Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 116 (2023) 378–383

www.elsevier.com/locate/procedia

30th CIRP Life Cycle Engineering Conference.

Sustainability Assessment of Electronic Waste Remanufacturing: The Case of Laptop

Yagmur Atescan Yuksek[a,*], Yousef Haddad[a], Emanuele Pagone[a], Sandeep Jagtap[a], Steve Haskew[b], Konstantinos Salonitis[a]

[a] Sustainable Manufacturing Systems Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, MK43 0AL, United Kingdom

[b] Circular Computing, Unit E Railway Triangle, Walton Road, Portsmouth, Po6 1TY, United Kingdom

* Corresponding author: yagmur.atescanyuksek@cranfield.ac.uk

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 few 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 a remanufacturing company using Life Cycle Assessment. The system boundaries include all the operations of the remanufacturing company, 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 due to the 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 MT 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 reasons for the short lifetime of these electronics are due to their fast technological evolution, the requirement for better performance to meet the needs of software technology advances, and the way companies' marketing strategies make people think they need to upgrade to stay current which results in premature obsolescence and underutilized lifetimes for devices [4], [5]. As a result of this

10.1016/j.procir.2023.02.064

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 sustainable manner [6]. Pazowski [6] defines the fundamental approaches in Green IT 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 environmental damage. CC is a method of extending the productive lifetime of a device by using different measures such as reuse, repair, remanufacturing, and recycling [7]. 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 [8]. For example, remanufacturing discarded laptops can decrease the utilized energy during manufacturing by up to 80% due to the exclusion of raw materials extraction and processing [9]. In addition, remanufacturing can save significant amounts of water compared to producing a new product from the beginning [10]. Repair and remanufacturing are also more applicable than recycling as e-waste is one of the most complex waste streams due to the wide variety of commercial products, from mechanical devices to highly integrated systems [11]. To address the issue of electronic waste, the European Union (EU) has proposed several regulations to promote CC and reduce waste. These include measures to increase the interchangeability of batteries in electric devices, allowing consumers to replace them and extend the life of the devices easily, and a ban on gluing components together in certain types of electronic devices, such as smartphones, to enable consumers to repair them as part of the "right to repair" initiative [12].

Fig. 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. EoL processes, new raw material extraction, and energy-intensive production are avoided on the circular use of a product, 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 [13].

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

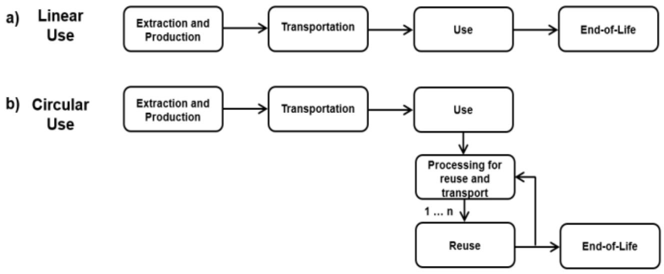

Fig. 1. Process flow of (a) linear use of the product, (b) circular use of the product.

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 case company.

2. Sustainability assessment of remanufacturing

Remanufacturing of existing goods eliminates the need for new raw materials extraction, energy-intensive 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 Fig. 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 but are sent to a remanufacturing facility 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 between air, sea and ground transportation. In addition, emission at high altitudes is more environmentally damaging than ground-level emissions due to increased interaction with gases in the atmosphere [14].

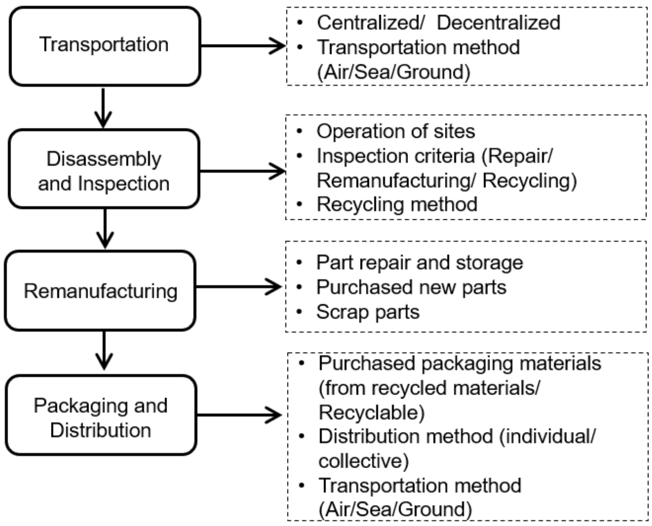

Fig. 2. Operations of remanufacturing for reuse.

