorted, tested and cleaned separately before depositing in the accessories warehouse. In the sorting process, accessories and batteries are removed from the phones. The phones may be tested for functionality and cosmetics, from which older phones may be sent for recycling. The mobile phones that can be directly reused 'as is' can be cleaned or refurbished to the extent necessary to achieve desirable quality level. The mobile phones to be remanufactured are then registered according to brand and model by detecting the International Mobile Equipment Identity (IMEI) number. Next, the phones are sorted according to brand and types, and disassembled, and the separate components cleaned, usually using detergents such as alcohol. The cleaned components from old phones and spare parts (new components) are then reassembled. Software upgrading is also carried out such as formatting the phone memory, ringing tones etc. [34]. Some electronic components may be easier to remanufacture. A typical example is the remanufacture of printer cartridges. The remanufacturing process for printer cartridge may involve disassembling, inspecting, cleaning, replacing worn parts, reassembling, and filling the cartridge with toner or ink.

In 2003, an estimated 3 to 4 million mobile phones were remanufactured and sold [50]. Skerlos et al, [50] observed that mobile phone remanufacturing has become a reality in both Europe and the US. Citing remanufacturing facilities in the developing countries has become necessary considering that a greater percentage of the remanufactured product finally end up in the developing countries. Experts in this field have however observed that the successful remanufacturing of mobile phones must meet the challenges of continuously falling prices for new phone models, short life cycles, disassembly of unfriendly designs and prohibiting transport, labor and machining costs in high-wage countries [51] [52].

Remanufacturing of electronic products is one way of creating economic value while at the same time obtaining environmental benefits. Remanufacturing lengthens a product’s life, enhances the re-usability of components, divert waste and energy, while creating economic value. Resource conservation over the life cycle of products is a key component of sustainability.

V. Challenges and Limitations in Achieving Efficient Remanufacturing

The motives and barriers to achieving effective remanufacturing can be both economical and technical [33]. Characteristics that significantly complicate production planning and control activities in remanufacturing environment have been identified. These are:

1) The uncertainty timing and quality of returns;
2) The need to balance returns with demand;
3) The disassembly of returned products;
4) The uncertainty in materials recovered from returned items;
5) The requirement for a reverse logistics network;
6) The complication of material matching restrictions, and,
7) The problems of stochastic routing for materials for remanufacturing operations and highly variable processing time [49] [53].

These are huddles in achieving efficient and cost-effective remanufacturing of electronics. In the developing countries, these challenges may become compounded considering that most EoL electronics are in storage and that most consumers traditionally repair EEE using even components from different manufacturers and models which end up changing the equipment features. These changes would pose challenges to remanufacturing especially where disassembly line is automated. Most of the EoL EEE in storage may also be obsolete equipments. Ritchey et al, [26] observed that it is more suitable to remanufacture a product that fails functionally rather than one that is discarded due to obsolescence. Similarly, only components that retain their value and conformance can be reused without compromising the durability or reliability of the final product.

Other challenges and obstacles to effective remanufacturing of electronics identified in literature include:

1) *Finding a ready market and customer demand* - It is important to gain information on future market needs for remanufactured products.
2) *Variation in product specific characteristics* - this is peculiar to mobile phones. Taking into consideration all attributes of a mobile phone such as software version or regional configurations, there are over 1,800 variants in the market. Even when the consideration is reduced to brand name and model, there are still about 600 different variants for remanufacturing to deal with [34].
3) *Varieties in EEE standards* - for example in North America, several different cell phone standards such as TDMA (Time Division Multiple Access), CDMA (Code Division Multiple Access), and GSM (Global System for Mobile Communication) are commonplace, resulting in an inhomogeneous market. As a result, technological and logistic challenges are high due to the various different types of phones collected. Most of these standards, except GSM, are not globally circulated. As such, remanufactured phones of other standards except the GSM may not find ready markets as most emerging and developing countries have adopted the GSM standard [34].
4) *Labor cost* - the labor cost of remanufacturing must be less than or equal to the cost of manufacturing in order to be feasible. The labor cost constitutes a considerable part of a company costs especially in the developed countries, but it can be less in the developing countries and/or compensated by reuse of components. For example at Xerox, the labor cost of remanufacturing are approximately double the cost of primary production, but remanufacturing reduces the amount and costs of materials used resulting in savings of $200 million in 1999 through product remanufacturing [54].
5) *Funding and technology* - especially if the remanufacturing activity is to take place in a developing country.
6) *Sabotage* - There are indications that some remanufacturing firms are contending with “sabotage” by the OEMs while trying to protect their very profitable business. The inkjet printer manufacturing companies install smart chips to disable the printer if a remanufactured inkjet is installed. Europe has outlawed the smart chips.
7) *Speed of technological changes* - the speed of technological changes in EEE design and manufacture may limit the market for remanufactured goods. Thus as the recovered products face competition from the new products, the investment on product recovery may become a risky venture [55]. There is also the difficulty of the return flow of used EEE.

