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Repurposing end of life notebook computers from consumer WEEE as thin client computers – A hybrid end of life strategy for the Circular Economy in electronics

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ABSTRACT

This paper presents an investigation into the feasibility of repurposing end-of-life notebook computers as thin client computers. Repurposing is the identification of a new use for a product that can no longer be used in its original form and has the potential to become a hybrid re-use/recycling end-of-life strategy for suitable e-waste when direct reuse is not economically or technically feasible. In this instance, it was targeted to produce thin client computers using motherboards, processors and memory from used laptops while recycling all other components.

Notebook computers are of interest for this type of strategy due to having a substantial environmental impact in manufacturing but often not having the option of direct reuse as they are prone to damage and experience a rapid loss of value over time. They also contain multiple critical raw materials with very low recycling rates.

The notebook computers were sourced from Civic Amenity sites (CA) and originated from business-to-consumer (B2C) channels.

A total of 246 notebook computers were collected and analysed. The paper outlines a methodology developed to identify, test, analyse, and disassemble suitable devices for repurposing. The methodology consists of the following stages with associated pass rates; Visual Inspection & Power-on Test (32%) the Initial-stage functionality test comprised of Functionality Test (56%), Diagnostics (100%) and Benchmarking (86%).

The Disassembly stage had a pass rate of 100% and the Post-Disassembly Test comprised of a Validation test (86%). The Final-stage functionality test had a pass rate of 61%.

The overall results show that 9% of the notebook computers were suitable for repurposing as thin client computers. It recommends the following design changes to notebooks/laptops that would support repurposing; 1) PCB mounted Fan and Heatsink assembly, 2) Eliminate daughter and I/O boards, 3) A separate Power Button assembly, 4) Reduction in size of the motherboards surface area or physical size. These design changes would allow for a more efficient transition for a change of role.

A streamlined lifecycle analysis based on Cumulative Energy Demand (CED) was undertaken to compare the impact of repurposed notebook computers with new thin client computers. The results indicated that there are significant potential savings to be made by extending lifetimes and offsetting the production of new thin client computers under a range of assumptions.

1. Introduction

1.1. Background

The growth and prevalence of consumer electronics in the past 20 years has been tremendous and has had many beneficial impacts on our lives. However, this growth in consumer electronics has also had an impact on the environment with the amount of electronic waste (e-waste) or Waste Electrical & Electronic equipment (WEEE) generated has been increasing year on year. Currently this e-waste is predicted to grow by 21% by 2018 (Baldé et al., 2015). E-waste is a complex waste stream with many diverse materials from precious metals to plastics and presents us with many challenges as to how

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to manage, dispose and recycle it.

The United Nations Environment Program (UNEP) and the European Union (EU) have identified resource efficiency as a key objective to further protect our economic, environmental and societal well-being for the coming years (European Commission, 2011) (UNEP, 2016). A key aspect of Resource Efficiency is the Circular Economy which aims to promote appropriate and environmentally acceptable use of resources to enable a green economy (EMF, 2013). The Circular Economy is divided into two business models, the reuse and product lifetime extension model and the recycling for material recovery model (Stahel, 2015).

Several critical raw materials are also present in e-waste but currently they are not being recycled or recovered. Critical raw materials are categorised as such by the EU, due to their economic importance, increasing demand and due to potential supply interruption (European Commission, 2014; UNEP, 2016).

Recent reports have highlighted the low recycle rates of critical raw materials with typical rates of less than 0.1% (Graedel et al., 2011; Reck and Graedel, 2012; UNEP, 2011). Critical raw materials also have poor substitution rates, meaning there are no substitute materials with the same performance that can be used instead of the existing materials (Graedel et al., 2011; Reck and Graedel, 2012).

Reuse has been identified as the most appropriate end-of-life strategy for suitable electronics (Williams et al., 2008). Reuse extends the products lifetime and offsets the embodied energy created during manufacturing (Babbitt et al., 2009). This form of reuse is referred to as direct reuse, and is dependent on the hardware specifications meeting current requirements, the product having a market, all the components be working correctly and the unit to be in good cosmetic condition. Reuse often requires repair or reconditioning beforehand. Reuse has been identified as having an important social aspect such as job creation and it has an impact on prosperity on low income families (O'Connell et al., 2013). In recent years Reuse has gathered momentum and its engagement has increased by a variety of different business models (Kissling et al., 2012) with a defined set of barriers and success factors (Kissling et al., 2013).

The Circular Economy has identified several methods of product lifetime extension strategies. Remanufacturing is the process of recovering used products to a "like-new" functional condition (Zlamparet et al., 2017). Repair is the correction of a fault and returning the device to a working condition (Watson, 2008). Refurbishment is the recovery of a product to a used or specified quality level (den Hollander et al., 2017).

Repurposing has been described as the identification of a new use for a product that can no longer be used in its original form (Long et al., 2016) and has been defined as one of the nine levels of circularity (Cramer, 2014). The repurposing methodology being proposed in this paper is based on product-specific approach that combines the benefits of reuse and lifetime extension with liberation through disassembly for repair and recycling.

Repurposing has also been described as adaptive reuse in certain instances (Cooper and Gutowski, 2015) and has been defined as recontextualizing in circular Product Design (den Hollander et al., 2017). Long et al. (2016) also state that the limitations of repurposing are the due to the singular nature of electronics. Repurposing e-waste has been designated as a representative design strategy in certain circumstances (Kwak et al., 2011). Kwak et al. have identified some examples of repurposing such as the example of LCD screens being reused as televisions. There have been examples of smartphones being repurposed as parking meters and this repurposing has been highlighted as being an environmentally preferable EoL strategy to refurbishing (Zink et al., 2014). ATX Power supplies being repurposed from desktop computers as a battery charging Maximum Power Point Tracking converter (MPPT) for Photovoltaic (PV) applications in developing countries (Rogers et al., 2013). Abuzed et al. (2016) presented the repurposing of ATX Power supplies for battery charging applications. Repurposing can also be described as an attempt to keep components at their highest level of utility when whole product use is not possible or viable. There are opportunities for innovation through design for repurposing that can impact product and component lifetimes and overcome the singular nature of electronics.

