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Sustainability Assessment of Electronic Waste Remanufacturing: The Case of Laptop

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Abstract

Over the years, electronic waste accumulation has been on a steep rise, parallel with the technological evolution of electrical and electronic equipment. Companies have adopted circular economy approach to overcome the emerging waste issue in the last couple of decades, where goods can return to manufacturers or remanufacturers. They can be used after certain modifications or remanufacturing processes. The remanufacturing of a laptop refers to the disassembly, inspection, part repair, and upgrade of the original laptop to give it a new life, along with a warranty that it is as good as a new product. The goal of this study includes studying and evaluating the total environmental impact of remanufacturing operations of a laptop conducted by remanufacturing company using Life Cycle Assessment. The system boundaries include all the operations of Circular Computing, starting with collecting discarded laptops and ending with distributing remanufactured laptops. The results show that transportation, with maximum contribution from air transportation, has the highest CO_2eq emission as a result of centralized remanufacturing operations of the company. It is also proven that remanufacturing a laptop has a much smaller environmental impact than a newly manufactured laptop.

Keywords: Remanufacturing; E-Waste; Life Cycle Assessment; Sustainability

1. Introduction

Solid waste management is a global issue in terms of environmental contamination, climate change and sustainability. Reducing waste generation through prevention, reduction, recycling, and reuse is the main goal for manufacturers and policymakers. Amongst others, electronic waste (e-waste) has been identified as the rapidly accumulating waste stream from past decades. According to the Global E-Waste monitor report, e-waste increased from 41.8 MT in 2014 to 53.6 MT in 2022, which is predicted to reach 74.7 by 2030 [1]. The constant evolution of electrical and electronic equipment (EEE), predominantly in terms of energy efficiency and functionality in the use phase, is the most contributing factor to this e-waste accumulation [2]. Within EEE, consumer electronics with a fast evolution speed and short lifetime, such as mobile phones, laptops, computers, etc., are the primary reason for this e-waste generation [3]. This short life cycle of consumer electronics is not always the result of devices breaking down beyond repair or becoming obsolete. Indeed, in some cases, electronic devices collected from landfills are still operational. The reason for these electronics short lifetime is their fast technological evolution, which results in premature obsolescence and underutilized lifetimes [4]. As a result of this underutilized lifetime of electronics, large volumes of electronics can be recovered and reused in the Sustainable IT (Green IT or Circular Computing) concept [2].

Green IT refers to the accountable and resourceful production, usage, and disposal of electronic devices while sustaining financial feasibility and improving performance in a green manner [5]. Piotr Pazowski [5] defines the fundamental approaches in Green IT by using four concepts: Green Use, Green Disposal, Green Design, and Green Manufacturing. Between those, Green Disposal is the leading approach for circular computing (CC), as it refers to a greener method of disposal where the original equipment manufacturers can obtain the used product based on a return policy to avoid any damage to the environment. CC is a method of extending the productive lifetime of a device by using different measures such as reuse, repair, remanufacturing, and recycling [6]. Among these measures, reuse, repair, and remanufacturing are more beneficial when compared to recycling to mitigate the adverse environmental impacts of manufacturing new products since most of the energy consumption is in the production phase, not in the materials extraction [7]. Remanufacturing of discarded laptops can decrease the utilized energy during manufacturing up to 80% due to the exclusion of raw materials extraction and processing [8]. Repair and remanufacturing are also more applicable than recycling as the e-waste category is one of the most complex waste streams due to the wide variety of commercial products, from mechanical devices to highly integrated systems [9].

Figure 1 shows the process flows of linear use and circular use. Linear use includes raw material extraction and processing, transportation, use and End of Life (EoL) phases after a single use of a product. Unlike linear use, in circular use, the product is taken to a reprocessing stage where it is repaired or remanufactured and prepared for reuse. These reprocessing and reuse phases can be repeated as many times as possible (n times) with existing materials and technology. On the circular use of a product, EoL processes, new raw material extraction, and production are avoided, along with all needed transportation. However, the processing for reuse and transportation to, and from, reprocessing is added. Based on this, a basic formula for "avoided impact" by reuse is given in Equation 1, where EP is the extraction and production, T is the transportation, $RePT$ is the re-processing and transport, and n is the number of reuses [10].

$$Avoided\ impact = (EP + T + EoL - RePT) * n \qquad (1)$$

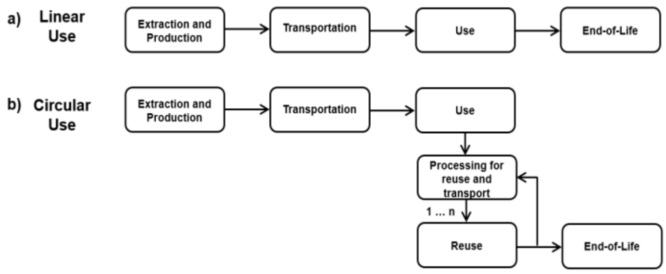

Figure 1. Process flow of (a) linear use of the product, (b) circular use of the product.

