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LIFE CYCLE ASSESSMENT OF COMPUTERS AND ELECTRONIC DEVICES: A COMPREHENSIVE REVIEW OF ENVIRONMENTAL IMPACTS

[1]MIGUEL FERREIRA, [2]IDALINA DOMINGOS, [3]JOSE FERREIRA

[1]IT Department, Technology and Management School, Polytechnic University of Viseu, Av. Cor. José Maria Vale de Andrade, 3504-510 Viseu, Portugal
[2,3]Centre for Natural Resources, Environment and Society-CERNAS-IPV and Technology and Management School, Polytechnic University of Viseu, Av. Cor. José Maria Vale de Andrade, 3504-510 Viseu, Portugal
E-mail: ferreira.miguel@estgv.ipv.pt, ijd@estgv.ipv.pt, jvf@estgv.ipv.pt

Abstract - The objective of this study was to evaluate Life Cycle Assessment studies applied to computers with respect to temporal and geographical distribution, research subjects, impact assessment methods, databases and software utilized, and principal findings. To achieve this, a bibliographical search was conducted using the Web of Science Core Collection database platform, using the keywords "Life cycle assessment" "AND" "computer" for title topic. The search yielded 12 publications selected from 28, for which a descriptive analysis was performed. It was determined that most of the studies (six in total) took place between 2011 and 2020. Geographically, the majority of these studies were conducted in Asia and the USA/Canada, with six studies in each region. The majority of studies (6) have aimed to evaluate the environmental impacts of computers (desktop/all-in-one). Regarding the impact assessment methods employed, there is considerable variation among ReciPe (2), Ecoindicator (2), IPCC (2), and CML (1), although some studies have utilized multiple methods. The primary findings indicate significant environmental benefits from adopting newer, energy-efficient technologies (APCs and LCDs), improving formal e-waste management, and focusing on recycling and sustainable manufacturing. Proper End-of-Life handling and the minimization of informal disposal also yield substantial environmental gains.

Keywords - Life Cycle Assessment, LCA, Computer, Computer’s Device.

I. INTRODUCTION

The UN warns that rapid growth of the digital economy could potentially harm the environment, as highlighted in the Digital Economy Report 2024 by the UN Trade and Development Agency [1]. Currently, the digital economy operates predominantly in a linear manner. A shift towards a more circular digital economy would focus on minimizing waste, promoting reuse, and recycling digital devices and infrastructure, including extending their operational life. This can be accomplished through various means such as sharing, leasing, donating, performing regular maintenance and repairs, reselling and redistributing, and remanufacturing and refurbishing. These practices can contribute to reducing emissions associated with mineral extraction, processing, manufacturing, and disposal. Ideally, transitioning to a more circular digital economy would maintain comparable levels of economic growth and corporate profitability as the linear model while significantly improving environmental sustainability. Researchers employ life-cycle assessments (LCAs) to gain a comprehensive understanding of the environmental consequences of digitalization. These assessments evaluate the ecological impact of products and services throughout their entirety. As outlined in ISO 14040 [2] and ISO 14044 [3] standards, Life Cycle Assessment (LCA) is a methodology that measures and contrasts the potential environmental effects of a product from its raw material extraction to its final disposal. LCA provides a structured, all-encompassing analysis of a product or process and offers a thorough evaluation and quantification of its environmental implications. In the context of digital transformation, Life Cycle Assessment (LCA) can be used to pinpoint phases with significant environmental consequences from user devices and Information and Communication Technology (ICT) infrastructure, including networks and data centers. It can also emphasize potential environmental compromises and evaluate the sustainability benefits of replacing non-digital technologies with digital ones [4].

Owing to data constraints, LCAs in the digital economy typically concentrate on greenhouse gas (GHG) emissions. However, this narrow focus has several limitations. Such limited analysis may result in environmentally suboptimal production processes, potentially leading to "greenwashing." For example, while upgrading servers more frequently can decrease electricity consumption in datacenters, it also generates more electronic waste.

Tekwawa et al. [5] suggest that Life Cycle Assessments (LCAs) are valuable tools for creating environmentally conscious personal computers. They identified crucial elements such as minimizing power usage, implementing LCD technology, and utilizing plastic casings to encourage eco-friendly practices in the technology sector. Research on PCs indicates that substantial environmental impacts occur during manufacturing and operation, emphasizing the need for improvements in areas such as energy efficiency and material selection. The main purpose of this review is to assess the key outcomes of Life Cycle Assessment research focused on computers and related devices published in respected academic journals. The aim was to provide a comprehensive overview of sustainable computing in the context of the digital economy.

