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A comprehensive review of the end-of-life modeling in LCAs of digital equipment

Marion Ficher[1] · Tom Bauer[2,3] · Anne-Laure Ligozat[4]

Abstract

Purpose In the context of the Anthropocene and the widespread use of ICT, the growth of digital e-waste should be tackled. In this paper, we examine the role of the of end-of-life (EoL) in relation to the other life cycle stages in life cycle assessments (LCA) of digital equipment. We investigate how LCAs of digital equipment model the EoL, what the results are for the environmental impacts of EoL treatments, and if the LCAs published after the ETSI standard and the ITU-T 1410 recommendation follow EoL modeling criteria.

Method We did a systematic literature review with three main research criteria. The LCA must (1) concern digital equipment or compare digital devices, (2) consider several impact categories, and (3) be from cradle-to-grave. As the number of scientific papers found was relatively small, we included LCAs of manufacturers, master thesis, and technical reports when they were appropriated. We found twenty-six references from academic and industrial sources corresponding to our research criteria.

Results and discussions Our review is structured according to the ISO 14040-14044 standards. EoL modeling is mainly in the scenario description, which is the first step of the LCA. For EoL modeling, we examine the allocation procedure, scenarios, distribution of scenarios, data source, transport modeling, EoL treatment rates, purity and quality of recycled materials, treatment of specific and hazardous components, and informal flow modeling. We identify the missing elements in the studies and compare them to ETSI and ITU-T 1410. We find it unclear whether ETSI and ITU-T 1410 are being followed in LCAs, as there are no noticeable changes in the EoL modeling. EoL often generates low environmental impacts compared to the other life cycle stages, except for some impact categories. Choices made in EoL modeling, such as using substitution with avoided impact approach or unspecified allocation, can result in low-impact estimates. We underline the need for more transparency in EoL allocation modeling to enable comparisons and interpretation of results from clear reporting.

Conclusion There is no clear consensus on how to model EoL in an LCA. As the EoL of a digital device is highly uncertain, modeling needs to be more consistent and detailed. LCA practitioners should go beyond these guidelines. We identify several missing elements in current LCAs. We provide recommendations for future LCAs, including providing more detail on the substitution approach, considering informal flows, using primary data, and implementing a hybrid methodology.

Keywords Digital equipment · End-of-life modeling · E-waste · LCA · LCA modeling · Sustainable ICT

1 Introduction

E-waste is one of the fastest-growing waste streams in the European Union (EU), which, if not properly treated, is hazardous (EU 2022; Balde et al. 2024; Forti et al. 2020). At a global level, 62 Mt of e-waste were generated in 2022. Only 22.3% was documented streams, i.e., collected e-waste that may be properly recycled, and 77.7% undocumented streams (Balde et al. 2024). E-waste from undocumented streams have an uncertain fate going from stockpiling, illegal exportation to sorting errors, etc. (Arushanyan et al. 2014; Rochat et al. 2021; Huisman et al. 2015; Balde et al. 2024).

In particular, the production of digital electrical and electronic equipment (EEE), used for used for information and communication technologies (ICT) services daily, is increasing (Guillaume et al. 2022; Murthy and Ramakrishna 2022; Forti et al. 2020). This growing production of digital EEE leads to an increase in the generation of waste electrical and

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Extended author information available on the last page of the article electronic equipment (WEEE), or e-waste, at the end-of-life (EoL).

Several studies have reviewed LCAs of digital EEE (Scharnhorst 2008; Andrae and Andersen 2010; Arushanyan et al. 2014; Teehan and Kandlikar 2012; Clément et al. 2020; Yao et al. 2010; Suckling and Lee 2015). Among them, (Teehan and Kandlikar 2012; Clément et al. 2020) explicitly exclude the EoL from their analysis because it has negligible impacts regarding the global warming potential (GWP) indicator. Yao et al. (2010) do not justify why they exclude this stage; the authors note that a focus limited to the manufacturing and use stages may not fully capture the overall impact. Arushanyan et al. (2014) highlight that this stage is less documented than other stages in the LCAs reviewed. (Scharnhorst 2008) partly focus on EoL and show that LCAs have opposing views about the environmental relevance of EoL stage: either the EoL is neglected in the life cycle of electronics, either the EoL has a vital importance with the precious metals recovery. Suckling and Lee (2015) express that EoL disposal of smartphones may cause multiple problems: leakage of materials, stockpiling, and release of toxic substances in the environment. Guillaume et al. (2022) express that a desktop computer's most environmentally damaging steps are manufacturing and disposal. The authors point out that most computers (8 out of 10) are still ending up in landfills. These reviews underscore the need to broaden the analysis to incorporate other environmental impact indicators aside from GWP. Five reviews focus their analysis on CO2e emissions (Teehan and Kandlikar 2012; Andrae and Andersen 2010; Clément et al. 2020; Suckling and Lee 2015; Yao et al. 2010), and sometimes on energy consumption. The GWP indicator is not the most relevant for EoL, which is why we will analyze multi-criteria LCAs. These LCA reviews show that the EoL phase is ignored or given relatively limited consideration. However, it seems essential to improve its modeling. In our analysis, we will focus specifically on the EoL phase. The main challenges in integrating the EoL are the uncertainties related to the fate of the e-waste, with its diversity of scenarios, and the lack of reliable data (Arushanyan et al. 2014; Suckling and Lee 2015; ITU 2014). Significant variations exist between regions and future end-of-life treatments (EoLT) technologies, and their applications are unknown (ITU 2014).

Other studies focus on the EoL of digital equipment only (Hibbert and Ogunseitan 2014; Bian et al. 2016; Van Eygen et al. 2016; Yao et al. 2018; Alcántara-Concepción et al. 2016; Song et al. 2018; Fritz et al. 2020). These LCAs mostly aim to evaluate the WEEE management system and strategy or the potential of hazardous waste (Ismail and Hanafiah 2019). It differs from our goal. However, we can use their modeling to connect it with our research. Scharnhorst (2008) highlight that neglecting a life cycle phase may strongly influence the results.

Performing a LCA on digital equipment is guided by the ISO 14040-14044 standards (ISO 2006a, b) and may follow the ETSI ICT standard (Standard 2014), the ITU-T recommendations (ITU 2014, 2015) or Arcep/Ademe (Arcep/ADEME Technical experts committee on measuring the environmental impact of digital and technologies 2023). Our review provides a temporal analysis, and analyzes if EoL modeling recommendations are followed in the LCAs reviewed after the publications of ICT standards and recommendations for LCA. We highlight the missing elements, and we provide opportunities for improving future LCAs and EoL modeling.

This review aims to study the position of the of EoL regarding the other life cycle stages in the LCAs of the digital equipment. We investigate how LCAs of digital equipment model the EoL, what the results for the environmental impacts of EoL treatments are, and if the LCAs published after the ETSI standard and the ITU-T 1410 recommendation follow EoL modeling criteria. We also intend to go beyond the previous recommendations by exploring modeling criteria that are not expressed in the standard or recommendations. The following research question (RQ) is tackled: How do full LCAs of digital equipment model the EoL?

Section 2 explains our review processes methodology with our criteria. Section 3 makes an overview of the research criteria to answer our research question in the LCA studies of digital equipment. Section 4 expresses the observations and results from our review; this Section is divided into five parts following LCA steps defined in ISO 14-040-14044 standards. Section 5 highlights the limitations of the results and our methodological considerations. Section 6 concludes the review and opens perspectives for future research.

2 Research methodology

Our methodology is based on a systematic literature review of LCAs of digital devices. It was conducted following the criteria summarized in Table 1. We selected documents with the following inclusion criteria: LCAs or comparisons of LCAs, in which the authors performed the LCA(s); LCAs considering several impact indicators; LCAs considering the entire life cycle, including the EoL; peer-reviewed journal articles, conference papers, original equipment manufacturer product reports, technical reports, and master thesis; written in English.

We kept one exclusion criterion. The criterion concerns scientific papers: the conference papers had to be referenced in Conference ranks (Conference Ranks 2024), and for journal papers, the journal had to be referenced in Scimago Journal & Country Rank (Scimago Journal & Country Rank 2024) with a Q3 ranking minimum. We estimate that these papers were robustly peer-reviewed. However, our expertise

Table 1 Research methodology process

Research question	- how do the full LCAs of digital equipment model the EoL? (RQ)
Keywords	(i) LCA/ life cycle assessment/ environmental assessment/ lifecycle assessment and
	(ii) digital equipment name: smartphone/ mobile phone/ laptop/ tablet/ network equipment/ server/ TV/ television device/ computer/ personal computer/ IoT
Search process	- iterative search process
	- snowballing
Inclusion criteria	- scope: LCA studies of digital equipment including the end-of-life and multi-criteria
	- type of research: LCAs or comparisons of LCAs
	- source: peer-reviewed journal articles and conference papers, OEM products, technical reports, master thesis
	- period of time: articles published between 1997 and 2023
	- language: English
Exclusion criteria	- source: Q3 ranking minimum for scientific papers and conferences papers referenced in Conference ranking

led us to integrate one conference paper that does not meet this criterion but had a clear scientific methodology and was cited more than 100 times. This exception concerns (Ercan et al. 2016).