In this study, avoided impact in terms of CO_2 equivalent (CO_2eq) emission by remanufacturing a laptop instead of buying a new one is calculated. In addition, a Life Cycle Assessment (LCA) study is conducted to evaluate the environmental impact of remanufacturing operations, and key operations that make the highest impact are defined. All the represented results are specific to this case study regarding data obtained from a real company.

2. Sustainability assessment of remanufacturing

Remanufacturing of existing goods eliminates the need for new raw materials extraction, production of the parts and waste disposal while adding re-processing operations as stated in the previous section. In most cases, the environmental impacts of re-processing operations, are much lower than the eliminated operations and remanufacturing is more eco-friendly than new manufacturing. However, the environmental impacts of remanufacturing operations still need to be evaluated to improve them and provide feedback to the remanufacturing companies on their operations.

Remanufacturing operations include transportation, disassembly and inspection, remanufacturing, packaging, and distribution, as shown in Figure 2. Even though transportation is not a primary operation for remanufacturing, the operation system of remanufacturing company and transportation methods used can impact the overall environment. The operation system of the company can be either centralized or decentralized. In the centralized system, the remanufacturing center is located in one place, and all the discarded items are transported to this location for remanufacturing. In the decentralized system, items are not transported to a remanufacturing center; instead, they are sent to a remanufacturing plant near the pickup locations. As the decentralized system decreases the total transportation distance, it is found to be more eco-friendly [2]. In addition, the selected transportation method is also effective on environmental impact. Air transportation leaves the largest carbon footprint. Emission at high altitudes is more environmentally damaging than ground-level emissions due to increased interaction with gases in the atmosphere [11].

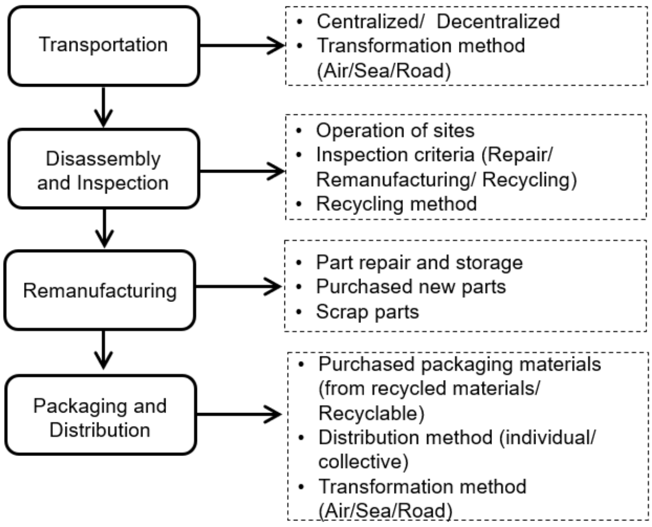

Figure 2. Operations of remanufacturing for reuse.

After disassembly and inspection, repairing or remanufacturing products for reuse are the most environmentally preferable options, as most of the processed parts are used again, and only specific components of the laptop are replaced with newer versions for upgrading [12]. Recycling is the option for the parts that are not functional anymore. Laptops consist of highly precious metals and non-metals, such as nickel, zinc, silver, platinum, gold, steel, aluminum, glass, carbon, and polymer. These materials can be recovered from laptop waste which eliminates the raw material extraction for new product manufacturing. Thus, functional recycling instead of incineration should be processed [12].

In remanufacturing process, non-functional parts and the parts that need to be upgraded are replaced with new parts to have the remanufactured laptop in the same condition as the new one. Since the remanufacturing idea is about using the same components instead of manufacturing new ones, measuring the number of new components purchased or used can reflect the sustainability assessment of the remanufacturing process. In addition, scrap parts from remanufacturing also need to be functionally recycled [13].