After disassembly and inspection, the most environmentally preferable options are repairing or remanufacturing products for reuse. Most of the processed parts are used again, and only specific laptop components are replaced with newer versions for upgrading [15]. Therefore, recycling is the option for the parts that are not functional anymore. Laptops include 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 [15].

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 [16].

Packaging remanufactured 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 [17].

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 laptop remanufacturing processes environmental impact and 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 the previous user to the next user) for re-processing operations considering the aim of the study. Transportation from the previous user to the remanufacturing facility, disassembly and inspection, remanufacturing, packaging, and transportation to the new user is involved in the system boundary. Inputs and outputs of the system boundary are shown in Fig. 3. The functional unit is defined as "remanufacturing of one laptop" to estimate the potential savings from remanufacturing one laptop over buying a new manufactured one.

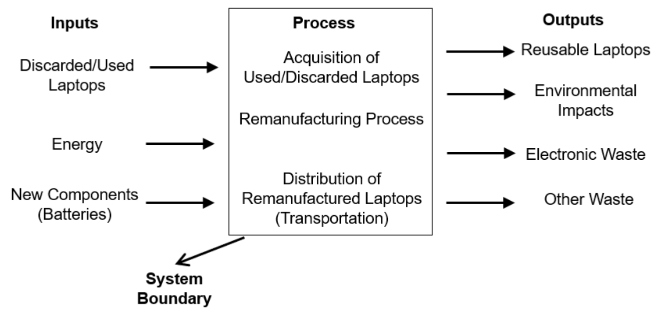

Fig. 3. Product system boundary.

3.2. Life cycle inventory

The inventory of the remanufacturing process of the laptop is taken from the remanufacturing company as foreground data on its activities for one year. It consists of information about sites in operation by the company with the electricity consumption in various processes of remanufacturing laptops, including grid-specific data, transportation of laptops and 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 have 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 the UK and pickup points on each continent. All the collected laptops from each continent are transported to the remanufacturing center via air or sea transportation. In the continent, transportation from sources to the pickup locations, and from pickup locations to the ports is conducted via trucks. Details of the transportation data, the distance that has been covered, transportation type, shipment loads, and the number of shipments are 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 energy intensive.

Regarding foreground data, the battery is the most purchased new part, with an average of one battery for every 13.5 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 weightthese materials accumulated to approximately 109,000 kg. In addition, similar materials are selected for the type of packaging materials unavailable in the Ecoinvent database.

3.3. Results assessment and interpretation

The remanufacturing system given in Fig. 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 [18]. 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 Fig. 4 below, reveal that the transportation of the discarded and remanufactured laptops between pickup points and remanufacturing center, and electricity consumption contribute the most for most of the 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 remanufacturing stages, in terms of % CO_2eq emission, is shown in Fig. 5. The highest CO_2eq emission comes from transportation at 53% followed by electricity consumption at 39%.

As transportation has three methods, air, sea, and ground, the contribution of different transportation methods to the

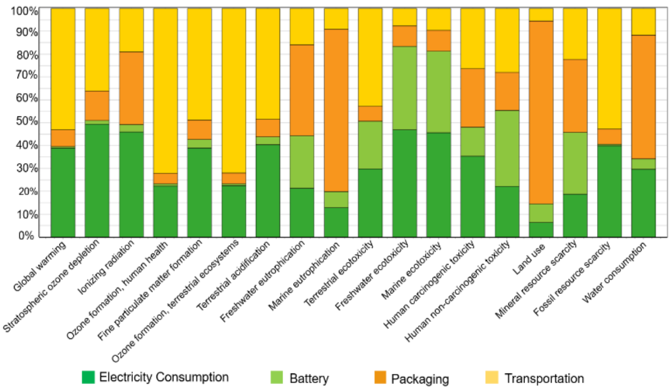

Fig. 4. LCIA results for the midpoint indicators.