The first step of the research methodology was an iterative research process. This consisted of using a combination of keywords (see Table 1) as research on scopus, for example, "("life cycle assessment" OR "LCA" OR "lifecycle assessment" OR "environmental assessment") AND ("laptop")." A large sample of papers appeared on the results of scopus, with 720 references in total. We also specified other types of equipment like server, router, multiplexer, and VRs. However, these searches did not bring any supplementary references. We first cutoff by practical screenings of titles and abstracts, which led to 115 papers remaining. We then applied the inclusion to the sample, drastically reducing the number of selected papers and articles to 30 references. By applying the exclusion criterion, the pool of papers reduced at 16 (Tekwawa et al. 1997; Kim et al. 2001; Socolof et al. 2001, 2005; Choi et al. 2006; Duan et al. 2009; Hischier and Baudin 2010; Song et al. 2012; Grzesik-Wojtysiak and Kukliński 2013; Moberg et al. 2014; Hischier et al. 2014; Bhakar et al. 2015; Hischier 2015; Subramanian and Yung 2017; André et al. 2019; Loubet et al. 2023).

Regarding the limited scientific resources found, we expanded our research using the web and the Google Scholar platform. We searched for OEM product reports from ICT manufacturers and recommendations from researchers in the digital sustainability domain and found 15 references. OEM product reports can be a rich source of LCA because they represent the analysis from the ICT product manufacturers. Then, we applied the inclusion, which reduced the selection to 5 EOM product reports (Proske et al. 2016, 2020; Sanchez et al. 2022; Herrmann 2019a, b) and 3 references (Ciroth and Franze 2011; Güvendik 2014; Van Galen 2023) on Google Scholar.

Due to the small number of remaining documents, we opted to leave the document's date flexible.

The second step of the methodology was the snowballing strategy. This involved searching for the references cited in the papers. We analyzed several review articles found on scopus and the selected papers. This strategy brought 2 new references (Ercan et al. 2016; Louis et al. 2015).

The final sample of selected references consists of 26 LCA studies.

3 Meta-description of the LCA studies reviewed

This section describes the meta-criteria of the LCA studies. We first looked at the considered perimeters (studied system, geographical region), shown in Fig. 1. Then, we looked at the studied system LCA, shown in Fig. 2. We finally looked at the LCA publication and general methodology (computational tool and the life cycle impact assessment (LCIA) method(s) used), shown in Table 2.

Figure 1 shows the distribution of LCAs regarding temporal and geographical perimeters. We found four recent studies published less than 5 years ago, thirteen published between 5 and 10 years ago, and nine published more than 10 years ago. Because of the fast evolution of ICT devices, this criterion is significant for understanding the studied system. LCAs are a long and drawn-up process; most often, equipment is already outdated when the LCA is performed. Moreover, ETSI standard (Standard 2014) and ITU-T 1410 (ITU 2014) were published in 2014; thirteen studies are published after. We study the evolution of modeling in 5.2. Most

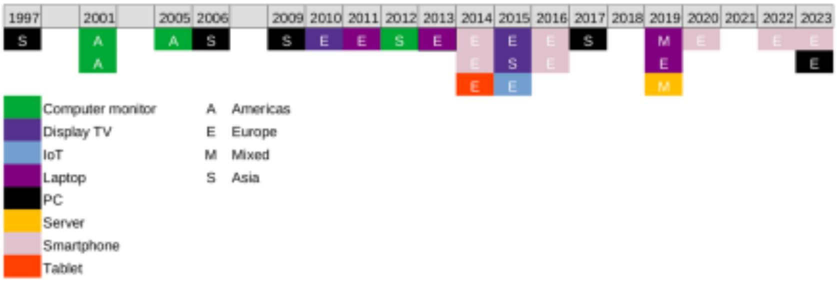


Fig. 1 Distribution of the LCAs regarding temporal and geographical perimeters

LCAs are from Europe (15 out of 26 LCAs), five are from Asia, three are from America, and three are from a mix of continents. None are from Africa or Oceania.

Figure 2 shows the distribution of the type of equipment of the LCAs related to the European WEEE categories. Thirteen LCAs are performed on digital equipment from category 6, with smartphones and computers. Twelve LCAs from category 2, laptops, displays, and tablets. And two LCAs from category 4, with servers.

Table 2 references the other main meta-criteria of the LCA studies. We first looked at the LCA publisher. Seventeen LCAs are from a scientific source (international journals and conferences), seven are from industry (equipment manufacturers or technical reports from sustainability companies), and two are master theses. We also looked at a possible conflict of interest; nine studies are performed with or by the industrial, nine LCAs are entirely academic, five are academic with governmental financial support, and three are performed by the academic and sustainability industry.

The LCIA method is critical for assessing the studied system's environmental impacts. Each LCIA method develops its characterization factors, used for the indicators of the impact category of the LCIA method. Eight LCAs used a mix of LCIA methods to perform the complete LCA. The ILCD Handbook (European Commission-Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook 2011) recommends different LCIA method depending on the impact category. Six used CML method (2001 or 2002), six other used ReCiPe (midpoints or endpoints) method, two used Eco-Indicator 99 method, two created their methodology, and two did not explain. None of the studies use PEF methodology, developed by the European Commission.

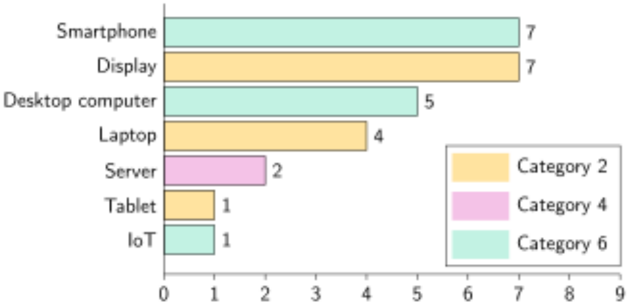


Fig. 2 Distribution by type of equipment. Note: One study has two equipment categories

The computational tool is an interface for modeling. Proprietary software is mostly used; seven used SimaPro, seven used Gabi, two used a mix of software, and one used Umberto. One study used OpenLCA, an open-source software. Five studies did not specify the computational tool used, and three expressed that they used their software. The computational tools are mostly private applications requiring a license, like Gabi, SimaPro, and Umberto. Only OpenLCA is an open-source and free software, used in one LCAs.

We also noticed that five LCAs have been the subject of a critical review, while twenty-one studies did not mention a critical review. LCAs published in scientific journals and conferences are peer-reviewed, which we considered an alternative validation of the process (Standard 2014; ITU 2014).

4 Results

This section follows the steps of the ISO 14040-14044 standards (ISO 2006a, b): goal and scope, life cycle inventory, life cycle impact assessment, interpretation of results, critical review. The last section is not always a mandatory step of LCA. However, it is strongly recommended to validate the LCA. That is why we add it to our analysis. We analyze criteria related to the general methodology of LCA and specific to the EoL.

4.1 Goal and scope

4.1.1 Product system

One primary piece of information is the description of the digital equipment, i.e., its components and materials details. The bill of material (BOM) condenses this information. The BOM is generally available at the component level (20 out of 26 LCAs) but not at the material level. Only (Socolof et al. 2001) provide a bill of primary material inputs for CRT and LCD monitors in which there are the material/component, the mass in kg, and the percentage of weight. Kim et al.

Table 2 Summary information about the LCAs

Information	Statistics
Publication	International journals (14), EOM from equipment manufacturers or partners (5), conferences (3), technical report (2), master thesis (2)
Conflict of interest	Performed with IT equipment manufacturers (9), fully academic (9), academic with governmental financial support (5), performed with academic and sustainability industrial (3)
LCIA method	mix of LCIA methods (8), CML (2001 or 2002) (6), ReCiPe (midpoints or endpoints) (6), Eco-indicator 99 (2), their own method (2), did not explain (2)
Computational tool	SimaPro (7), Gabi (7), did not explain (5), their own software (3), mix software (2), OpenLCA (1), Umberto (1)
Critical review	Did not highlight a critical review (21), highlight a critical review (5)

(2001) provide a material balance for each component of the studied equipment, omitting, however, to put the weights of each material in the component. If the BOM is not supplied by the equipment manufacturer, LCA practitioners rely on the size and weight of the equipment components to estimate the material nomenclature after teardown (17 out of 26 LCAs) and/or use data from existing LCA databases. Extrapolation for the materials mapping is, therefore, a current practice.