Packaging recycled laptops is also not a primary remanufacturing process, similar to transportation. However, since the remanufacturing process is not energy intensive, all contributing processes become critical to evaluate while trying to achieve a net zero emission. Thus, materials should be selected from recycled materials with minimum embodied energy and waste packaging materials should be functionally recycled to be reused [14].

3. LCA case study

In this section, LCA analysis of laptop remanufacturing operations is carried out to demonstrate sustainability assessment.

3.1. Goal and scope

The LCA analysis aims to evaluate the environmental impact of the laptop remanufacturing process and to compare the overall result with the newly manufactured laptop. The goal of the remanufacturing company is to have carbon-neutral, remanufactured laptops with a higher sustainability aspect and still of the same quality as a newly manufactured laptop. Therefore, the outcomes of this study could provide comprehensive data for them to evaluate their operations and achieve their goal.

The system boundary of the study is defined as gate-to-gate (from previous user to the next user) for re-processing operations considering the aim of the study. Transportation from the previous user to remanufacturing facility, disassembly and inspection, remanufacturing, packaging, and transportation to the new user are involved into the system boundary. Inputs and outputs of the system boundary are shown in Figure 3. The functional unit is defined as “remanufacturing of one laptop” in order to estimate the potential savings of remanufacturing the laptop over the newly manufactured one.

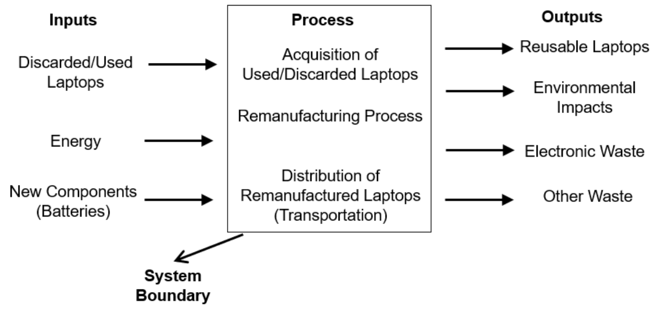

Figure 3. Product system boundary.

3.2. Life cycle inventory

The inventory related to remanufacturing process of the laptop is acquired as foreground data from remanufacturing company, consists of the information about sites in operation by the company with the electricity consumption in various processes of remanufacturing of laptop, including the details about whether the electricity is from renewable sources or not, transportation of laptops and its spare parts between sites, purchased new parts, purchased packaging materials and, electronic and other waste. Furthermore, regarding the transportation done between various sites, detailed information has been collected in terms of how much distance has been covered by each means of transport, i.e., air, sea, or ground. In addition to that, information about what types of vehicles have been used and their loading capacities has also been collected and reviewed for assessment.

The company has a centralized system with a remanufacturing center based in the Middle East, a warehouse based in UK and pickup points on each continent. All the collected laptops from each continent are transported to remanufacturing center either via air or sea transportation. In the continent transportations from sources to the pickup locations and from pickup locations to the ports are conducted via trucks. Details of the transportation data; the distance that has been covered, transportation type, shipment loads, and the number of shipments is summarized in Table 1.

Table 1. Summary of transportation data.

Category	Air Transport	Sea Transport	Ground Transport	Unit
Total Distance	1,535,308	57,931	423,256	km
Total Number of Shipments	224	351	831	units
Avg. Weight of Shipments	758	3181	2890	kg

Electricity consumption is collected for the on-site operations. The used energy amount is 911,858 kWh for remanufacturing center in the Middle East, while it is 93,559 kWh for the warehouse in the UK. The voltage level of used electricity is selected as low since the remanufacturing processes of the laptop are not that energy-consuming.

Regarding foreground data, the battery is the most purchased new part, with 8200 new batteries for 110,000 remanufactured laptops. The impact of battery fabrication is added to the LCA model. The average battery weight is calculated as 350g using mostly remanufactured laptop models and their battery weight information.

Packaging materials, cardboard boxes, bubble rolls, paper, polypropylene tapes, etc., are included with their manufacturing impacts according to their weight. The total weight of these materials accumulated to approximately 109,000 kg. Similar materials are selected for the type of packaging materials that are not available in the Ecoinvent database.

3.3. Results assessment and interpretation

The remanufacturing system given in Figure 3 is modelled in SimaPro 9.2 software. In the model, four main contributors are defined as; transportation, electricity consumption during remanufacturing operations on site, newly purchased batteries and used packaging materials. As for the Life Cycle Impact Assessment (LCIA) process, the ReCiPe 2016 methodology is used [15]. ReCiPe 2016, one of the most widely used LCIA methodologies, has been chosen due to its worldwide coverage, including characterization factors for midpoint and endpoint indicators.