1.2. Notebook computers

This paper presents repurposing as an end-of-life strategy that contains elements of reuse, recycling and refurbishment which can offer the following environmental, economic and societal benefits for notebook computers. The process of repurposing notebook computers can enable the disassembly of all components. Components that have high critical raw material content can be liberated through disassembly to improve the resource efficiency for material recovery (batteries, hard disk drives) and components with a large embodied energy from manufacturing can recovered for reuse (motherboard, RAM). The recovery of materials in consumer electronics by recycling has concentrated on precious metals and larger fractions. The technology and metallurgy required to recover these materials are well developed and highly efficient but there are losses of many other materials that occur in smaller quantities. Critical raw materials are lost during the smelting process and end up as slag at the end of the recovery process (Schüler et al., 2011). Notebook computers have quantities of critical raw materials such as Cobalt (Co) which is required for the Lithium-ion Battery (Zeng et al., 2015; Zeng and Li, 2014), Neodymium (Nd) in Hard Disk Drives (Buchert and Manhart, 2012; Sprecher et al., 2014; Ueberschaar and Rotter, 2015) and Indium (In) and Europium (Eu) in the Liquid Crystal Displays (Buchert and Manhart, 2012; Li et al., 2015). ICT equipment is also a sizeable user of certain conflict minerals, in particular Tantalum (Ta) (Fitzpatrick et al., 2015). A deep disassembly process is needed to allow the recovery of these critical materials and separation of the components has shown to improve the efficiency of recovery. Repurposing and reuse enable product lifetime extension of suitable parts and potentially eliminates primary production through displacement (Zink et al., 2014). Repurposing allows for reuse where a market may not exist for the original model due to a defect, external or cosmetic damage (Lee et al., 2001; Manhart et al., 2016). Repurposing can act as a source of parts supply for the repair industry and the creation of a repurposed product can offset the cost of manual disassembly.

The research presented in this paper sets out to answer the following questions:

- Is it feasible to repurpose suitable parts from end of life notebook computers to be used in another function or role?
- How feasible is it to source these notebook computers from consumer WEEE?
- Can a methodology be developed to inspect, test and validate the suitability of these parts/components?
- Can we develop eco-design criteria that would enable the repurposing of notebook computers as thin client computers?

1.3. Repurposing notebook computers as thin client computers

The repurposing of Notebook computers sourced from WEEE can provide a hybrid end-of-life strategy as it allows the reuse of the system board, central processing unit (CPU) and memory (RAM) modules in tandem with the disassembly of the notebook for the recycling of parts that contain the most concentrated quantities of critical raw materials such as batteries, hard drives, LCD and the larger fractions for recycling. The most prominent contributor to greenhouse gas emissions (GHG) from the production of a notebook computer is from the RAM at 36% and the Motherboard at 34% while the CPU contributes 2% (Manhart et al., 2016). All three components produce up to 72% of the total production greenhouse gas emissions.

Fig. 1.1 presents the concept of repurposing notebook computers from e-waste and Fig. 1.2 shows an example of the motherboard, RAM and CPU from a disassembled notebook computer.

Thin Client computers have their origins in terminal networks whereby terminals connect to a single host computer or server. The host computer or server carried out all computational processes while the terminals connected to the server and displays the information (Stamper, 1994). The advent of cloud computing and virtualisation has seen a re-imagining of terminal computing. There are many benefits to thin client computing; reduced IT support costs due to less administration, increased data security as no sensitive data is stored locally, reduced energy consumption in comparison to a PC, better reliability due to less moving parts. The model being proposed in this research is as a "software" thin client which allows any pc or notebook to be repurposed as a thin or zero-like client (StratoDesk, 2017).

The feasibility of repurposing end-of-life Notebooks from consumer WEEE needs to meet several conditions;

1. The system boards, processors and memory need to be in perfect working order.
2. The architecture and design of the system board needs to be suitable for reuse in a new housing.
3. The repurposed components need to match the specifications of current thin client computers.
4. The processing power of the Notebook computers needs to meet or exceed the processing power of current or nearly new Thin Client computers.
5. The Input Output specifications need to match the same specifications as a new Thin Client computer.
6. The disassembly process needs to be conducted with care to prevent the system board, CPU and memory from incurring any damage which will affect operation and functionality.

The methodology that is presented in the following section expands with the specifics of the process required to undertake this

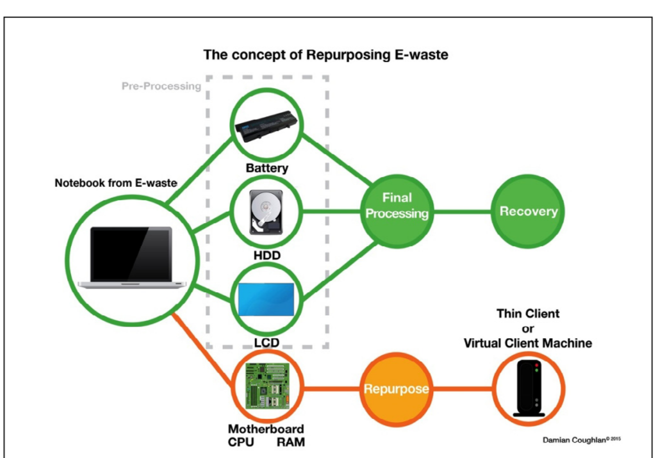

Fig. 1.1. Concept of repurposing notebook computers from E-waste.

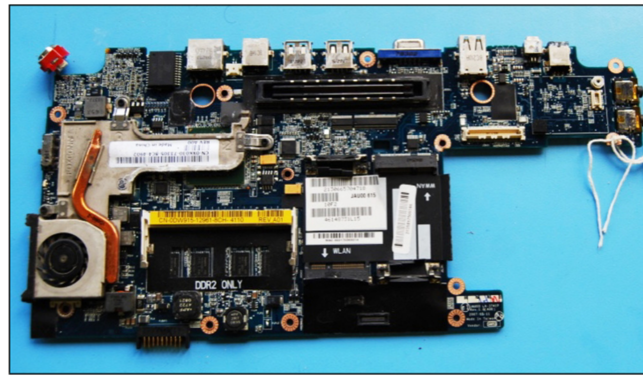

Fig. 1.2. Motherboard & integrated Heatsink and Fan assembly.

feasibility test and has been developed to validate the suitability for repurposing of Notebook computers sourced from a WEEE takeback scheme.