II. REVIEW METHOD

This study is based on a scientific literature review. Reference retrievals were carried out using the online Web of Science Core Collection database platform because it includes only content from reputable and established sources, ensuring that the data are reliable and of high quality. The study concentrated on the findings derived from the search for the title topics "Life Cycle Assessment," "AND" "computers". Considering the objectives for the environmental impacts of personal computers, only studies of LCA applications on computers or computer devices were included. In addition, this work focuses on LCA practices that adhere to the ISO 1440/44:2006 standard, which provides a descriptive analysis. Studies written in languages other than English were also excluded. After retrieval and screening, 12 articles were selected from a total of 28. Then, these studies were classified and analyzed thoroughly according to the authors, journal, year, location, publication title, goals, life cycle stages covered, LCIA method/database/software, and main findings.

III. RESULTS

A. Basic study characteristics

From the Web of Science database, the search retrieved 28 studies: 13 articles, 13 proceedings papers, one letter, and one other. Of these, only 12 fit the objectives of this study that were grouped into 8 LCA studies [6]-[7]-[8]-[9]-[10]-[11]-[12]-[13], 3 LCA reviews and 1 LCA others. A general description of these 8 LCA studies is reported in Table 1.

B. Research Time and Region of the Studies

The oldest study was published in 2000 in the USA and the most recent in 2023 in France, as illustrated in Fig. 1. 5 of the studies were published between 2000 and 2010, 6 between 2011 and 2020, and 1 in 2023, as illustrated in Fig. 1. The year with the most publications is 2012, with 3 publications, followed by the year 2009 with 2 publications.

Author, year, journal, location	Publication Title
LCA studies:	
[6] Loubet et al., 2023, The International Journal of Life Cycle Assessment, French	Life cycle assessment of ICT in higher education - a comparison between desktop and single-board computers
[7] Subramanian and Yung, 2017, Journal of Cleaner Production, Hong Kong	Life cycle assessment study of an integrated desktop device comparison of two information and communication technologies: Desktop computers versus all-in-ones
[8] YadavandSrivastava, Electronics Goes Green 2012+, 2012, India	Integrated_Life_Cycle_Assessment_of_End_of_Life_of_Computers
[9] Noon et al., 2011, Resources, Conservation and Recycling, USA	A life cycle assessment of end-of-life computer monitor management in the Seattle metropolitan region
[10] Duan et al., Science of the Total Environment, 2009, China	Life cycle assessment study of a Chinese desktop personal computer
[11] Choi et al., The International Journal of Life Cycle Assessment, 2006, Korea	Life Cycle Assessment of a Personal Computer and its Effective Recycling Rate
[12] Kim et al., The International Journal of Life Cycle Assessment, 2001, Korea	Life cycle assessment study of color computer monitor
[13] Socolof et al., Proceedings of the 2000 IEEE, 2000, USA	Preliminary life cycle assessment results for the design for the environment computer display project

Table 1. Overview of the reviewed studies

All the remaining years had only one publication each. Regarding geographic distribution, most of the studies were conducted in the USA, Canada, and Asia with five studies each, while two of the studies were carried out in Europe (France and Switzerland), as shown in Fig. 2. Of the studies carried out in Asia, Korea accounted for 2 while Hong Kong, India and China accounted for 1 each.