4.1.2 System boundary

The system boundary influences the results to a large extent because it specifies all considered processes (Moberg et al. 2014). All LCAs analyzed are from cradle-to-grave. In three LCAs, the studied system includes the digital equipment and accessories like in Ercan et al. (2016); Sanchez et al. (2022); Duan et al. (2009). Some differences in the system boundaries may appear with the inclusion of some stages like distribution, packaging, refurbishment, and reuse. Some studies present the system boundary in a diagram (Grzesik-Wojtysiak and Kukliński 2013; Choi et al. 2006; Duan et al. 2009; Güvendik 2014; Hischier and Baudin 2010; Hischier 2015; Loubet et al. 2023; André et al. 2019; Van Galen 2023; Socolof et al. 2001; Song et al. 2012), as recommended in the standard ISO 14044 (ISO 2006b). Cut-offs and exclusions are also expressed clearly in Ercan et al. (2016); Herrmann (2019a, b). For example, (Ercan et al. 2016) precise to not consider the impact from material beyond the thirty most contributing materials.

Regarding the EoL, the system boundary can also be explicited with a diagram. Three studies present a diagram to describe the EoL system boundary (André et al. 2019; Song et al. 2012; Choi et al. 2006). André et al. (2019); Song et al. (2012) propose detailed diagrams, showing what treatment is modeled for each considered part of the digital equipment. Choi et al. (2006) detail chemicals used for each EoLT of the desktop computer (for example, nitric, sulfuric, hydrochloric acid). These recycling processes require either energy or chemical resources, which can have a significant environmental impact regarding the environmental indicators considered. Song et al. (2012) propose a precise diagram of the treatment and disposal procedures for each part of the discarded TV in China.

4.1.3 Scenarios description

Several points concerning scenarios may or may not be described in the LCAs. We take an in-depth look at these steps: transport and collection modeling to each EoL treatments modeling. Figure 3 shows the distribution of EoLT scenarios for the studies.

Transport, collection, and stream

Collection modeling is missing in the LCAs. The collection is usually modeled as transportation only. Twelve studies express or partly express, the EoL transport modeling. This generally refers to the transport between the collection point and the modeled treatment(s). As the line "Transport modeling" of Table 3 shows, transport modeling is not systematic. The distances and transportation modes considered vary

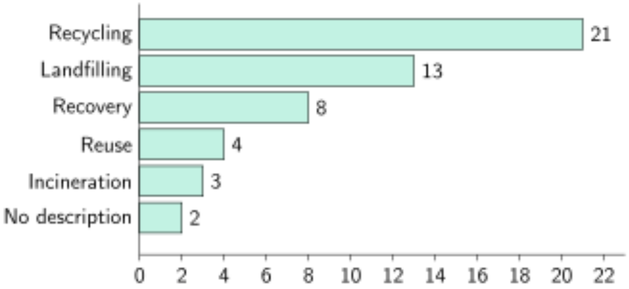


Fig. 3 Distribution of EoLT scenarios

Table 3 EoL modeling criteria statistics

EoL modeling criteria	Statistics	ETSI, ITU-T	Section
Allocation procedure	Substitution (12), did not explain (9), allocation by economic flows (1), mix of 50/50 and substitution (1), mix of allocation by economic flows and substitution (1), cut-off (1), allocation by cause-effect analysis (1)	No	4.2.2
Scenarios	100% recycling (6), recycling and landfilling (5), recycling and landfilling and recovery (3), no description (2), recycling and recovery (2), recycling and landfilling and incineration (2), recycling and landfilling and recovery and reuse (2), landfilling and recovery (1), landfilling and reuse (1), 100% incineration (1)	Yes	4.1.3
Several distribution EoLT	Not available (21), Available (5)	No	4.1.3
Data source	Secondary data (13), mix of primary and secondary data (12), did not explain (1)	Yes	4.2.1
Type of loop	Not available (18), Mix closed-loop and open-loop (5), Closed-loop (2), 50/50 (1)	Yes	4.2.2
Transport modeling	Not available (14), Available (8), Partly available (4)	Yes	4.1.3
Collection rate	Not available (17), 100% (6), 50% (1), 46% and 100 % (1), 8-10 % (1)	No	4.1.3
Recycling rate	Not available (9), 100% (6), =>50% (4), <50% (3), mix (4)	No	4.1.3
Recovery rate	Not available (18), <=20% (4), mix (4)	No	4.1.3
Incineration rate	Not available (25), 100% (1)	No	4.1.3
Landfilling rate	Not available (16), >=90% (2), 55–71% (2), 50% (2), mix (4)	No	4.1.3
Reuse rate	Not available (22), <20% (3), 20% (1)	No	4.1.3
Material recycling rates - for metals and plastics	Not available (16), Available (10)	Yes	4.1.3
Purity and quality of recycled materials	Not available (22), Available (4)	No	4.1.3
Treatment of the specific and hazardous components	Not available (15), Available (11)	Yes	4.1.3
Information on recycling residues	Not available (16), Available (7), Partly available (3)	No	4.1.3
Informal flows modeling	Not available (23), Available (3)	No	4.1.3

depending on modeling or geographical perimeter: 680 km by truck for recycling for Herrmann (2019b, a), 1500 km with 75% truck and 25% train for Proske et al. (2016, 2020); Sanchez et al. (2022); Güvendik (2014), 300 km by heavy truck for Van Galen (2023), 30 km and 100 km for recycling and 50 km for reuse by truck for Tekwawa et al. (1997), Ericsson internal conditions for recycling for Ercan et al. (2016), Swiss recycling system for Hischier and Baudin (2010), state of the art for André et al. (2019), use of fossil oil with no distance for Choi et al. (2006). (Choi et al. 2006) find that recycling inhibits the burdens of resource depletion, acidification, global warming, and other environmental parameters, they identify transportation as the primary source of environmental burdens for recycling. Four studies do not consider EoL transportation (Socolof et al. 2001, 2005; Bhakar et al. 2015; Louis et al. 2015) and ten do not explain transportation modeling. Transportation should be considered in EoL modeling regarding ETSI and ITU-T 1410. ETSI models EoL transportation with a mass, a distance, and a factor emission for the transportation used.

The collection rate is significant information regarding WEEE management; yet it is not mentioned in most LCAs (17 out of 26 LCAs). Our definition of collection rate is the ratio between the amount of e-waste collected and the amount of e-waste put on the market. The collection rate is not equivalent to the recycling rate because not all the e-waste collected undergoes recycling. Our definition of the recycling rate is the ratio between the amount of e-waste that goes to recycling treatment and the amount of e-waste collected. Nevertheless, in the review, when the collection rate is mentioned, it is associated with and modeled as recycling. To facilitate modeling, (Sanchez et al. 2022; Proske et al. 2016, 2020; Güvendik 2014; Van Galen 2023) assume that the phone is discarded in the regular recycling stream. This is why they assume a collection rate at 100% for which they model 100% recycling. Güvendik (2014) points out that studies about the percentage of mobile phones which end up in incineration facilities or landfill areas are missing. Even if the mobile phones' collection rate is rather low, they choose to model a collection rate of 100%. Hischier (2015) also model a collection rate at 100%. André et al. (2019) model it at 50%, according to the literature review (Buchert et al. 2012). Choi et al. (2006) perform one LCA with two EoL scenarios. The first scenario assumes a collection rate of 46%, the then-current collection rate of the country. This rate is used as a recycling rate of 46%, and the remainder is landfilled. The first scenario is the closest to reality. The second scenario is considered as an optimistic scenario with a 100% collection and recycling rates. Ciroth and Franze (2011) model collection and recycling rates at 8–10%, according to Greenpeace.

Five studies conduct multiple scenarios to model the EoL (Choi et al. 2006; Duan et al. 2009; Song et al. 2012; Ercan et al. 2016; Subramanian and Yung 2017), allowing for the visualization of various EoLT distributions possibilities. These scenarios reflect the uncertainties of EoL scenarios, varying into optimistic, pessimistic, and realistic. Optimistic scenarios assume high recycling rates, which can go to 100%, while pessimist scenarios consider a greater proportion of landfilling. Realistic are the closest to reality. Song et al. (2012) compare four EoLTs: sanitary landfilling, hazardous waste incineration, recycling treatment by formal dismantling enterprises in China , and EU recycling. They find that controlled landfilling generates low environmental burdens while incineration generates the highest burdens among the EoLT options. Recycling in China generates the most significant avoided impacts, and EU recycling generates low avoided impacts. Subramanian and Yung (2017) investigate four EoL scenarios. The authors conclude that a combination of 75% incineration with energy recovery and 25% landfilling is the most favored option, even preferred than 75% recycling and 25% landfilling. Choi et al. (2006) perform two EoL scenarios: the first with the current collection and recycling rate at 46% and one optimistic scenario at 100% recycling. They found that recycling inhibits EoL burdens with the production of recycled materials. Duan et al. (2009) perform three EoL scenarios varying the recycling conditions and landfilling. The best recycling scenario is state-of-the-art recycling. Worst-case recycling is recycling without sanitary protection, as in the current situation in China. The worst-case scenario is landfilling without proper treatment of toxic substances. They find that managing toxic substances during recycling processes can reduce the environmental burden of EoLT by approximately 75 to 80%.