Conditions in takeback systems dictate that the methodology needs to be robustly applied to ensure quality standards for reuse and repurposing. The end-of-life Notebook computers are collected at Civic Amenity (CA) sites designed to allow electronic waste to be dropped off by the public. The public deposit their waste in designated cages and there is no charge when dropping off WEEE. The devices are returned to a depot from where the WEEE is sorted by type into containers for transportation for recycling.

The current design and layout of these CA sites often requires that WEEE be stored outside with little or no protection from the weather. The methodology has been developed to account for the current conditions in a recycling-centric takeback infrastructure with no regard for reuse.

2. Repurposing methodology development

The methodology was developed to investigate the feasibility of undertaking the repurposing of notebook computers from consumer WEEE. An initial sample of 35 notebooks was collected to work out a streamlined and repeatable process to eliminate failures at the earliest possible occasion and establish the exact steps required to test and rebuild the units as thin clients. Once refined, this method was then applied to a separate batch of 246 notebooks to ascertain how many of them had the potential to be repurposed. Fig. 2.1.

2.1. Inspection

Based on the initial sample of 35 notebooks examined it was immediately apparent that a thorough inspection would result in the elimination of a large number of unsuitable devices and thus save a lot of unnecessary further testing. Therefore, an inspection methodology was developed to allow the sorting and categorising of the Notebook computers into suitable or non-suitable devices. The test required an initial visual inspection for physical damage followed by an inspection of technical specifications.

The process of visual inspection followed the "preparation for reuse" as outlined in PAS 141(BSI, 2011). Several categories were developed from structural damage, water damage, input/output availability, display connection and power connection. Optional criteria were defined to support the visual inspection process for the purposes of identification including items from manufacturers labelling, the wheelie bin logo or printed technical specifications on labels.

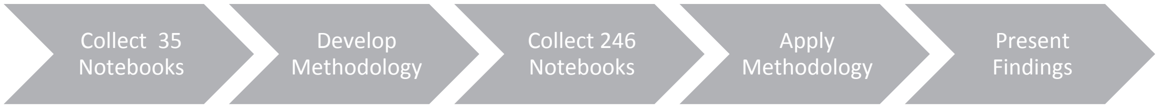

Fig. 2.1. Study ProcessThe methodology was initiated with the collection of notebook computers by a WEEE compliance scheme in Ireland. Devices were diverted from the normal process of recycling and collected from WEEE cages over a 3-month period. Fig. 2.2 displays a selection of the collected Notebooks from the WEEE stream.

Fig. 2.2. Collected notebooks from WEEE.

Structural damage – the criteria was developed to allow assessment of the physical structure of the notebook computers. There are many stress points in the structure of the notebook computer. For the purposes of direct reuse an area of concern would be the hinge mechanism for the LCD, also warping of the main body and damage to the outer casing from a fall. The benefit of repurposing the motherboard, processor and memory in a notebook computer is that external condition does not play a significant part in the suitability for reuse.

Water damage – the ingress of water to electronic circuitry nearly always has dire consequences once power is applied to the device. Allied to the issue of lack of covered storage during take-back, there is an issue with water ingress at the civic amenity sites. These criteria are critical to the inspection process. There are also health and safety implications in the testing of equipment that may have been affected by water ingress and the subsequent damage through corrosion.

Input/output –The characteristics of a Thin Client computer have shared specifications with desktop and notebook computers in general. There are a few basic input output requirements for thin client operation. These are USB connections, Video display (VGA/DVI) connection, Network (LAN) connection and Power input. At present, there is little demand for Wireless LAN and Bluetooth in Thin Client computing due to security concerns.

2.2. Initial-stage functionality analysis

The requirement to test for an operable and functioning device is essential to a successful outcome as a repurposed product as it is important to understand if the device still works before being dismantled. The functionality analysis was conducted both onsite and offsite. An initial power-on functionality test was completed on-site using a Universal Power Adapter (Innergie 90 W) with a selection of power jacks. This test consisted of a simple procedure whereby the unit was powered on to ascertain if the power led was illuminated when connected to the power supply. Due to the unknown condition of the devices, the test was a pass if the led was illuminated.

The second stage of the analysis of the functionality of the notebook computers was developed with four phases, preparation, operability, BIOS and diagnostics. This second stage functionality analysis was conducted off-site. This stage consisted of powering on the notebook computer and booting the device with an external USB key which contained industry standard diagnostics. This stage of the process allowed for possible interventions to access the BIOS to change the boot order to allow booting from USB or to remove any setting which may prevent successful booting. The diagnostics that were used are PC-Check® which provides hardware reliability testing.

2.3. Benchmarking analysis

The benchmarking analysis was developed to analyse the performance of the hardware being repurposed and to measure its performance in relation to current Thin Client computers and record same. The benchmarking process is important as it allows the development of a metric to assess and record the performance of the Central Processing Unit (CPU) and other components. The metric from benchmarking provided a score of overall system performance. The score for performance allowed a direct comparison with the hardware specifications of purpose built Thin Client computers. The benchmarking was undertaken using a 32-bit version of Geekbench 3 software. Geekbench was installed on a USB key containing a Linux distribution Lubuntu. Lubuntu is a lightweight version of Ubuntu. The system was booted from the USB key and Geekbench was initiated. The results are uploaded to the Geekbench Browser website which stores all data in relation to the testing.

Geekbench™ uses several different benchmarks to measure performance. These benchmarks include Integer Workloads: AES, Twofish, SHA1, SHA2, BZip2 compression and decompression, JPEG compression and decompression, PNG compression and decompression, Sobel, Lua and Dijkstra. The software also uses Floating Point workloads such as Black-Scholes, Mandelbrot, Sharpen Image, Blur Image, SGEMM and DGEMM, SFFT and DFFT, N-Body and Ray trace (Geekbench, 2017). The Memory Workloads are STREAM copy, STREAM scale, STREAM add and STREAM triad. Geekbench™ can measure all the cores in a system, as it is Multi-core aware (Geekbench, 2017). All single-core and multi-core scores are uploaded to the Geekbench browser website.

2.4. Disassembly

A key aspect of the overall methodology was to enable the liberation of the motherboard, processor and memory and the disassembly of components that contained critical raw materials.