Results for the midpoint indicators, given in Figure 4 below, reveal that the transportation of the discarded and remanufactured laptops between pickup points and remanufacturing centre, and electricity consumption contribute the most for nearly all indicators.

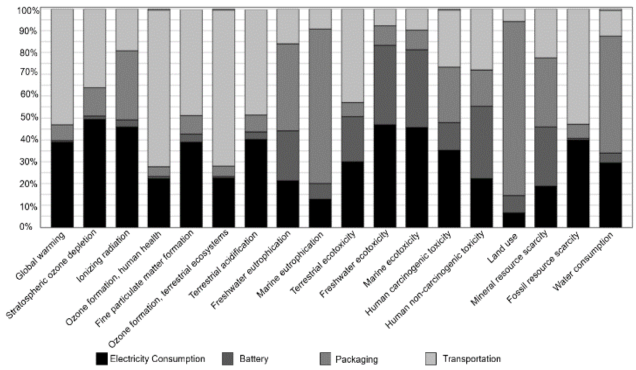

Figure 6. LCIA results for the midpoint indicators.

Global Warming Potential (GWP, kg CO_2eq) is the most crucial impact category as it represents climate change, the main impact discussed by manufacturing and/or remanufacturing companies, and most changes made in the manufacturing industry revolve around climate change. The comparison between the product stages, in terms of % CO_2eq emission, is shown in Figure 5. The highest CO_2eq emission comes from transportation with 53% and is followed by electricity consumption with 39%.

As transportation has three methods, air, sea, and ground, the contribution of different transportation methods to the overall transportation is given in Figure 6. Air transportation has the highest CO_2eq emission, with 91% between transportation methods. This high emission percentage of transportation and the excessive contribution of air transportation can be attributed to the centralized system of the CC company, as all the collected laptops need to be transferred to the remanufacturing center.

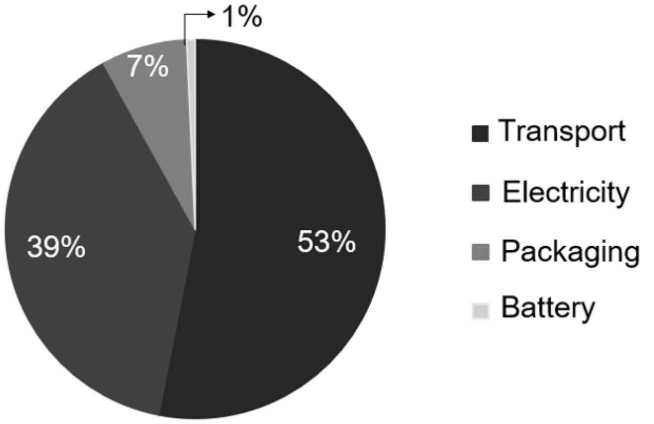

Figure 4. CO_2eq emission comparison between remanufacturing stages.

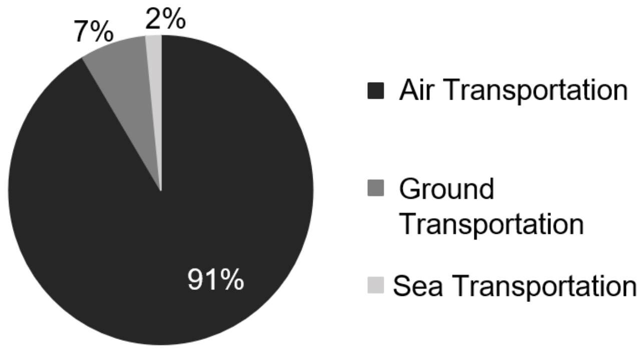

Figure 5. CO_2eq emission comparison between transportation methods.

The comparison between the newly manufactured laptop and CC remanufactured laptop in terms of total CO_2eq emissions is given in Figure 7. An average number for CO_2eq emission of one manufactured laptop on extraction, production, transportation, and EoL phases is obtained from background data as 331kg. CO_2eq emission of one remanufactured laptop is calculated as 21kg. Even though the emission of the manufactured laptop is not accurate, the remanufactured laptop result is accurate according to the remanufacturing company operations. Avoided impact with remanufacturing is calculated using Equation 1. This distinctive CO_2eq emission difference between manufactured and remanufactured laptops proves the environmental superiority of remanufacturing.