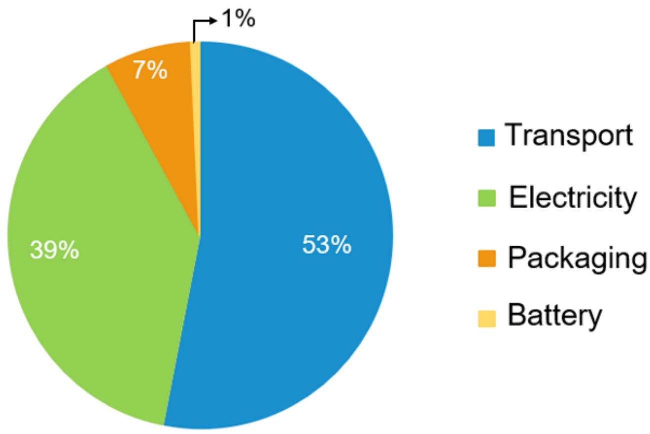

Fig. 5. CO_2eq emission comparison between remanufacturing stages.

overall transportation is given in Fig. 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 transported to the remanufacturing center.

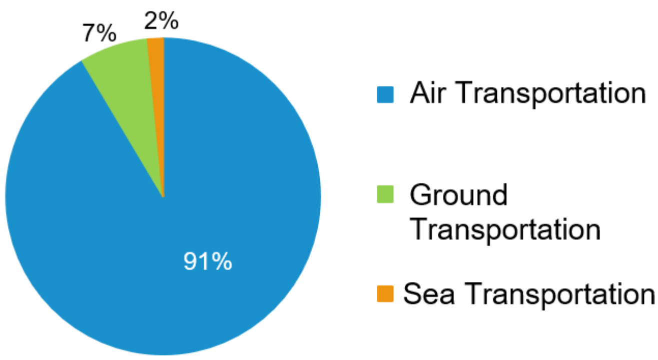

Fig. 6. CO_2eq emission comparison between transportation methods.

The comparison between the newly manufactured laptop and CC remanufactured laptop in terms of total CO_2eq emissions is given in Fig. 7. For a newly manufactured laptop, the average number of CO_2eq emission in extraction, production, transportation, and EoL phases is obtained from manufacturing companies' databases as 331kg. Based on the remanufacturing company's operations, the CO_2eq emission is calculated as 21 kg for a remanufactured laptop. The impact prevented by remanufacturing is calculated as 310 kg using Equation 1. This distinctive CO_2eq emission difference between manufactured and remanufactured laptops proves the environmental superiority of remanufacturing.

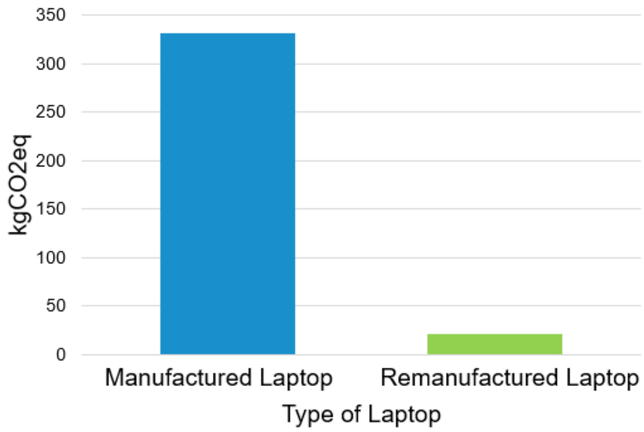

Figure 7. CO_2eq emission comparison between new manufactured and remanufactured laptop.