Within the development of this methodology, the taxonomy was important to highlight the terms that are being used at the legislative level. The term developed for the liberation of components was disassembly. The European Union have defined disassembly as being different to dismantling. Disassembly is characterised as removing or liberating components from e-waste with regard for the condition that they finally end up as (Ardente and Mathieux, 2014). Dismantling is regarded to imply that the liberation of components is not important and can be damaged during the process. disassembly can be described an non-destructive or preservative (Cong et al., 2017) whereas dismantling can be described as being destructive (Ardente and Mathieux, 2014). The Recycling industry has always highlighted time as a major impediment to successful economic outcomes when it comes to disassembly or dismantling (Wang et al., 2012). With this background in mind the successful disassembly of notebook computers required time to liberate as being the key performance indicator of a successful outcome.

The liberation process was determined by an initial examination of a notebook computer. On this basis, a standard methodology for disassembly was developed as notebook computer design tends to follow similar methods of assembly.

A methodology was developed to allow a uniform and repetitive process of disassembly among all notebook computers. The acronym for this methodology is derived from the order of disassembly. The B.H.O.M.L stands for Battery, Hard disk drive, Optical media device, Motherboard with CPU/RAM and the Liquid Crystal Display.

A common feature across notebook computer design is in the use of fasteners. The methods of fastening the device and components were by latches and screw connections. For example, many of the Batteries were secured in the device with latches that allowed quick and easy removal of the component.

2.5. Post-disassembly analysis

The post-disassembly testing and analysis is required to examine if the components that are being repurposed need to be reconditioned or if they required triage to check for continued functionality. It concentrated on the power aspects of the units and was used to determine whether the unit had an attached power jack and whether the power button was attached directly to the motherboard or to the keyboard. This stage allowed for the cleaning and reconditioning of certain aspects like the Fan enclosure and application of Thermal Insulating Material if needed.

2.6. Final-stage functionality analysis

The final stage functionality step is required to test and diagnose any hardware issues which may have occurred during the disassembly and post-disassembly stages.

It ensures that the Motherboard, CPU and Memory are all operating normally before the repurposing stage. The final-stage functionality analysis included several longer tests developed to test the motherboard, CPU and RAM after disassembly to confirm that the components were still in working order and did not suffer any damage during the process. The overall methodology developed to test the suitability for repurposing of notebooks is shown in Fig. 2.3.

3. Results

3.1. Introduction

The methodology was applied to a sample of 246 Notebook Computers. The results are presented from each stage of the methodology. The overall results of each stage of the methodology are presented in Fig. 3.1. As can be seen from this data, the vast majority of failures are eliminated in the first two stages of testing ensuring the process is highly efficient and a minimal amount of time is spent working on devices that will ultimately fail. The initial visual inspection was successful in removing any devices that had structural damage or damage which could be hazardous to the end user. The amount of failures through each stage of the process drastically reduced once the onsite analysis and initial stage functionality analysis were completed.

3.2. Visual inspection and power-on test

The results of the combined visual inspection & power-on test of the sample of 246 notebook computers indicated that 78 units passed the tests and that 168 units failed. The devices that were collected and inspected have been categorised and displayed in Fig. 3.2.

3.3. Initial-stage functionality analysis

The results of the initial-stage functionality analysis were 44 devices passed and 34 devices failed. Of the 34 failed devices, 74% units failed for display issues, 15% failed for power issues, 12% for input/output issues and 3% failed for security issues. The display issues occurred due to the different methods manufacturers use to divert the video signal from the internal display to the external display. The diagnostic analysis was conducted using Eurosoft's PC-Check Diagnostic software. The testing lasted an average of 20 min and the time required by the operator to setup and start the diagnostics testing took an average of 65 s in the lab. The times could be reduced in a production environment.

The diagnostic testing indicated 1 failure but as this was due to a bad RAM module. The unit was retested with a similar capacity RAM module and passed.

3.4. Benchmarking

The benchmarking software was run on all devices as well as two thin client computers. The WYSE R90L (manufactured 2009) and the DELL OptiPlex FX170 (manufactured 2012) were benchmarked. These thin client models were selected as the majority of

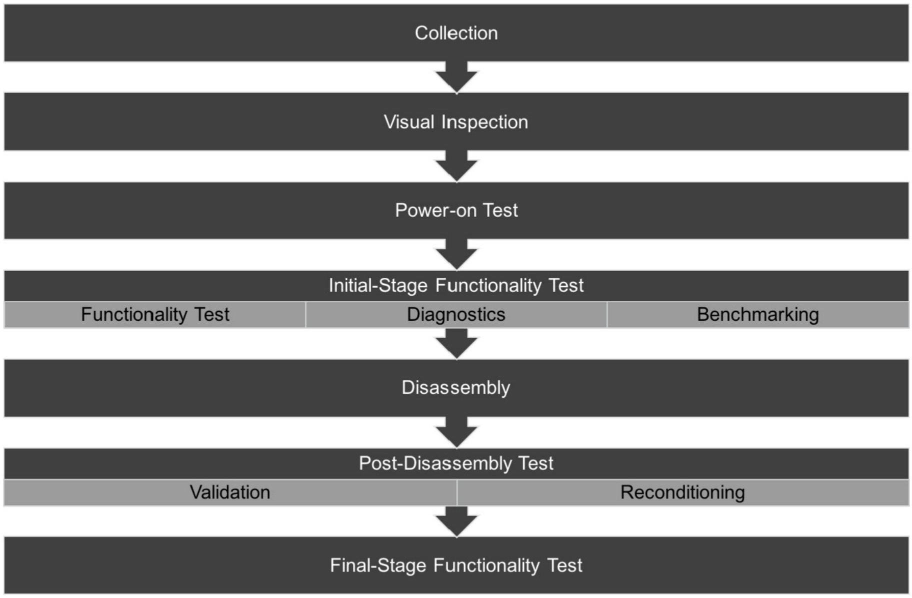

Fig. 2.3. Methodology for Repurposing suitability.