Six studies perform several scenarios to consider the influence of repairing, refurbishment or modularity (Sanchez et al. 2022; Proske et al. 2016, 2020; Güvendik 2014; André et al. 2019; Van Galen 2023), which extends the life of the digital equipment but the scenarios are not modeled in the EoL disposal.

As the line "Informal flows modeling" of Table 3 shows, most LCAs do not consider informal flows (23 out of 26 LCAs), even though they are part of the majority of e-waste at a global level (Forti et al. 2020; Balde et al. 2024). Informal flows refer to undocumented e-waste that undergo unregulated treatments. Hischier et al. (2014) model informal flows as incineration with energy recovery. André et al. (2019) model informal flows as controlled landfill. Ercan et al. (2016) perform the LCA with two scenarios for the EoL, one with the informal flows as formal recycling and another scenario with informal flows as landfill. With high rates of recycling, EoL impacts are decreasing significantly for some impact categories. Song et al. (2012) estimate that the informal recycling sector in China represents 74% of discarded TV EoL. However, they do not consider informal flows due to a lack of data, such as Subramanian and Yung (2017). Ciroth and Franze (2011) model informal flows as informal recycling in Guiyu (China). The authors conducted a social LCA but could not conduct an environmental one by lack of data.

Recycling

In most LCAs, information about EoLT is generally limited to the type of treatment (e.g., 22% landfill, 78% recycling), with no indication of the treatment steps. Kim et al. (2001) detail the pre-treatments' steps. Other studies describe the EoLTs' steps: Güvendik (2014); Herrmann (2019a, b); Hischier (2015); Hischier et al. (2014); André et al. (2019); Socolof et al. (2001). And Ciroth and Franze (2011) describe informal recycling.

As Fig. 3 shows, recycling is modeled in most studies (21 out of 26 LCAs). In six LCAs, the modeling is 100% recycling (Duan et al. 2009; Güvendik 2014; Proske et al. 2016, 2020; Sanchez et al. 2022; Van Galen 2023). Güvendik (2014) points out that there is a lack of reliable data for the environmental impact of landfilling and incineration of electronic devices. This is why she only focuses on recycling. In seventeen LCAs, recycling is mixed with landfilling, recovery, incineration or/and reuse. Herrmann (2019a, b); Hischier (2015); Hischier and Baudin (2010); Kim et al. (2001) model full recycling for some components or materials but not all equipment. Moberg et al. (2014) model 25% recycling in China and 25% recycling in Sweden. Ciroth and Franze (2011) model a recycling rate at 8–10%, according to Greenpeace.

Most of the studies detail the list of materials modeled for the recovery processes in recycling (15 out of 26 LCAs). In other cases, it is only Plastics, Metals, or Steel or undefined. Figure 4 shows the materials modeled in recycling. Some materials such as aluminum, silver, gold, copper, palladium, and steel are often modeled as recovered. Cobalt, chromium, nickel, lead, platinum, antimony, tin, plastics, and glass are less or rarely modeled as recovered. Some studies do not detail the list of materials recovered and expressed

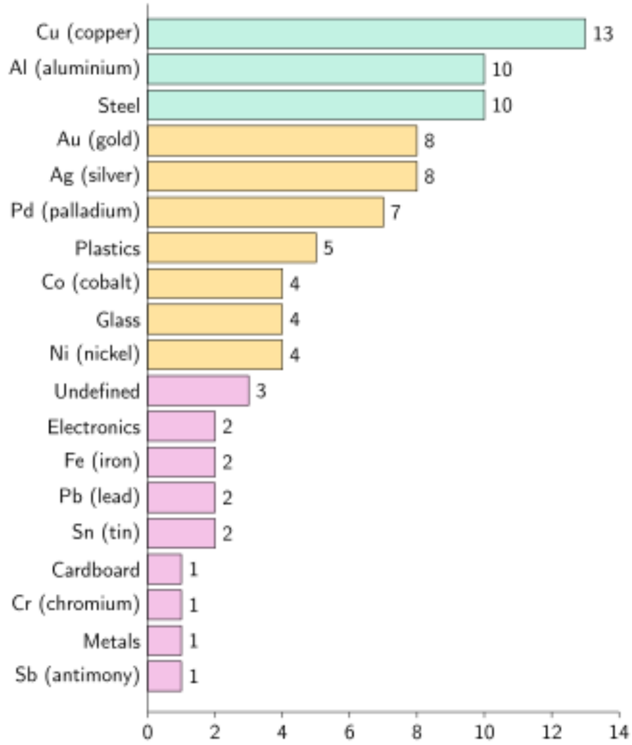


Fig. 4 List of materials modeled for recovery in recycling

only metals or electronics. For example, Ercan et al. (2016) consider thirty of the most impactful metals for raw material extraction and manufacturing stages. However, they do not specify whether these thirty metals are also modeled in the EoL phase. Lead can be recycled from cables (Hischier and Baudin 2010), and copper and cobalt or just cobalt from batteries (Proske et al. 2016, 2020; Sanchez et al. 2022). ETSI and ITU-T 1410 recommend to list the most important materials recovered.

Plastic recycling is considered in five LCAs and glass in four LCAs (see Fig. 4), but in most EoL scenarios, glass and plastic are either incinerated or not indicated. Glass is recycled from the screen panel and avoids the production of sand (Hischier et al. 2014). Plastic is generally recycled from housing or packaging (Ciroth and Franze 2011). Ciroth and Franze (2011) state that plastic packaging is recycled. Both LCAs that consider glass recycling perform an LCA on a tablet, digital equipment with a large screen. Hischier et al. (2014) indicate that glass goes to mechanical treatment and model sand avoided in the production of primary raw production material. Duan et al. (2009) consider that all the plastic is recycled. Choi et al. (2006) assume that plastic is recycled and does not share its material recycling rate. Song et al. (2012) indicate in the EoL process diagram that plastics such as PP/PE and ABS and 30% of the panel glass go for reuse. Van Galen (2023) considers that mixed plastics have a recovery rate varying between 47.2 and 74.2%, the variation depending on the material type, and the packaging glass has a recovery rate of 74,2%. ETSI and ITU-T 1410 model the plastic recycling as optional.

Ten LCAs share their assumptions of the material recycling rates modeled for recycling. The material recycling rate is the percentage of material recovered after recycling of metal or plastic). Proske et al. (2016, 2020); Sanchez et al. (2022) consider 95% material recycling rates. André et al. (2019) assume that the amount of recycled metals contained in the laptop at his EoL is equal to the amount of primary metals used in the production, due to lack of data on metal losses in components production. The authors express that it may potentially overestimate the avoided impacts of recycling because of the metal losses in components production. Nevertheless, avoided impacts are only assessed on expensive metals like gold, for which the metal losses are negligible. Ercan et al. (2016) use the UNEP recycling rates. In terms of material recovery rates, Van Galen (2023) is the most precise study: the authors share in detail different recovery rates for each ecoinvent material type and the waste treatment. Material recycling rates vary from 47.2% for mixed plastics and PET to 78.8% for aluminum, chromium, and copper.

Additionally, the assumed purity and quality of the secondary material (obtained after recycling) are rarely given (4 out of 26 LCAs). Kim et al. (2001) indicate that the recycled plastic from the monitor's cabinet produces plastic toys or other low-grade plastic products. Proske et al. (2020) specify that there is no loss in quality in gold and copper recycling. Herrmann (2019a, b) say that aluminum and steel can be almost wholly recycled and have the same value as the primary.

Lastly, some studies share information on the fate of recycling residues (7 out of 26 LCAs). Recycling residues may undergo incineration, recovery, or landfilling. These residues are the materials that are not recycled during the recycling process and remain. Sanchez et al. (2022); Proske et al. (2020, 2016) assume that recycling residues are lost and do not consider them. Herrmann (2019a, b) assume that recycling residues go to landfilling and generate minor impacts because they are inert, Kim et al. (2001) go either to landfilling or incineration, Hischier et al. (2014) landfilling or recovery. Hischier and Baudin (2010) assume that lead and copper cables and plastic go to incineration. Song et al. (2012) assume that they go to incineration. Van Galen (2023) indicates that 19.15% of the residues are incinerated while 80.85% of the remains are landfilled. When recycling residues fate is not clearly expressed, we do not know whether or how they are considered in environmental impact modeling.