4. Conclusion

The problem of e-waste has increased significantly in recent years as technology advances rapidly, and products become outdated quickly. Remanufacturing of consumer electronics is recognized as a crucial step towards reducing e-waste and improving overall sustainability. The goal of the study was to estimate the CO_2eq emission of remanufacturing a laptop and calculate the emission savings achieved by avoiding the production of a new laptop which includes the extraction of new materials, energy-intensive production, EoL processes and the required transportation. LCA study was conducted to estimate the CO_2eq emission of remanufacturing a laptop using one year of operation data from a remanufacturing company. The results show that remanufacturing leads to a significant reduction in environmental impact compared to manufacturing new products. Furthermore, the LCA analysis of the remanufacturing processes shows that the processes that contribute the most to the CO_2eq emission of remanufacturing operations are air transport and electricity consumption. Therefore, to improve the remanufacturing operations of the company, the following actions are recommended:

- Switching to a decentralized system with remanufacturing plants near each pickup location. The decentralized system involves the procurement of used laptops from various sources or directly from the customers. However, unlike the centralized system, these laptops are not transported to a remanufacturing center but are sent to a remanufacturing plant near these pickup locations. By having multiple remanufacturing facilities located closer to the pickup locations, the total transportation distance for used products and remanufactured laptops is reduced, which results in reduced environmental impact. In addition, a decentralized system can increase the efficiency of the remanufacturing process by reducing the time and costs associated with transportation and allowing for more remanufacturing of products. Finally, with multiple remanufacturing sites, it can be easier to manage the logistics of collecting used laptops and distributing remanufactured laptops.
- Shifting deliveries from air transportation to sea and rail transportation. As ships and trains have lower emissions per ton.km than airplanes, switching to these options can significantly reduce the transportation impact on total CO_2eq emission. However, it is important to consider the trade-offs and limitations of each mode of transportation when planning logistics. For example, since sea and rail shipping take longer, a substitution plan may need to be implemented in cases where a quick return of the remanufactured laptop is required, such as providing a loaner product to the customer during the remanufacturing process.
- Switching to renewable energy on all possible sites. Identifying maximum energy-consuming operations and determining possible replacements. Switching to renewable energy is an important step in reducing the company's carbon footprint and contributing to the transition to a low-carbon economy. The maximum energy-consuming operations within the organization must be identified to implement this. This may involve conducting an energy audit to identify where the majority of energy is used and what the potential savings could be. Once these operations have been identified, it is possible to determine possible replacements or alternatives that use renewable energy.
- Packaging with recycled materials and recycling of used waste packaging materials. Using packaging made from recycled materials and recycling used waste packaging materials are both important steps in reducing waste and promoting sustainability. Both of these strategies can help to conserve natural resources, reduce CO_2eq emissions, reduce the amount of waste sent to landfills and reduce the overall environmental impact of packaging.

This work attempts to evaluate the environmental impact of a remanufacturing operation and calculate avoided impact in terms of CO_2eq emissions by remanufacturing a laptop instead of buying a new one. While this gives baseline information on the impacts of remanufacturing, further research is necessary to evaluate the performance of remanufacturing. With this aim, the next scope of research needs to be a multi-life cycle assessment (MLCA). MLCA is a method that can provide a more accurate assessment of the environmental impact of remanufacturing operations. Another potential research area is the multi-life cycle performance of remanufactured laptops with more data-driven analysis and identification of the useful life of individual components in order to meet certain performance requirements. This could involve collecting data from sensors and other sources to track different components performance over time and identify when they are likely to fail or need replacement. This information could then be used to guide the remanufacturing processes, ensuring that devices meet certain performance requirements. These research areas will provide a more comprehensive understanding of the environmental and performance impacts of remanufacturing and could help to improve the sustainability of the remanufactured laptops by reducing the environmental impact and increasing the performance of the devices.

Acknowledgements

We would like to thank Cranfield University group project students Jerin Chittilappilly Francis, Kumar Mitesh, Priyadarshini Rajguru, Joel Macwan, and Mohammed Al Smary for their contribution to this study.

References

[1] V. Forti, C. P. Balde, R. Kuehr, and G. Bel, "The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential," 2020.

[2] A. Mann, P. Saxena, M. Almanei, O. Okorie, and K. Salonitis, "Environmental Impact Assessment of Different Strategies for the Remanufacturing of User Electronics," *Energies (Basel)*, vol. 15, no. 7, 2022, doi: 10.3390/en15072376.