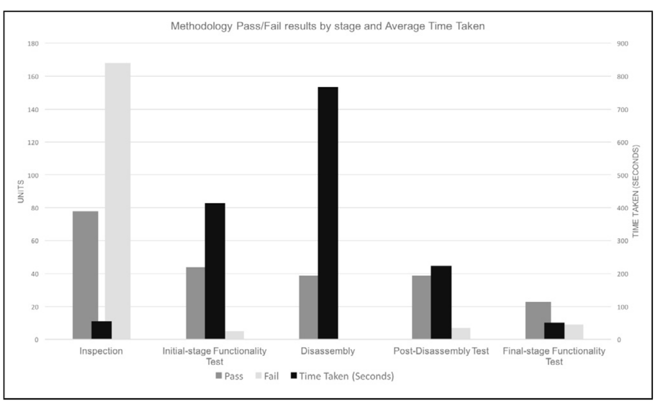

Fig. 3.1. Methodology results by each stage and average time taken.

notebooks collected were from 2007 to 2008 as seen in Fig. 3.3 and a comparison was required against newer model thin clients. The resulting scores from the DELL OptiPlex FX170 were used as a baseline score. The baseline score was used as the pass-fail indicator for the notebook computers. The results graph also presents the benchmark score of a DELL WYSE 3290 (2015) to indicate the comparison with a newer model thin client. The results were based on the multi-core benchmark score from Geekbench.

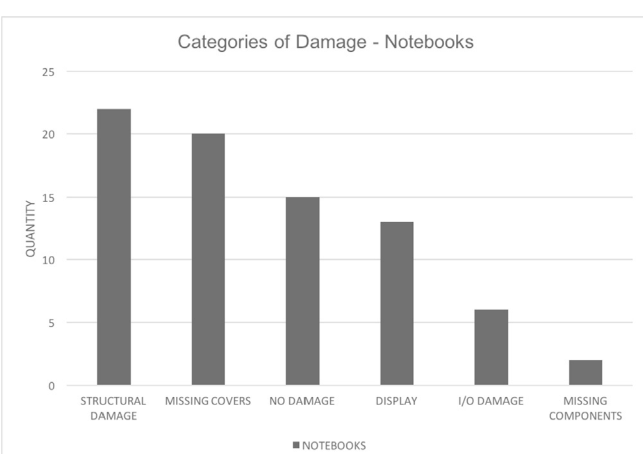

Fig. 3.2. Categories of damage from collected Notebooks.

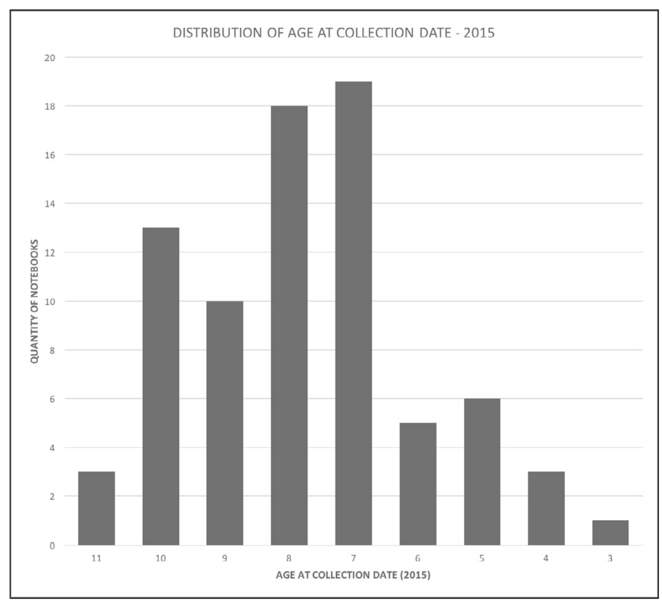

Fig. 3.3. Age distribution of collected devices.

3.5. *Disassembly*

The disassembly process was conducted under controlled conditions in a lab environment using video recording equipment for analysis. The process was conducted using the iFixit Classic Pro Tech toolkit and included all commonly required driver bits, spudgers and associated tools for disassembly and repair.

44 devices passed the initial-stage functionality analysis and these units went forward for disassembly. 38 of the 44 Notebook

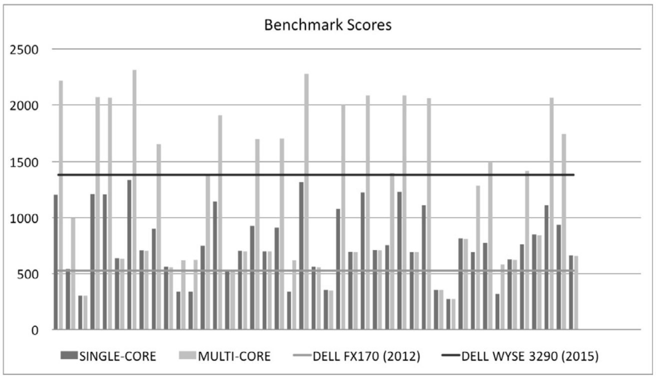

Fig. 3.4. Geekbench® Multi-Core Benchmark scores with DELL FX170 as baseline.

computers completed the disassembly process. Fig. 3.5 presents the results and distribution of the times taken for disassembly. The average time taken was 12 min and 46 s to dismantle each device. Fig. 3.6 presents a boxplot of the disassembly data.

3.6. Post-disassembly test validation

The post-disassembly testing was undertaken to analyse the suitability of the motherboard, CPU and RAM to function outside of the notebook chassis. The validation investigated possible issues with ancillary connections such as the power button, input/output devices and daughter-boards. The design and manufacture of notebook computers introduces processes which prevent or reduce the success of disassembly.

The results of this test uncovered an obvious issue with some designs of notebook whereby the power button was located on the keyboard assembly preventing the notebooks motherboard from being suitable to be a repurposed as a thin client.

The inventory of notebook motherboards can be described as having cooling systems (fan & heatsink) that were either PCB mounted or chassis mounted. The chassis mounted cooling systems required disassembly to successfully liberate all the remaining components. The PCB mounted fan cooling did not require any operator intervention for replacing the thermal insulating material (TIM). There was a need for reconditioning the cooling system to remove any dust or debris from the fan assembly in some cases.