Other treatments

After recycling, landfilling is the second modeled EoLT (13 out of 26 LCAs), as Fig. 3 shows. Some LCAs model a sanitary landfill or controlled landfill, i.e., infrastructures that minimize the release of toxic substances into the environment (Song et al. 2012; André et al. 2019). Duan et al. (2009) model a worst-case scenario landfilling, in which there is no control of the release of toxic substances. The following LCAs do not describe the landfilling scenario: Moberg et al. (2014); Socolof et al. (2001, 2005); Ercan et al. (2016); Kim et al. (2001); Tekwawa et al. (1997); Loubet et al. (2023); Choi et al. (2006); Herrmann (2019b, a); Subramanian and Yung (2017).

Preparation for reuse is rarely estimated in LCAs (4 out of 26 LCAs), as this treatment is very limited. For example, in France, reuse (life extension by repairing) represents 1% of WEEE tonnages processed in France (Jover et al. 2020). Two studies consider the reuse of digital equipment or components of the digital equipment as part of the EoL disposal scenario (Tekwawa et al. 1997; Ciroth and Franze 2011). Ciroth and Franze (2011) model that 20% of the laptops are reused in China. They assume that the reuse lasts 2 years. Socolof et al. (2001, 2005) model the rate of remanufacturing between 3 and 15%. ETSI and ITU-T recommend that preparation for reuse be included as a step in EoL.

Furthermore, eight studies consider reuse as part of the life cycle, and not in the EoL modeling (Proske et al. 2016, 2020; Sanchez et al. 2022; Güvendik 2014; Van Galen 2023; Socolof et al. 2001, 2005). Five out of these eight studies consider repair scenarios (changing components) and compare the repair scenario to the main EoL disposal scenario (Proske et al. 2016, 2020; Sanchez et al. 2022; Güvendik 2014; André et al. 2019). Proske et al. (2016, 2020); Sanchez et al. (2022) find that production of the spare parts generates most of the impacts, with the specific impact depending on the type of component being replaced. However, the repair scenario generally results in lower overall emissions, except for the integrated circuit on the PCB replacement that generates most of the impacts. Van Galen (2023) performs a case study by creating different user profiles to examine the environmental benefits of reusing a smartphone. Socolof et al. (2001, 2005) consider the reuse in the use stage.

There are two types or incineration: incineration without recovery and incineration with recovery. The authors do not systematically specify what type of incineration is modeled. We here define "recovery" as incineration with energy recovery, and "incineration" as incineration without recovery. Recovery is modeled in eight LCAs and incineration in three LCAs, as Fig. 3 shows. Hischier et al. (2014) describe two types of incineration plants: heat-only boiler plants and combined heat and power plants. Hischier et al. (2014) assume that 65% of e-waste is sent to combined heat and power plants, while the remaining 35% is sent to heat-only boiler plants. Herrmann (2019b, a) model recovery only for packaging (paper and plastic). The following studies do not describe recovery (Hischier and Baudin 2010; Socolof et al. 2001, 2005; Loubet et al. 2023). Song et al. (2012) model hazardous waste incineration, in which the incineration plant is equipped with a pollution control system and meets national emissions standards.

Some studies (10 out of 26 LCAs) indicate that specific and hazardous components (like a printed wiring board (PWB), printed circuit board (PCB), batteries, SSD or HDD, etc.) have different treatments. ETSI and ITU-T 1410 indicate that environmental hazardous waste may go to destruction, recovery, or special landfill. Information is generally limited, and the treatment steps are not detailed. Song et al. (2012) describe the fate of PWB. PWB is divided into electric components and PCB. Electric components go to incineration whereas PCB is shredded, separated for copper and nonmetallic material recovery. Kim et al. (2001) specify that the PCB is reused in China and goes out of the scope. Louis et al. (2015) indicate that PCB and hazardous parts, such as the LCD screens, are separated and sent for material recovery or treatment. Proske et al. (2016, 2020); Sanchez et al. (2022); Güvendik (2014); Van Galen (2023) indicate that the battery goes to recycling but do not indicate specific treatment for the PCB. Herrmann (2019b, a); Hischier and Baudin (2010) indicate that PWB and electronics parts are shredded to recover precious metals and do not specify the fate of the battery. Hischier et al. (2014) state that the battery and PCB are recycled. PCBs are not fully recyclable; raw materials are never recycled at 100% due to process losses (Mori de Oliveira et al. 2022).

4.2 Life cycle inventory

4.2.1 Data collection

ETSI and ITU-T 1410 express that primary data or ICT-specific secondary data should be used for recycling, storage/ disassembly/ dismantling, shredding, for ICT-specific EoLT, and preparation for reuse of ICT goods. For other EoLT, secondary data can be used.

Regarding the data collection, some studies use primary data for EoL modeling combined with secondary data (9 out of 26 LCAs). When primary data is used, its origin (field data or recycler information) is not always specified. Only Choi et al. (2006) state that they use specific-site data to collect, disassemble and pre-manipulate a waste computer provided by Korea Computer Recycling. Song et al. (2012) indicate that they use field surveys to reference the EoLT processes in order to know the current practice in professional dismantling enterprises. Socolof et al. (2001, 2005) use primary data for most of the life cycle inventory of the LCA and partly for the EoL. The authors collected primary data from three companies for CRT recycling facilities, particularly the CRT shredding-and-materials-recovery process. They also express the geographical and temporal perimeters of the data sets. However, LCD was a too recent technology, and recyclers did not have a specific process for recycling these displays. In their study, landfilling and incineration are from secondary data. Recyclers cited for EoL primary data source are: Wisetek (Herrmann 2019a, b), Korea Computer Recycling (Choi et al. 2006) and Stena Recycling (André et al. 2019).

Most of EoL data are secondary data. Fifteen studies used only secondary data to assess the EoL impacts. Sources of secondary data vary from LCA databases (ecoinvent, ecobilan), computational tool (Gabi, SimaPro) to literature. The Swiss WEEE Recycling database is also used by Duan et al. (2009); Hischier and Baudin (2010) for secondary data. In other studies, recyclers cited for EoL data source are Umicore (Sanchez et al. 2022; Proske et al. 2020, 2016) and Boliden (Moberg et al. 2014; Ercan et al. 2016). Tekwawa et al. (1997); Bhakar et al. (2015) do not specified EoL data source.

4.2.2 Allocation

As the line "Allocation procedure" of Table 3 shows, substitution, with the avoided-impacts approach is the most employed approach in the LCA studies (12 out of 26 LCAs). As a result, the EoL often generates environmental credits on all the impact categories assessed, which represent the avoided impacts. Nine studies do not describe their allocation procedure, which prevents the reproducibility of research, which is a large part of such an impacting factor. Güvendik (2014) uses an allocation with the economic flow for recycling, according to the price of the recovered materials obtained from the recycling company. Van Galen (2023) applies a cut-off allocation. The author defines the cut-off when the smartphone enters the recycling facility. In this way, there are no environmental burdens and avoided impacts assessed from the production of the secondary materials. Ercan et al. (2016) apply a mix of 50/50 and substitution. The 50/50 allocation is only modeled for gold recycling. André et al. (2019) use a mix of allocation with economic flow and substitution. The substitution is applied only to the primary inputs of the laptop while economic allocation is applied for the multi-output of the metal production processes. Kim et al. (2001) apply an allocation by cause-effect analysis for the waste management.

In most cases, when the substitution approach is employed, only the final results are visible (13 out of 14 LCAs, in which the substitution is used), as in Choi et al. (2006); Hischier and Baudin (2010); Song et al. (2012); Moberg et al. (2014); Hischier et al. (2014); Hischier (2015); Ercan et al. (2016); Proske et al. (2016, 2020); Sanchez et al. (2022); André et al. (2019); Herrmann (2019a, b). The authors do not distinguish between environmental burdens of EoLT and avoided impacts. The potential burdens of EoLTs are invisible in most of the LCAs. One study shows the environmental burdens of the treatments and the avoided impacts associated in a figure (Duan et al. 2009). Hischier and Baudin (2010); Hischier (2015) show the emission and resource consumption factors by materials. In one case, EoL results are entirely invisible because they are directly included in the extraction phase (Ercan et al. 2016). André et al. (2019) share in the appendixes the exact list of materials modeled for recycling with the formulae of the calculation of the net secondary output for the EoL; nevertheless, the formulae is cropped and not fully readable. The authors explain that to avoid over-crediting the merits of metal recycling, the avoided impact approach was applied to the primary inputs of the laptop after loss in the recycling processes. Another issue highlighted is the impossibility to model the production as entirely composed of primary materials because of the lack of relevant data on ecoinvent. When the substitution is not specified and recycling or recovery modeled, only the final results are visible as well (Kim et al. 2001; Socolof et al. 2001, 2005; Ciroth and Franze 2011).

ETSI standard and ITU-T 1410 recommendation recommend the expression of the loop type, with the precision of the approach 100/0, 0/100, 50/50 or mixed. As the line "Type of loop" of Table 3 shows, in most LCAs (18 out of 21 LCAs, in which recycling is modeled), there is no explanation of the type of loop (open or closed) allocation for the recycling system. Only two LCAs mention the closed-loop system (Kim et al. 2001; André et al. 2019). Socolof et al. (2001) express that depending on the type of material recovered, it can be an open-loop or a closed-loop. Ercan et al. (2016) apply a 50/50 approach for gold recycling.