[3] T. T. Suhariyanto, D. A. Wahab, and M. N. A. Rahman, "Multi-Life Cycle Assessment for sustainable products: A systematic review," *Journal of Cleaner Production*, vol. 165. 2017. doi: 10.1016/j.jclepro.2017.07.123.

[4] A. Puca *et al.*, "Energy and eMergy assessment of the production and operation of a personal computer," *Resour Conserv Recycl*, vol. 116, 2017, doi: 10.1016/j.resconrec.2016.09.030.

[5] A. S. Ali and Z. K. Akalu, "E-waste Awareness and Management Among People Engaged in E-waste Selling, Collecting, Dismantling, Repairing, and Storing Activities in Addis Ababa, Ethiopia," *Environ Health Insights*, vol. 16, pp. 1–8, 2022.

[6] P. Pazowski, "Green Computing: Latest Practices and Technologies for ICT Sustainability," *Joint International Conference*, 2015.

[7] H. André, M. Ljunggren Söderman, and A. Nordelöf, "Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse," *Waste Management*, vol. 88, pp. 268–279, Apr. 2019, doi: 10.1016/j.wasman.2019.03.050.

[8] E. D. Williams and Y. Sasaki, "Energy analysis of end-of-life options for personal computers: Resell, upgrade, recycle," in *IEEE International Symposium on Electronics and the Environment*, 2003. doi: 10.1109/isee.2003.1208072.

[9] H. André, M. Ljunggren Söderman, and A. Nordelöf, "Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse," *Waste Management*, vol. 88, 2019, doi: 10.1016/j.wasman.2019.03.050.

[10] M. P. O'Connor, J. B. Zimmerman, P. T. Anastas, and D. L. Plata, "A strategy for material supply chain sustainability: Enabling a circular economy in the electronics industry through green engineering," *ACS Sustain Chem Eng*, vol. 4, no. 11, 2016, doi: 10.1021/acssuschemeng.6b01954.

[11] H. Y. Kang and J. M. Schoenung, "Estimation of future outflows and infrastructure needed to recycle personal computer systems in California," *J Hazard Mater*, vol. 137, no. 2, 2006, doi: 10.1016/j.jhazmat.2006.03.062.

[12] J. Szaniawski, "A new Circular Economy Action Plan For a cleaner and more competitive Europe EN," *Official Journal of the European Union*, vol. COM(2020), no. 98 final, 2020.

[13] Jonatan Wranne, "Product databases: the environmental benefits of reuse: The climate benefits of reusing IT products and the method for creating databases," Jan. 2020.

[14] L. Scelsi *et al.*, "Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment," *Express Polym Lett*, vol. 5, no. 3, 2011, doi: 10.3144/expresspolymlett.2011.20.

[15] D. L. Diener and A. M. Tillman, "Component end-of-life management: Exploring opportunities and related benefits of remanufacturing and functional recycling," *Resour Conserv Recycl*, vol. 102, 2015, doi: 10.1016/j.resconrec.2015.06.006.

[16] E. Williams and Y. Sasaki, "Strategizing the End-of-Life Handling of Personal Computers: Resell, Upgrade, Recycle," 2003. doi: 10.1007/978-94-010-0033-8_9.

[17] L. K. Ncube, A. U. Ude, E. N. Ogunmuyiwa, R. Zulkifli, and I. N. Beas, "An overview of plasticwaste generation and management in food packaging industries," *Recycling*, vol. 6, no. 1, 2021, doi: 10.3390/recycling6010012.

[18] M. A. J. Huijbregts *et al.*, "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," *International Journal of Life Cycle Assessment*, vol. 22, no. 2, 2017, doi: 10.1007/s11367-016-1246-y.

Sustainability assessment of electronic waste remanufacturing: the case of laptop

Atescan Yuksek, Yagmur

2023-04-18

Atescan Yuksek Y, Haddad Y, Pagone E, et al., (2023) Sustainability assessment of electronic waste remanufacturing: the case of laptop. Procedia CIRP, Volume 116, pp. 378-383. 30th CIRP Life Cycle Engineering Conference 2023, 15-17 May 2023, New Brunswick, Canada

https://doi.org/10.1016/j.procir.2023.02.064