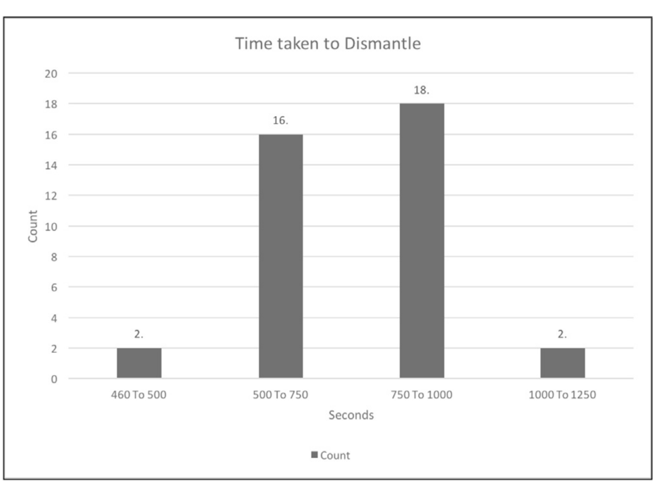

Fig. 3.5. Distribution of disassembly time in seconds.

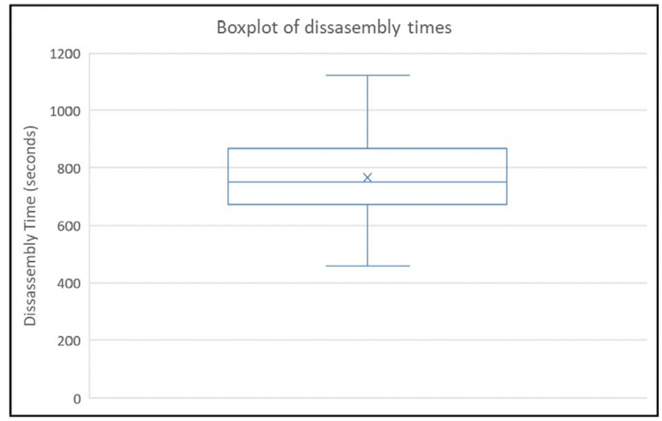

Fig. 3.6. Boxplot of Disassembly times.

3.7. Reconditioning

The reconditioning process was developed to assess the chassis mounted fan & heatsink cooling systems. The disassembly process in some instances required that the motherboard, fan, heatsink and processor required unfastening. This unfastening has an impact on the thermal insulating material (TIM) which enables safer cooling as it provides an efficient method of removing the heat from the processor to the heatsink. The process has several steps; (a) the removal of TIM from the heatsink and processor, (b) the application of TIM on the heatsink and processor, (c) removal of dust and debris on from the heatsink, fan and motherboard. The average time taken to complete this process was 3 min and 45 s (225 s). Fig. 3.7 displays original TIM application, methods of fastening and second application of TIM during reconditioning.

3.8. Final-stage functionality analysis

The final-stage functionality analysis comprised of the same tests that were carried out in the initial-stage functionality analysis. The main differences at this stage of testing were that the diagnostics executed on each computer comprised of a more rigorous analysis which had a duration of an average of 60 min per device. The diagnostic analysis tested the Processor, Memory, Cache, Video Memory, Motherboard and USB. The other difference with this analysis is that the notebooks had been dismantled and the testing and diagnostics are being carried out only on the motherboard, CPU & RAM. This procedure was introduced to confirm that the devices were still in a usable state after the disassembly process.

3.9. Technical requirements for repurposing notebook computers

The results for the technical requirements can separated under the following six headings; **Input Output (I/O)** - The input output

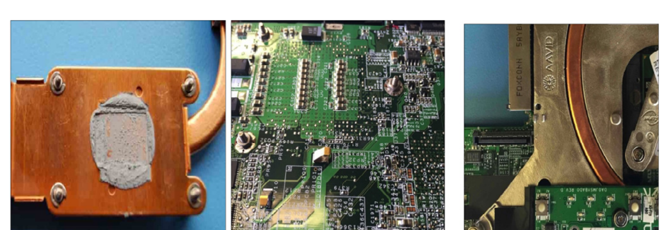

Fig. 3.7. Reconditioning – Removal of TIM and re-fastening of Heatsink & Fan.

ports are required for different functions to connect peripherals, displays and communications. The most common functions for thin client computers are USB, Network and Display. The USB ports would need to be USB 2.0 ports. The networking component would be a LAN port or in some instances a WLAN card is required. The display port should be VGA or DVI connection.

Graphics Display - The graphics card requires the ability to auto-sense the output port. This will allow the card to distinguish between having an internal LCD display or an external display connected through VGA or DVI.

Cooling - Cooling is essential to the safe operation of the CPU and in some cases the GPU. The heatsink and fan assembly is required to be PCB mounted. This will prevent any user intervention that may affect the thermal transfer of heat generated by the CPU and GPU.

Processor - The CPU requirement is essential to provide an adequate speed at which to carry out all instructions. The technical requirement is that a multi-core CPU is preferred for present and future needs.

Power - Given the singular construction of notebook and laptop motherboards the requirement is specified to allow a suitable power button assembly design.

RAM - The requirement for memory requirements is superfluous as it can be added although this may incur an extra expense. For the needs of a technical specification we would state that a minimum of 2 GB of RAM is required for suitable operation as a thin client computer. These requirements have been compared with current products on the market and the specifications have been aligned with the needs of a thin client computer. These are the basic requirement for a device of this nature.

4. Streamlined lifecycle analysis

4.1. Background

A streamlined Lifecycle Assessment (SLCA) was undertaken to indicate the scale and environmental benefit of repurposing Notebook motherboards as thin client computers. The environmental performance of WEEE reuse is an emerging aspect in the literature (Bovea et al., 2016; Parajuly and Wenzel, 2017). The streamlined LCA is based on cumulative energy demand (CED). The SLCA was chosen over a full LCA due to being a much quicker and simpler method obtaining similar results to a full LCA (Bennett and Graedel, 2000; Gehin et al., 2007; Graedel, 1998, 1997; Lifset, 2006) The streamlined LCA provides a quick and efficient method of examining the impacts of the manufacturing phase for all devices and the use phase and compares the energy required to manufacture and operate these devices. A comparative SLCA was conducted on three devices shown in Fig. 4.1 to investigate if an environmental benefit from the strategy is obvious.

This assessment focuses on the manufacturing and use phases. These phases were selected as the data for each phase were readily accessible and previous assessments have indicated that CED is the most used indicator in Lifecycle Assessment (Peiró and Ayres, 2012) Cumulative Energy Demand has previously been used in Lifecycle Analysis and Remanufacturing (Quariguasi-Frota-Neto and Bloemhof, 2012). These devices were selected to be representative of the types of comparable devices in a thin client installation.