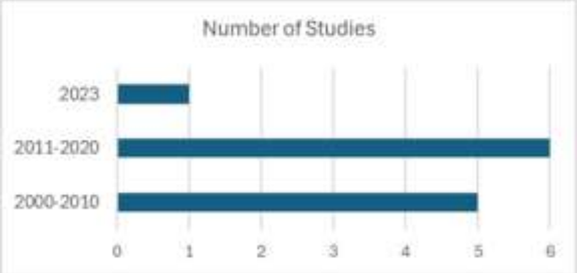

Fig. 1 Time distribution of the reviewed studies

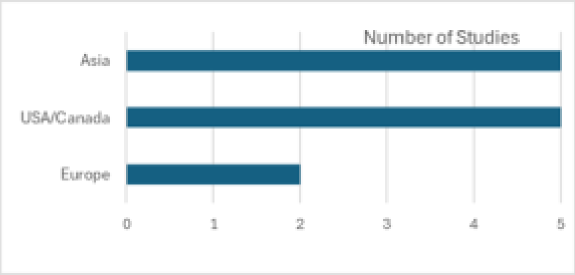

Fig. 2 Geographical distribution of the reviewed studies

C. Goal and scope of the Studies and Research Subject

The LCA methodology is applied in 6 of the selected studies, to evaluate the environmental impacts of computers (desktop/all-in-one) and in 2 to evaluate the environmental impacts of monitors (CRT/LCD), as illustrated in Fig. 3. Of the remaining studies, 3 analyze published LCA studies on computers (desktop/all-in-one) and 1 study the evolution of the lifespan of personal computers.

In the majority (6) of the studies, all stages of the life cycle were evaluated, that is, they were cradle-to-grave (LCA) studies, while two evaluated only the end-of-life phase, one the production + use phase, and one only the use phase.

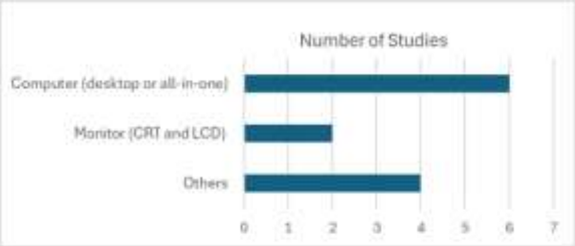

Fig. 3 Research subject of the reviewed studies

D. LCIA Method, Databases and Software

The ReciPe, Ecoindicator, and IPCC methods were used in two studies each, whereas the CML method was used in one study, as illustrated in Fig. 4. Of the remaining studies, two used Data Meta-Analysis, one Case Study, one Korean accreditation board, and one Multi-Stakeholder Partnership.

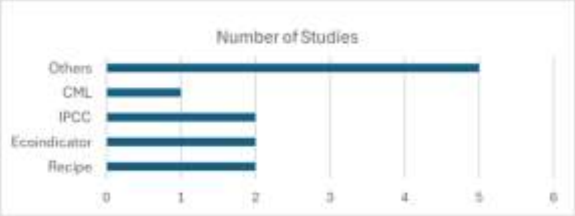

Fig. 4 LCIA methods used in the reviewed studies

For background data, the ecoinvent database was the most used (in four studies), while Buwal, CIT Ekologik, and Greet were used in one study each, as illustrated in Fig 5. Other databases, such as the Korean National Database and Company World Wide Web sites, were also used in one study each. Other studies did not specify the databases used or the criteria were not applied.

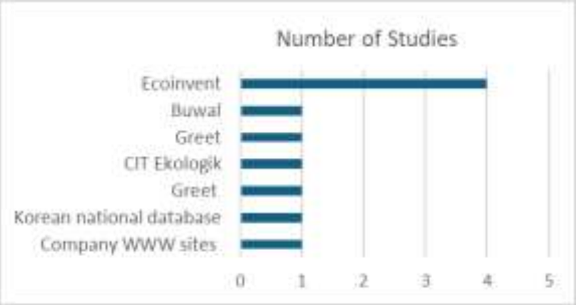

Fig. 5Databases used in the reviewed studies

The most used LCA software was Sima Pro (in four studies), while open LCA and LCA iT were used in one study each (Fig. 6). The remaining studies did not specify any software, or this criterion did not apply.

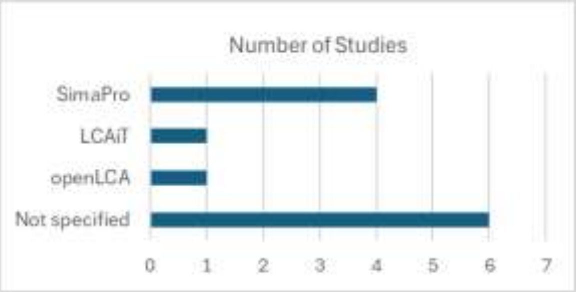

Fig. 6Databases used in the reviewed studies

It is important to acknowledge that certain studies have employed similar methodologies, software, or databases. However, the versions used may vary, which may pose challenges when attempting to draw comparisons between the outcomes.