VI. Opportunities for Developing Countries

A. Conditions predisposing developing countries to the business of remanufacturing

The business concept of remanufacturing is based on the idea that resources that were used in the manufacturing of the product are reused, thereby making remanufacturing advantageous [33]. Remanufacturing is a successful production process for many companies in the developed world and is becoming increasingly adopted given the clear economic and environmental benefits associated with it. This unfortunately is presently not the case in most developing countries. Initiating remanufacturing activities in developing countries could be a good venture considering the phenomenal demands for ICT wares in these countries. Other peculiarities of the developing countries that may make remanufacturing a good venture are: 1) large and ready market that has over the years become used to cheap secondhand goods; 2) cheap and readily available workforce, including graduate engineers; 3) non-stringent environmental and business legislation and, 4) the lower prices for remanufactured products are within the low purchasing power in the developing countries. Because remanufacturing involves less automation than processes of primary production operations, more labor force could be needed. This could in the near future create the much-needed employment in the developing countries. Remanufacturing activities and local production of replacement components for faulty parts would go along way in developing the electronic manufacturing sector in the developing countries.

B. Business openings from remanufacturing in developing countries

Remanufacturing brings lower prices to the consumer, typically on the orders of 30 to 40 percent less than similar new products [42]. It is expected that there would be a ready market for remanufactured products in which warranty is issued. Remanufacturing of EEE in the developing countries could have positive social and economic effects as well ecological gains if appropriately implemented. It could in the future create job opportunities in the areas of EoL product reverse logistics, the remanufacturing process and distribution and divert EoL EEE from going toward crude recycling processes and open dumps in these countries.

Giutini and Gaudette [42] reviewed the economic opportunities derivable from remanufacturing and identified the various enterprises who are stakeholders in any successful expansion of remanufacturing. These include:

1) Firms that use remanufactured products, enabling them to reduce their capital investment expenditure.
2) OEMs (and third-party remanufacturers) which can use the remanufacturing process and the remarketing of the resulting products as a business strategy to increase profit.
3) Manufacturers of specialized equipment used in the remanufacturing process, such as cleaning and test equipment.
4) Information technology suppliers, who would help build the IT infrastructure to support remanufacturing.
5) Management consultants, who would assist new-condition product manufacturers in incorporating remanufacturing into their business models.
6) Design engineering software suppliers, who would develop design optimization tools for the remanufacturing process of disassembly and reassembly.
7) Financial services firms, which would finance the capital investment needed for companies to enter the remanufacturing sector.
8) Third-party logistics suppliers, which would experience a large increase in reverse logistics activity [42].

In the developing countries, some of the above listed sectors of the economy would be boosted by the introduction of remanufacturing. This would ultimately result in improvements in existing infrastructures for assembling or manufacturing of electronics in the developing countries. The focus on better uses for end-of-life electronics by product recovery could give rise to new opportunities for employment in these sectors in the developing countries. A large number of jobs have been created in the waste management sector in the developed countries and this could be replicated in the developing countries.

C. Nigeria a case study

As a direct result of energy savings, remanufacturing is extremely effective in reducing waste generation and environmental pollution. Formal remanufacturing of EEE is almost non-existent in Nigeria. However, there is a high level of refurbishing and repair of EoL EEE for reuse. These activities are at advanced levels at the Ikeja Computer Village and the Alaba International (Electronics) market both in Lagos, Southwest Nigeria. The computer village sitting on 6 hectares of land and host more than 3500 registered businesses involved in the sales, repairs, refurbishment, and software upgrading of electronic devices. Some of these registered businesses though operating in small shops and disused containers have as much as 10 employees [56]. Many of these businesses are operated by graduate engineers and technicians. The BAN study observed that about half the businesses in the Computer Village are involved in the repair and refurbishment of imported used equipment and parts. The study interviewed the employees at the Computer Village and observed that "*the level of education, training and expertise is surprisingly at a very high level, many people having graduate degrees in electronic engineering, which seemed incongruous considering the rough, primitive shops in which the engineers were employed*" [56].