4.3 Life cycle impact assessment

4.3.1 Impact categories

In the LCAs selected, we notice that there is no standard in the characterization of LCIA methods for the entire life cycle and, therefore, for the EoL. We also observe several units of reference for a single indicator. For example, we notice three different units for the ADPf indicator: kg Sb eq, MJ, and kg Oil eq. We made similar observations for all the indicators except for the GWP indicator. The number of midpoint impact categories considered ranges from 3 to 20.

Another important consideration in the modeling is the time horizons used to create the indicators. These time horizons are not visible in the LCAs and can lead to variations in results. According to Moberg et al. (2014), the burdens on the environment (water, soil, air) and human health (with exposure to toxic substances which act slowly) are often estimated over short periods. The authors explain that the short time horizons measurements can lead to a reduction in the value of the results, mainly if the burdens are generated on a non-human and geological time scale. It is the case, for example, for the impacts of burying non-biodegradable waste such as e-waste or nuclear waste. The authors indicate that ecoinvent covers a long-term 60,000 years for landfill-related impacts, but this is generally not the case. Time horizons are essential information, especially for landfilling treatment (Le Guern et al. 2011).

4.3.2 Impact assessment

Socolof et al. (2001, 2005) are an exception among the others. The authors develop their own LCIA methodology. The authors attempt to consider chemical toxicity often ignored in LCIA methods. Socolof et al. (2001) share the formulae for each characterization factor, in which EoL is included (p236-248). No other LCAs set out the modeling formulae for the EoL impacts assessment. The EoL modeling comes generally from the LCA software used.

Nine LCAs partly share the processes chosen in the LCA data sets or in the software to model the EoL process. The processes are shared in the reports or appendixes (André et al. 2019; Herrmann 2019b, a; Ciroth and Franze 2011; Güvendik 2014; Hischier 2015; Subramanian and Yung 2017; Louis et al. 2015; Loubet et al. 2023). Sharing these features helps to understand EoL modeling choices.

4.3.3 Standardization of results

There is no standardization in the expression of the potential environmental impacts; it can be expressed in midpoint or endpoint levels. LCIA methods assess either midpoints results, endpoint results or both. Midpoint impacts are the most common assessment (23 out of 26 LCAs). LCIA method should provide characterization factors on midpoint level (European Commission. Joint Research Centre. Institute for Environment and Sustainability 2010). Eight LCAs assessed the midpoints and the endpoints impacts and three LCAs share only the endpoints. ETSI and ITU-T 1410 recommend to share at minima midpoints impacts.

The presentation of results varies for each study. Nineteen LCAs present both absolute and relative impacts. Six studies present only relative impacts, and one only has absolute impacts. For absolute impacts, the unit for a single impact indicator may vary according to the LCIA method used. This lack of standardization prevents comparison of LCA results, even with a similar functional unit. Furthermore, Hischier (2015) shows the impact results only in ReCiPe points, which provides a characterized environmental impact result for each endpoint and midpoint category from the ReCiPe method only, which prevents any comparison with other LCIA methods.

4.4 Life cycle interpretation

4.4.1 Results by EoL treatment

Reading these LCA studies did not bring real answers to estimate the potential environmental impacts of digital devices at their EoL. The potential environmental burdens of EoLT are generally invisible when using the substitution because only the final results are shown. Table 4 summarizes information on the environmental burdens and avoided impacts and their sources, by EoL step or treatment, of each LCA analyzed. Human toxicity and ecotoxicity are the most critical impact categories for EoL.

None of the LCAs share information about the environmental impacts of the collection of WEEE. The closest information related to the collection is the transportation between the collection point and the EoLT factory, modeled in Choi et al. (2006). Choi et al. (2006) emphasize that transport can have important environmental burdens due to fossil oil consumption, whereas (Proske et al. 2020; Sanchez et al. 2022) find low environmental burdens for EoL transport for all impact categories.

Bhakar et al. (2015) state that the EoL stage of LCD and LED monitors can have severe impacts on human health and the environment if not properly disposed of: they contain toxic substances such as benzene, cyano-group, brominated flame retardants, etc. The authors also highlight that high concentrations of lead and brominated flame retardants are found in air, bottom, ash, dust, soil, water, and sediments in WEEE recycling areas of the developing countries, in comparison with developed nations. For CRT monitor, they find that EoL contributes more than 30% freshwater aquatic ecotoxicity potential, freshwater sediment ecotoxicity potential, and marine sediment ecotoxicity potential and more than 20% for malodours air, marine aquatic ecotoxicity potential. These contributions are higher than the use stage. For LED monitor, they also find higher contribution than the use stage for these impact categories. For LED monitors, they also find important impacts for acidification potential, unlike CRT and LCD.

As Choi et al. (2006) highlight, recycling has a significant contribution regarding human toxicity and ecotoxicity because of the consumption of substances during refinery (nitric acid, sulfuric acid, hydrochloric acid, and deoxidating agent). Ciroth and Franze (2011) state that recycling has environmental impacts due to dust, metals, gases, and dioxins emissions, water use, or waste generation. In some countries, like Belgium, modern technologies in recycling plants, such as de-dusting plants, specific filters, wastewater treatment plants, and sprinkling plants, limit the environ-

Table 4 Summary of environmental burdens and avoided impacts by EoL step or treatment

EoL step or treatment	Severity of environmental burdens	Burdens sources	Importance of avoided impacts	Avoided impacts sources
Collection	No data	-	Not relevant	-
Transport	Rather low (Proske et al. 2016, 2020; Sanchez et al. 2022) or relatively high (Choi et al. 2006), depending on the studies	Consumption of fossil oil (Choi et al. 2006)	Not relevant	-
Recycling	Possibly high for human toxicity and ecotoxicity (Choi et al. 2006; Duan et al. 2009; Ciroth and Franze 2011) and hazardous waste (Socolof et al. 2001). Rather low for other impact categories	Consumption of toxic substances during refinery, release of dust, metals, gases and dioxins emissions, water use, or waste generation (Ciroth and Franze 2011)	Possibly important for resource depletion, human health and ecotoxicity (Proske et al. 2020; Sanchez et al. 2022; Song et al. 2012)	Recovery of materials during recycling (Herrmann 2019b, a; Proske et al. 2020; Sanchez et al. 2022; André et al. 2019). Mainly from gold, tin, copper and other metals
Controlled landfilling	Rather low for human health (Song et al. 2012) or high for human toxicity (Choi et al. 2006) and hazardous waste (Socolof et al. 2001)	Minimum leak of toxic substances in the ecosystems (Song et al. 2012)	Not relevant	-
Non controlled landfilling	Possibly high for human toxicity and ecotoxicity (Choi et al. 2006; Duan et al. 2009)	Leak of toxic substances in the ecosystems (Choi et al. 2006; Duan et al. 2009)	Not relevant	-
Recovery	No data	-	No data	Recovery of energy or heat during incineration
Incineration without recovery	Possibly high for ecosystems quality (Song et al. 2012)	Emissions into water, air and soil (Song et al. 2012)	Not relevant	-
Reuse	No data	Production of the spare parts (Ciroth and Franze 2011)	Relatively high for GWP (Ciroth and Franze 2011)	Avoid the production of another equipment (Ciroth and Franze 2011)
Informal recycling	Possibly high for ecotoxicity and human health (Ciroth and Franze 2011)	Leak of toxic substances in the ecosystems (copper, lead, tin, nickel, cadmium), toxic substances brominated flame retardants found in air, bottom, ash, dust, soil, water and sediments (Bhakar et al. 2015)	No data	-

mental impacts. Ciroth and Franze (2011) find high burdens for terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity (between 3 and 7% of the results), for the disposal stage which is recycling in Belgium. In the recovery process, Proske et al. (2020); Sanchez et al. (2022) find high environmental burdens for battery recycling and copper smelting.

Ciroth and Franze (2011) find high avoided impacts for the reuse treatment in China. For GWP, the authors find that it avoids the production of 0,2 laptops. It is not possible to find precise information for the other impact categories because results are mixed with the recycling in Belgium.

The avoided impacts of the EoL come from the recovery of materials during recycling or from the energy recovery due to incineration. André et al. (2019) cite ten metals that contribute notably to the environmental results: gold, silver, palladium, platinum, indium, cadmium, lead, tantalum, tin, and copper. The higher environmental gain come from gold recycling (Ercan et al. 2016; Herrmann 2019b, a; Proske et al. 2020; Sanchez et al. 2022; André et al. 2019), followed by tin and copper (André et al. 2019). Indeed, the impacts associated with gold extraction are extremely polluting due to low environmental concentrations and extraction processes with irreversible consequences. According to SystExt (2022), gold is one of the complex and/or refractory ores. André et al. (2019) precise that the avoided impacts of EoLT is relatively small regarding climate change since it does not offset the dominant impacts in integrated circuit production, nor the casing since magnesium is not functionally recycled.