E. Impact Categories

Table 2 delineates the most pertinent impact categories, as derived from the findings of the investigation conducted by Subramanian and Yung [7], which were utilized in the analyzed studies implementing the Life Cycle Assessment (LCA) methodology pertaining to computers and electronic devices. These categories include HT (Human Toxicity),MEc (Marine Ecotoxicity),FEc (Freshwater Ecotoxicity), FEu(Freshwater Eutrophication), HH (Human Health), EQ (Ecosystem Quality), Res (Resources), EI (Ecoindicator). Although GWP (Global Warming Potential) is present in all reviewed studies, it does not hold the same level of significance as the aforementioned impact categories.

								End- point			Energy
				Study			Mid-point	**EQ**	**Res**	**EI**	
[6]	x	x	x		**GWP**	**HT**	**MEc**				
[7]	x	x	x	x	x		x	x	x		
[8]										x	
[9]	x										
[10]	x	x	x	x	x		x	x	x	x	
[11]	x	x	x*	x*	x						
[12]	x	x	x*	x*	x					x	
[13]											x

Table 2. Relevant impact categories at the midpoint and end-point level used in the selected studies. Acronym: GWP (Global Warming Potential), HT (Human Toxicity),MEc(Marine Ecotoxicity),FEc(Freshwater Ecotoxicity),FEu(Freshwater Eutrophication), HH (Human Health), EQ (Ecosystem Quality), Res (Resources), EI (Ecoindicator)

x: impact category included in the system boundary of the study
x*: the impact category used is Ecotoxicity

F. Main findings

A study conducted by Loubet et al. [6] in a French engineering institution revealed that utilizing 600 Raspberry Pi 4 single-board computers (APC) alongside six servers led to an 84-92% decrease in environmental impact across all categories when compared to 600 traditional desktop computers (DPC).

For APCs, a study by Subramanian and Yung [7] demonstrated that the sleep/standby mode during the use phase contributes most significantly to environmental impact, followed by the production stage. APCs have a considerably lower environmental footprint than conventional desktop computers during both the usage and manufacturing phases.

The informal sector's handling of e-waste disposal in India results in the most severe environmental consequences according to the study of Yadav and Srivastava [8]. However, disposal through official channels, particularly after the implementation of India's e-waste regulations, demonstrated a positive environmental effect, as indicated by a negative eco-indicator.

Noon et al. [9] found in their study that the disposal of LCD monitors in the Seattle metropolitan region has a lower environmental impact than Cathode Ray Tube (CRT) monitors in most categories, except for mercury management, where CRTs pose additional challenges.

In the study by Duan et al. [10], computer manufacturing and usage phases generated the highest environmental impact: approximately 41 Eco-Indicator'99 points (EIP) from production and 43 EIP from use. Distribution had a minimal impact (0.26 EIP), while end-of-life (EoL) treatment provided environmental benefits (approximately -22 EIP).

Choi et al. [11] showed that reduced recycling rates result in greater environmental burden on PCs. The pre-manufacturing stage (raw materials, components, and part production) had the most significant impact on the environmental parameters, except for human toxicity, where disposal was the primary contributor. In the study of a color computer monitor [12], the usage phase had the most substantial environmental impact. During production, cathode ray tube (CRT) and printed circuit board (PCB) assembly processes are the most environmentally significant. According to a study [13], CRT monitors consume approximately 2.7 times more energy during their operational phase compared to LCDs, making CRTs considerably less energy-efficient during use.

IV. CONCLUSION

This study highlights the significant environmental advantages of using single-board computers like Raspberry Pi 4 over traditional desktop computers, showing a remarkable 84-92% reduction in environmental impact across all stages. The sleep/standby mode in Raspberry Pi 4 has the highest environmental impact, followed by production, but overall, its environmental footprint is far lower than desktop computers.

In terms of e-waste disposal, informal handling in India leads to severe environmental damage. However, disposal through formal channels, especially after regulatory changes, has yielded positive environmental outcomes.

LCD monitors generally have a lower environmental impact compared to CRTs, except in mercury management, where LCDs pose greater challenges. CRTs are also less energy-efficient, consuming 2.7 times more energy than LCDs during use.

Across the life cycle of computers, the production and usage phases have the greatest environmental impact, whereas distribution has minimal impact. End-of-life treatment can provide environmental benefits. Recycling is crucial in reducing the overall environmental burden, particularly during pre-manufacturing, which has the largest environmental effect, aside from human toxicity, where disposal plays the key role. Finally, for CRTs, the cathode ray tube and printed circuit board assembly processes during production are the most environmentally harmful.

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