4.2. Manufacturing phase

The Dell Inspiron 1300 motherboard was sourced from a formal collection scheme while sampling in 2013. The Dell Inspiron 1300 was dismantled into its constituent parts and the motherboard was repurposed for use as the motherboard for a thin client computer. The environmental impact of a repurposed motherboard was considered and included the manufacture of a housing for the motherboard. The value for the housing of the unit was assessed using the same weight as the original Dell Inspiron 1300 notebook housing value. This is due to the surface area of the printed circuit board (PCB).

The WYSE R90L Thin Client and the Dell OptiPlex FX170 Thin Client contained a motherboard, processor, RAM and Flash memory. The WYSE thin client (manufactured 2009) has a much larger form factor than the Dell OptiPlex (manufactured 2012). The Dell OptiPlex is representative of current thin client design. The housing was manufactured using a mix of steel and plastic. Due to the mix of steel shielding and plastic housing in each device, an equal value was attributed to each. Each device was assessed using a breakdown of each component where possible based on weight and area. Each device was assessed using the energy value for a standard external power supply used for notebooks and thin client computers. The values used for the cumulative energy demand (CED) were sourced from ASHBY, M. F. (2012). The data from this publication provides values for the energy required to manufacture using the most common materials used for electronics in mega joules per kilogram (MJ/kg) with a lower and upper range (Ashby, 2012). For the purposes of the SLCA conducted in this study, a median value was applied to all material values.

The table in Fig. 4.2 presents the data for each major component contained in all devices. The newer versions of thin client computers (Dell FX170) have lower amounts of energy required to manufacture due to their overall physical size and design. The Dell FX170 is noticeably smaller than the WYSE R90L. The total energy calculated for the Repurposed Thin Client excludes the printed circuit board (PCB) as the impacts are not seen in the repurposing scenario.

To present a fair assessment of the environmental impacts of repurposing, we must consider the allocation of the impacts of manufacturing on the first lifetime and the second lifetimes. Under normal circumstances in life cycle assessments all the environmental impact of manufacturing is attributed to the first (only) lifetime of the product. Cooper and Gutowski (2015) state that no literature had been found on the environmental impact of cascading components for another application.

The literature has also stated that to return a device at end of life to a usable state we have to understand that the environmental benefits are best defined when compared to a non-reuse scenario (Cooper and Gutowski, 2015). We can also compare the environmental benefits of our hybrid indirect reuse and repurposing to

Make	Model	Year	Processor Type	Processor Speed	Memory	Flash
Repurposed Thin Client	Motherboard from INSPIRON 1300	2006	PENTIUM M	1.7GHz	512MB	N/A
WYSE	R90L	2009	AMD SEMPRON	1GHz	1GB	1GB
DELL	OPTIPLEX FX170	2012	INTEL ATOM N270	1.6GHz	2GB	4GB

Fig. 4.1. Computers used for SLCA.

DEVICE	COMPONENT	WEIGHT (kg)	ENERGY (MJ/kg) ASHBY (2012)	ENERGY (MJ/kg)	TOTAL
Repurposed Thin Client	Case (Plastic)	1.285	97	125	380
	Power Supply	0.445	574	255	
WYSE R90L Thin Client	PCB	0.47	4670	2195	2588
	Heatsink	0.34	210	71	
	Case (Plastic)	0.6	92	55	
	Case (Steel)	0.6	18.7	11	
	Power Supply	0.445	574	255	
Dell OptiPlex FX170 Thin Client	PCB	0.29	4670	1354	1652
	Heatsink	0.11	210	23	
	Case (Plastic)	0.17	97	16	
	Case (Steel)	0.17	18.7	3	
	Power Supply	0.445	574	255	

Fig. 4.2. Environmental Impact of Manufacturing Phase data from Ashby (2012).

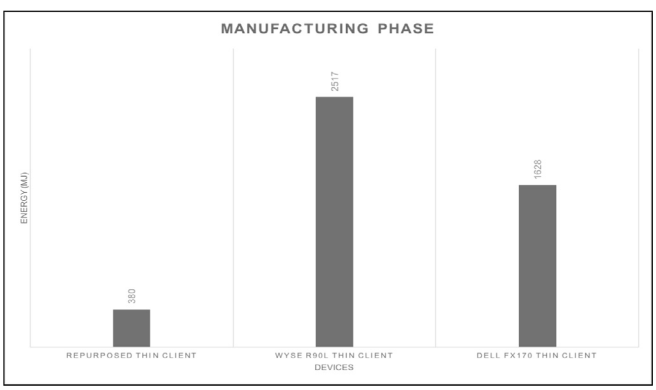

Fig. 4.3. Manufacturing phase for all devices.

remanufacturing. A case study into the energy savings of remanufactured laptops placed no energy burden on the remanufactured product (Gutowski et al., 2010).

The calculations for the Repurposed Thin Client included the addition of a case to house the repurposed motherboard. This was estimated as having the same impact as the manufacturing of a chassis of a Notebook Computer. Fig. 4.2 displays the energy required in the manufacturing phase for all the listed devices.

4.3. Use phase

The use phase of a typical thin client computer was considered using the results from Maga et al. where they analysed the impact on the use phase of a thin client computer (Maga et al., 2013). The paper defined the functional unit as the supply of a computer workstation with two or three applications simultaneously for a period of 5 years with 220 working days each year with each day comprising of nine working hours and the same functional unit was applied to this study. The idle time was recorded using a power meter. To record the idle time of each device, the same power supply was used to power and boot a USB key running a Linux operating system. The power output was recorded in accordance with Energy Star criteria to measure idle time power output. Fig. 4.4 displays the power meter readings that were collected in Watts and converted to kilowatt/hours and mega joules. The kilowatt/hours and mega joule values incorporate the Total Primary Energy Requirement (TPER). At present the conversion rate for Ireland is estimated to be approximately 2 (SEAI, 2017).

5. Results

The Streamlined LCA for this study quantified the environmental impact of the manufacturing and the use phase of thin client devices and compared them to two commercial thin client devices.

The results indicate that the main impact to the environment is from the primary production of thin client computers and this can be reduced when we reuse components that have been repurposed from a Notebook computer.

The streamlined Lifecycle assessment provides a valuable insight into the impact to the environment from manufacturing and use phases. The Streamlined Lifecycle analysis results indicate that there are impacts to the environment that can be offset if the correct action is taken on suitable products and the second lifetime is very important as it extends the lifetime of a product and offsets the impact of primary manufacturing.