Song et al. (2012) find much lower impacts for landfilling than incineration. The authors model landfilling in a controlled landfill, which minimizes the release of toxic substances into the environment. Nevertheless, Choi et al. (2006) point out that landfilling may be the most substantial factor leading to human toxicity, compared to the others EoLT (collection, disassembly, refinery processes for recycling, and incineration). Their example is the metals leak from landfill sites to the natural environment. Duan et al. (2009) also highlight that EoLTs could severely impact human health and the ecosystems if they are poorly managed. PCs contain many parts with hazardous materials, such as brominated flame retardants, tin-lead soldering on PWB, polychlorinated biphenyl in the transformer, and mercury in the switch. André et al. (2019) express that modern laptops are lead-free soldering, which reduces the toxicity impacts of landfilled laptops. They model the non-collected laptops disposed of in a controlled landfill, using ecoinvent processes for landfilling of aluminum, plastic, and hazardous waste. However, we cannot observe the environmental impacts of their modeling because the results are mixed with the avoided impacts of recycling.

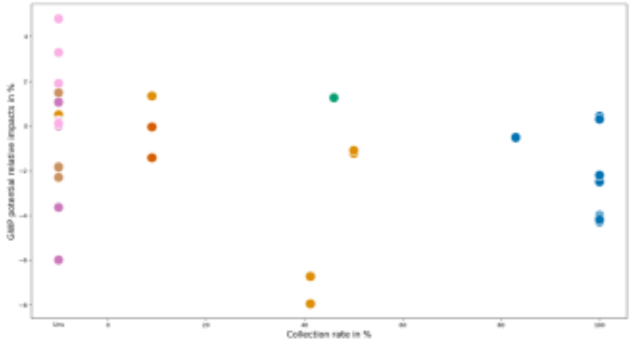
Ciroth and Franze (2011) argue that informal recycling happens in non-controlled conditions where workers apply crude methods such as acid baths with sodium cyanide, burning plastics, or manual disassembly of components. The authors model informal recycling in the Guiyu region (China), for a social assessment but not for the environmental assessment. The authors output that Guiyu region shows very high to high concentrations of several damaging substances. The concentration of copper, lead, tin, nickel, and cadmium in sediments of the discharge channel was 400–600 times higher than in sediments of uncontaminated rivers.

4.4.2 Results of the studies

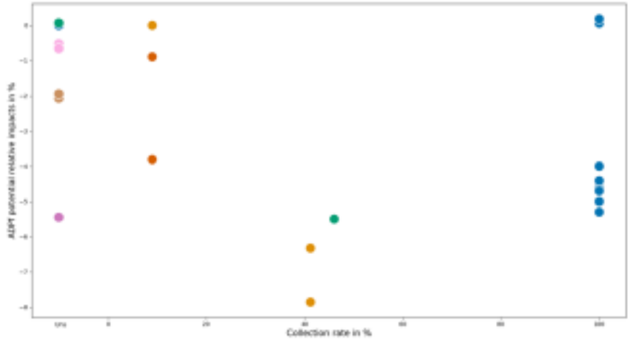
To understand the potential environmental impacts of the digital devices, we collected information on each LCA analyzed. To this end, we gathered relative and absolute impacts data from each study for the following impact indicators: global warming potential (GWP), abiotic depletion potential fossils (ADPf), abiotic depletion potential elements (ADPe), human toxicity (HumTox), ecotoxicity (EcoTox), and acidification potential (AP). For example, when results were given in a graph form only, we manually estimated the results. We did this for most studies (18 out of 26 LCAs). We could not extract EoL impact data for the following studies (Tekwawa et al. 1997; Kim et al. 2001; Duan et al. 2009; Louis et al. 2015). Some studies make comparisons of digital devices (Hischier et al. 2014; Hischier 2015; André et al. 2019; Loubet et al. 2023; Bhakar et al. 2015). In this case, we gathered environmental impacts for all the devices analyzed in the LCA. We could extract only GWP impacts even if all the LCAs are multi-criteria for the following studies (Moberg et al. 2014; Ercan et al. 2016; Loubet et al. 2023). GWP is the most common environmental impact indicator, included in each study and presented with more detail than others. Lastly, we could not normalize the results because of the variety of functional units and lack of time.

For each result, we kept the associated collection rate and the type of equipment. We chose to use the collection rate instead of the recycling rate because the recycling rate was not systematically provided. In Figs. 5 and 6, collection rate equals Uns are non specified values. Our collected data is presented in Figs. 5 and 6.

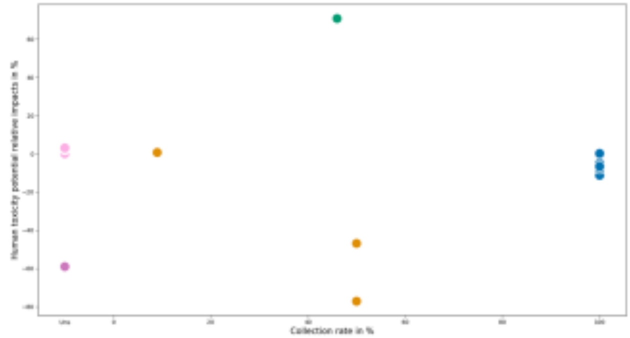
Figure 5 presents the EoL relative environmental impacts for each LCA. The three sub-figures present the distribution of the EoL relative impacts according to the collection rate: Fig. 5a for GWP, Fig. 5b for APDf, and Fig. 5c for HumTox. We chose to present GWP, ADPf, and HumTow because we found more data for them compared to the other environmental indicators. More generally, when the results are positive (>0%), the EoL generates environmental burdens on the impact assessed. Conversely, when the results are negative (<0%), the avoided impacts from the production of recycled material are significant and superior to the impacts of EoLT. We can observe a slight variation in the relative results of the studies for two environmental impact indicators: in Fig. 5a GWP varies between -7.95% and +1.9%



(a) EoL GWP relative impacts according to the collection rate



(b) EoL ADP fossils relative impacts according to the collection rate



(c) EoL human toxicity relative impacts according to the collection rate

(d) Legend

Fig. 5 Results of EoL relative environmental impacts of the LCAs

and in Fig. 5b ADPf varies between -7.9% and +1.25%. We observe a significant variation of results for three environmental impact indicators: in Fig. 5c HumTox varies between -77% and +70%, ADPe varies between -1260% and +0.12% and AP varies between -105% and +0.2%. The variation for EcoTox is between -10% and +27%. From Fig. 5, we did not see a significant difference in EoL impacts depending on the collection rate or the type of digital equipment.

Figure 6 exhibits absolute GWP impacts results. We did not make a graph of absolute results for other impact categories because of the lack of unit standardization and by lack of data. To have a better view on the results, we settled limits on the graph, which excludes one point (-199 kg CO2e for the server Dell (Herrmann 2019a)). We notice that the majority of GWP absolute impacts results vary from 1.3 to -2.3 kg CO2eq., with non-negligible cluster of points around zero. Observations show that EoL impacts do not seem to be correlated to the type of equipment. Most devices have low absolute impacts, which was to be expected because of the use of substitution. The excluded point is a server, the heaviest in weight equipment recorded. The server generates the most potential avoided impacts. As the allocation is done with the material weight of the equipment, and the equipment is the largest, the burdens or avoided impacts are more substantial. This notable difference is evident with GWP (the most supplied indicator), ADPf, and AP. Most other devices have tiny absolute impacts close to zero. Again, these results are explained with the substitution calculation, i.e., the calculation of the avoided impacts.

4.5 Critical review

The ILCD Handbook (p.341) (European Commission. Joint Research Centre. Institute for Environment and Sustainability 2010) formulates that the critical review is a one of the key features that assure the consistency of the LCA. This step is, therefore, mandatory to validate the scientific and technical LCA methodology and should be performed before the results are communicated. Only (Socolof et al. 2001, 2005) share the list of the fifty-six stakeholders involved in the critical review. Herrmann (2019a, b); Moberg et al. (2014) specify that a critical review was performed on their studies. Herrmann (2019a, b) precise the academic reviewer and share the critical review statement in the appendixes. The other eighteen studies do not declare a critical review.