Product recovery would be required in controlling and/or eliminating the various inappropriate management practices for EoL electronics in the developing countries, such as disposal with solid waste, into surface water bodies and crude backyard recycling practices. This is critical in ensuring resources conservation in the EEE sector and in protecting human health and the environmental.

New strategies for e-waste management in the developing countries can be achieved by sharing knowledge between countries and learning from other continents. This is necessary in developing new management routes, and potential markets for recycling products.

VII. The Role of The OEM

Remanufacturing of EoL products can be made easier and cost effective if the products are designed for remanufacturing. Following the design for remanufacturing guidelines discussed in literature, remanufacturable assemblies should be designed with special emphasis on the following: ease of disassembly; ease of cleaning; ease of inspection; ease of part replacement; ease of reassembly; production of products with reusable components, and standardization of production by making designs modular, standardizing the fasteners (eliminating difficult fasteners), and interfaces (using fewer parts to produce a large variety of similar products) [57].

Achieving efficient management strategies for EoL EEE would require more than investment and design changes by OEMs. It would require commitment and active involvement especially in the developing countries. An OEM may participate in product recovery in two forms:

1) An OEM establishing a fully (or partially) owned product recovery network, which includes refurbishing/remanufacturing (as well as recycling) infrastructure to process own appliances. Here the OEM has full control over operations and a direct involvement in the entire process.
2) An OEM collaborating or engaging a third party remanufacturers for the refurbishing/remanufacturing of own products. The level of engagement of the OEM is determined by the contractual agreement and can vary from full oversight of the process to insignificant engagement in how the contracted operations are performed.

In these scenarios, diverse sources of input are available. Returned products (products returned shortly after purchase, products under warranty, or a product recall) would constitute sources of core supply [33]. Products that failed OEM specifications at the manufacturing plant are also another source of materials. Remanufacturing conducted by the OEM carries the potential for increased process efficiency compared to the operations of third party remanufactures. This would eliminate sabotage, reduce cost, improve product-throughput, provide ready access to materials/components and product information. This would also result in reduced technological and logistic barriers. Often, the OEM is the only source for a given component, and the cost premium required for upgrading or obtaining a replacement could be very high [21]. Hence, the active participation of the OEM in these activities would maximize the value of the recovered components/materials, minimize the cost of remanufacturing/recycling, and minimize the total environmental burden. The adoption of globally sound management of electronic wastes with the effective application of product recovery would result in waste reduction, savings in landfill space, slow down global warming and greenhouse gas emissions, conserve natural resources, energy savings, and prevent pollution. The cooperation of the OEMs in initiating remanufacturing activities in the developing countries is essential. The full societal benefits of re-manufacturing (reduced energy and material consumption and reduced wastes) cannot be achieved unless design for re-manufacturing becomes an integral part of the product development process. Consequently, input and advocacy from governments, consumers, environmental managers, and other stakeholders will be key to adopting environmental designs in electronics manufacturing, and in transfer of technology for remanufacturing to the developing countries.

Remanufacturing may also be technically demanding, requiring expertise in some operations such as automated disassembly. This may not be readily available in most developing countries. Hence, the need for the OEMs to cooperate with third party remanufacturers and assist in creating this new business ventures in the developing countries. Consumers in the developing countries would in the future reward the OEM for 'caring about the environment' as this 'green image' would encourage better acceptance of the products of the OEM.

VIII. Conclusion

Remanufacturing is an ecologically preferable option to other EoL management practices for electronic goods such as recycling, incineration, and landfill. The implementation of extended producer responsibility in Europe and product stewardship in the United States has transformed product remanufacturing from a waste reduction/diversion strategy into a key business activity. However, EoL product reuse through remanufacturing is not encouraging in the developing countries. Solid waste reduction and new components savings are potential benefits of remanufacturing. Reducing the need to manufacture products exclusively with new components leads to a lower material and energy consumption. In these ways, remanufacturing may increase the resource productivity and moderate the environmental impact of a product system. Relatively cheaper products would also be readily available to the consumers in the developing countries if remanufacturing were adopted as a tool in checking e-waste generation. Using remanufacturing as a waste diversionary strategy and as a business venture in e-waste management is not a requirement of the future; it is a demand of today. With the introduction of innovative technologies in the electronic industry through design for environment, there are indications that new technologies would in the near future result in better EoL scenarios for EEE.

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