6. Conclusion

6.1. Opportunities for repurposing

This research has shown that there are opportunities for suitable laptops to be repurposed as thin clients. The process of repurposing has demands that are similar in characteristic to recycling and these demands need to be incorporated into the design process to be a

Model	Idle (watts)	kilowatt/Hours (kWh)			Mega Joules (MJ)		
		1 Yr	3 Yr	5 Yr	1 Yr	3 Yr	5 Yr
Remanufactured Thin Client	12.1	48	144	240	172	517	862
WYSE R90L	18.5	74	220	366	264	791	1319
DELL OptiPlex FX170	13.7	54	162	272	195	586	977

Fig. 4.4. Power measured in idle state for kilo watt hours and mega joules.

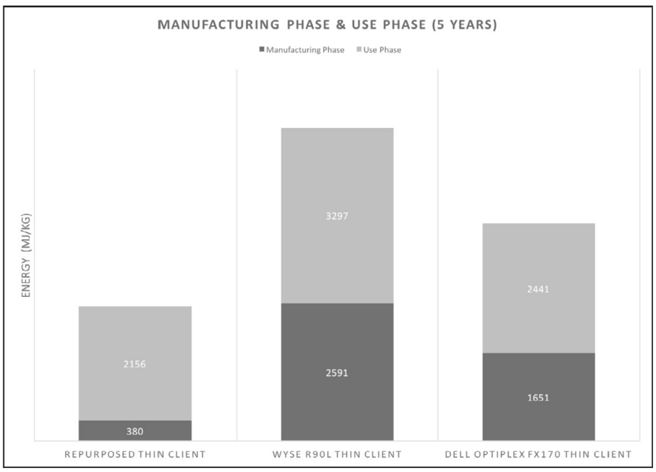

Fig. 4.5. Streamlined LCA results from Manufacturing and Use phases.

truly end of life strategy. The idea of repurposing electronic devices signifies a disruption in how we understand the use of devices. If we can consider that once a notebook or laptop reaches its end of life, we should have a process in place to dictate if the device can be repaired, reused, repurposed or recycled.

6.2. *Recommendations*

The recommendations from the research can be divided into several areas and applied to the waste collection infrastructure to product design and to user behaviour.

To support more reuse and repurposing, the infrastructure of the takeback schemes needs to be changed to integrate the strategy of reuse as a clear method of optimising product lifetime extension. It has been noted in the literature that all electronic items with the potential for reuse and repair should be stored in adequate areas to prevent the degradation and damage of potential revenue generating items. The current system is based solely on recovering the devices for recycling. Reuse is reliant on the proper manual handling of stock at all stages of the collection process as means to recovering consumer electronic waste and extending lifetimes.

Better product design can allow for better end of life outcomes be it for reuse or recycling. Products that are Designed for Disassembly (DfD) will have a better opportunity to minimise waste from electronics devices. The possibility of extending a products lifetime through better design either through modularity or by creating a pathway for a repurposed product.

User behaviour is very important factor in reuse, not only in determining attitudes towards reuse but also understanding the impacts of owning and disposing of a product. There are certain technical and non-technical barriers to repurposing. The technical barriers are items like notebook computer motherboard design and the infrastructure in place for WEEE takeback. The non-technical barriers are items such as cost and viability, adoption by relevant Recyclers/Refurbishers etc., consumer attitudes to reused products and environmental benefits.

6.3. *Eco-design*

The current design of notebook motherboards can present problems for component reuse. If the possibility of using these motherboards in a change of role function is to take place then the following items need to be considered. The guidelines will increase the possibility of pcb's being reused to extend their lifetimes.

- Motherboards have power buttons directly fixed to the pcb or connected by a cable to the pcb
- Motherboard's are characterised by either having pcb mounted fan and heatsink or chassis mounted fan & heatsink
- A new thin client housing design could incorporate a larger heatsink to eliminate the fan as fans can sometimes be a point of failure.
- A form of cooling is required for the processor to operate to its required performance levels.

6.4. *Suitability of consumer WEEE for repurposing*

An assessment of the research presented in this paper is required to understand the nature of the e-waste landscape and the challenges that arise from it. This study in repurposing Notebook computers from consumer WEEE presents the technical feasibility and the methodology required to implement a testbed situation for validating that the consumer WEEE is in part suitable for a type of reuse. The methodology presented in this paper highlights the requirements for repurposing. The papers findings present the barriers and opportunities of repurposing notebook computers as thin client computers from consumer WEEE with emphasis on the technical requirements. While the initial failure rate was very high, the subsequent tests showed a decrease in failure rates. The decreasing failure rates can be characterised as being a successful outcome of the robustness of the methodology under difficult conditions.

The high failure rate presented at the start of the methodology highlights the condition of the collected Notebooks from a WEEE takeback scheme. The research was conducted on the collected notebooks was in an “as is” condition. There was no intervention by any stakeholder to divert devices from pursuing the normal path of travel for all ICT waste.

The high failure rate also enables the research to highlight the need for a suitable collection method if items are to be suitable for reuse and repurposing.

The reuse and repurposing components at end of life also has the potential to include repair. The collection and disassembly of the notebook computers provides an opportunity for the recycling of critical materials and to provide a source of supply for the repair industry.

Further research is needed to ascertain the demand for repurposed products, this would explore looking at energy usage, consumer behaviour, market opportunities etc.

6.5. Future work

The research has proven that there is a potential for reuse and repurposing from WEEE. The research was conducted in what can be best described as baseline conditions. The implementation of a better system for the management of WEEE and its infrastructure would have a positive influence in creating a supply for reuse. Good quality WEEE benefits reuse and repurposing and allows the opportunity of providing part and component supply for repair. There is also the potential to repurpose end of life products from Business-to-Business (B2B) channels and Asset Recovery Services. These channels and services require that the collected equipment is relatively new (3–4 years old) and be of a much higher standard than consumer WEEE. Repurposing may provide an opportunity to reclaim value on devices that may be sent for recycling rather than repair. Repurposing has the potential in certain circumstances to be a hybrid end of life solution by combining recycling and reuse to create a resynthesized product and to recover critical raw materials from suitable components that are no longer necessary for use.

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