4. Conclusion

In this case study, where a LCA analysis is made on a remanufacturing company - air transportation and electricity consumption are identified as the most contributing processes in the remanufacturing operations. Therefore, to improve the remanufacturing operations of the CC company, the following actions are recommended:

- Switch to a decentralized system with remanufacturing plants near each pickup location.
- Shift deliveries from air transportation to sea transportation.
- Switch to renewable energy on all possible sites. Define maximum energy-consuming operations and determine possible replacements.
- Packaging with recycled materials and recycling of used waste packaging materials.

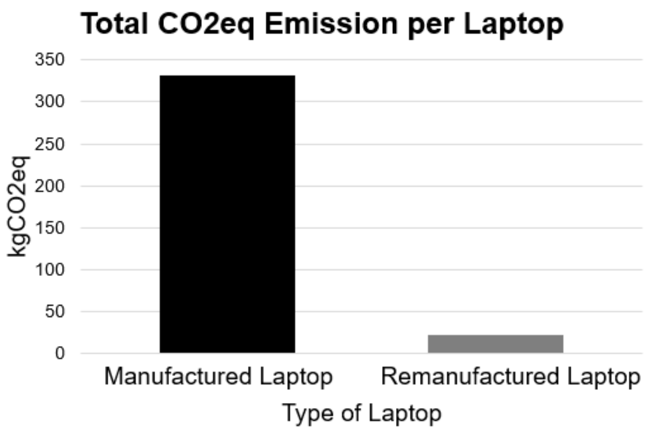

Figure 7. CO_2eq emission comparison between new manufactured and remanufactured laptop.

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References

1. Forti V, Balde CP, Kuehr R, Bel G (2020) The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential
2. Mann A, Saxena P, Almanei M, Okorie O, Salonitis K (2022) Environmental Impact Assessment of Different Strategies for the Remanufacturing of User Electronics. Energies (Basel) 15:. https://doi.org/10.3390/en15072376
3. Suhariyanto TT, Wahab DA, Rahman MNA (2017) Multi-Life Cycle Assessment for sustainable products: A systematic review. J Clean Prod 165
4. Puca A, Carrano M, Liu G, Musella D, Ripa M, Viglia S, Ulgiati S (2017) Energy and eMergy assessment of the production and operation of a personal computer. Resour Conserv Recycl 116:. https://doi.org/10.1016/j.resconrec.2016.09.030
5. Pazowski P (2015) Green Computing: Latest Practices and Technologies for ICT Sustainability. Joint International Conference
6. André H, Ljunggren Söderman M, Nordelöf A (2019) Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. Waste Management 88:268–279. https://doi.org/10.1016/j.wasman.2019.03.050
7. Williams ED, Sasaki Y (2003) Energy analysis of end-of-life options for personal computers: Resell, upgrade, recycle. In: IEEE International Symposium on Electronics and the Environment
8. André H, Ljunggren Söderman M, Nordelöf A (2019) Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. Waste Management 88:. https://doi.org/10.1016/j.wasman.2019.03.050
9. Kang HY, Schoenung JM (2006) Estimation of future outflows and infrastructure needed to recycle personal computer systems in California. J Hazard Mater 137:. https://doi.org/10.1016/j.jhazmat.2006.03.062
10. Jonatan Wranne (2020) Product databases: the environmental benefits of reuse: The climate benefits of reusing IT products and the method for creating databases
11. Scelsi L, Bonner M, Hodzic A, Soutis C, Wilson C, Scaife R, Ridgway K (2011) Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment. Express Polym Lett 5:. https://doi.org/10.3144/expresspolymlett.2011.20
12. Diener DL, Tillman AM (2015) Component end-of-life management: Exploring opportunities and related benefits of remanufacturing and functional recycling. Resour Conserv Recycl 102:. https://doi.org/10.1016/j.resconrec.2015.06.006
13. Williams E, Sasaki Y (2003) Strategizing the End-of-Life Handling of Personal Computers: Resell, Upgrade, Recycle
14. Ncube LK, Ude AU, Ogunmuyiwa EN, Zulkifli R, Beas IN (2021) An overview of plasticwaste generation and management in food packaging industries. Recycling 6:. https://doi.org/10.3390/recycling6010012
15. Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. International Journal of Life Cycle Assessment 22:. https://doi.org/10.1007/s11367-016-1246-y