5 Discussion

Our review focuses on EoL modeling criteria in LCAs to understand how the EoL is modeled in multi-steps LCAs of digital equipment. We analyze EoL modeling criteria and verify if they are included in ETSI standard and ITU-T 1410 recommendation. Table 3 summarizes the main EoL criteria. The first part of this section considers EoL criteria expressed in the recommendations. The second part highlights these recommendation's limitations. The third part relates a temporal analysis of the LCAs. Then, the fourth part analyzes

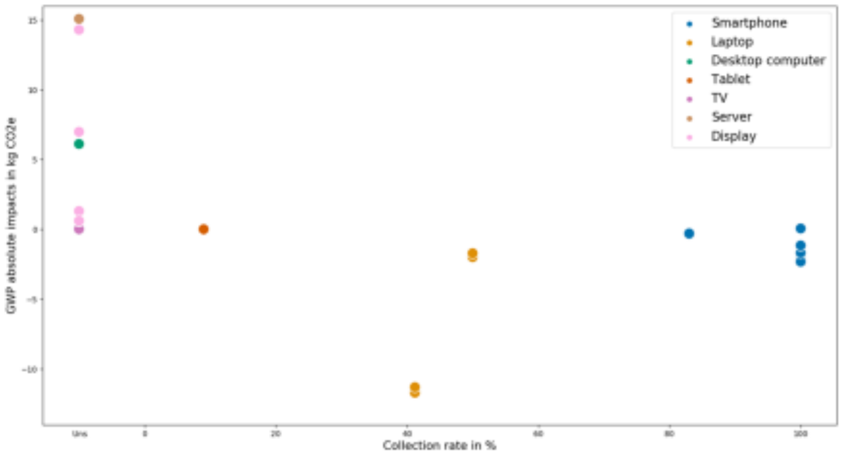


Fig. 6 Results of absolute GWP impacts according to the collection rate of the LCAs

the EoL stage regarding the other life cycle stages in an LCA. The last part evokes the limitations of this review.

5.1 EoL modeling criteria

LCAs should express the distribution of impacts between the systems and the type of loop, when recycling is modeled. Although the ETSI standard and ITU-T 1410 recommendation express this point with the expression of the type of approach:100/0, 50/50, or 0/100, the definitions given by the ITU-T 1410 recommendation are not precise enough and misleading. For example, regarding the 0/100 allocation, it is stated that it "allocates 0% of the primary raw material acquisition processes to the studied product system, i.e., 100% recycled raw material is assumed as input to the studied life cycle." It follows, in their examples, a non-inclusion of the impact of the primary raw material and a partial inclusion of the EoL impact (depending on the material recovery efficiency), which is nonsense. Furthermore, this allocation should be based on the market specificity of each raw material, which is never mentioned. Regarding the complexity of EEE it might become a challenge. Whatsoever, most LCAs do not follow it (22 out of 26 LCAs), which brings large modeling uncertainties. ETSI standard and ITU-T 1410 recommendation indicate a few rules for the distribution of impacts between raw material recycling and raw material acquisition: all elementary flows and environmental impacts should be allocated to the life cycle that generates them. LCA can be mixed with other approaches, depending on the material recovered and assessed. Ercan et al. (2016) apply a 50/50 approach for gold recycling, ignoring to express its approach for other recycled materials as well. It brings uncertainties for other materials. With no expression of the type of loop and distribution of impacts, there is a risk of double accounting of the net avoided impacts (André et al. 2019). To avoid these uncertainties, PEF methodology includes the A factor in the circular footprint formula of material, depending on the market situation, to distribute the impacts between systems and R2 for the substitution point and the displacement of impacts (EU 2021). If LCA practitioners share the distribution of impacts between systems, they create a transparent and clear modeling. So far, most LCAs of digital equipment do not publish this information. The type of loop is also not expressed as well (see Section 4.2.2), which generates uncertainties in the reuse of recovered materials. It is unclear if the material can be reused for the production of the same type of materials.

LCAs should collect primary data when possible. Primary data collection for EoL is complex as it depends on WEEE actors outside of the LCA practitioner's activities. Loubet et al. (2023) state that secondary data from ecoinvent for electronics may be outdated as they were produced in the 2000s. ETSI standard and ITU-T 1410 recommendations encourage primary data collection for all EoLTs except landfilling, incineration, and recovery. It is strongly advocated for recycling materials and specific and hazardous components. Seven studies out of the thirteen published after both recommendations mixed the collection of primary and secondary data for the EoL stage. Nevertheless, none express which data is collected for the EoL, rarely the time and geographical perimeters. The only information cited is the source. On the twelve LCAs of the review that use a mix of primary and secondary data for the EoLTs, only (Choi et al. 2006) detail which primary data is collected (collection, disassembly and pre-manipulation processes) and its data source (Korea Computer Recycling). Socolof et al. (2001, 2005) express the time and geographical perimeters. Primary data could the scenario distribution for the WEEE stream or the studied equipment, collection rates, the material recovery rates by material, etc. To complete ICT's recommendations for LCA, we therefore encourage to share the data, its source, its temporal time coverage, and its geographical perimeters for primary quality data. As EoL is assessed as a stage with no relevant impacts in most LCAs (see Section 4.4.2), the long process of collecting primary data collection for EoLT can be seen as less useful than other stages (Moberg et al. 2014).

LCAs should consider the collection and transportation processes recommended by ETSI and ITU-T 14140. The collection process is never described, even though it can be from multiple collecting points (suppliers, municipalities, etc.), before going to the specific EoLT. The process is often reduced to transportation from the collection point to the EoLT location. It is unclear whether the EoL transportation is integrated in Subramanian and Yung (2017): The authors model the transportation stage without explaining what is modeled for it. Bhakar et al. (2015) do not consider EoL transportation due to lack of data and the complexity of the transportation system. Hischier (2015) do not evoke transportation. Transport modeling is often neglected, as is the collection (see Section 4.1.3). Arduin et al. (2018) perform a study to evaluate the transport modeling in LCA recycling. The authors found that collection transport has fewer impacts than other e-waste treatment activities, even though the transportation impacts can be relevant for a few environmental categories. Choi et al. (2006) also highlight the importance of EoL transportation. This EoL step should be considered. In PEF methodology (EU 2021), collection and transport are considered in EoL stage. Transportation data are usually included in LCA datasets for landfilling, recycling, and incineration (Annexes 1 to 2). Depending on the geographical perimeter, LCA datasets may not reflect the e-waste situation of the studied perimeter. Modeling collection and transport should not be neglected in LCAs.

LCAs should be consistent and more straightforward regarding impacts and calculation reporting when the substitution approach. As underlined by Vadenbo et al. (2017), substitution modeling is often poorly motivated or inadequately described. The authors propose a framework for the systematic reporting of information. It includes waste-specific (physical) resource potential, recovery efficiency, and displacement rate. We notice in the review that the substitution approach invisibilizes EoL environmental impacts because the EoL results are displayed as final results only (potential burdens - potential avoided impacts) (see Section 4.2.2). Detailing the share of the potential burdens and the potential avoided impacts is a first doable step for assessment transparency. Then, sharing the distribution of impacts between system and type of loop is essential to understand allocation modeling. It should be transparent as well, like explained in the beginning of this Section. And sharing the avoided impacts calculation, as in André et al. (2019), helps determine the avoided impacts of EoLT recycling for each material modeled. Finally, the substitution approach is generally used in consequential LCA (CLCA), which is employed to demonstrate differences in impacts when there is a change in the system or to analyze the consequences of a decision (Schaubroeck et al. 2021; Ekvall et al. 2020). However, the LCAs selected are attributional LCA (ALCA). This draws an environmental balance of the digital equipment at a certain time and does not assess the consequences of a change or a decision, in which the avoided impacts of the change or decision are modeled. This choice of using the substitution approach (a CLCA approach) in an ALCA is a special case defined in (p.354) European Commission. Joint Research Centre. Institute for Environment and Sustainability (2010). The substitution approach suggests that the EoLT for the digital equipment are recycling and/or energy recovery, which is in most cases far from reality if the equipment goes to an undocumented stream. We encourage LCA practitioner to be consistent and transparent for the modeling choices and results, when the substitution is employed.

LCAs should indicate the material recovery rates, the fate of the recycling residues, and the purity and quality of secondary raw material. Regarding the material loss during recycling, few studies share the material recovery rates with the list of materials modeled for the EoL (see Section 4.1.3). Both pieces of information are crucial for conducting a comprehensive impact assessment. In PEF methodology (EU 2021), they are part of the circular footprint formula. The ETSI standard and ITU-T 1410 recommendation express that the list of the most important materials modeled for recycling should be shared. However, we need to find out how the importance is defined, and only the list of materials modeled is not sufficient information to understand the model. Material loss and recovery depend on the specific recycling process used (Fairphone 2017) or the type of material (Van Galen 2023). Recycling rates for certain metals used in digital equipment manufacturing can be less than 1% (Hagelüken 2014). It is therefore necessary to provide the list of materials recycled and their recovery rates. Another important neglected point in the EoL modeling is the recycling residues fate. A few LCAs express it and model the residues as landfilled or incinerated or recovered. By doing so, the recycling residues fate modeling is explicit. To go further, Helbig et al. (2022) define types of downcycling: reduction of material quality, suitability only for less-demanding applications, use in less-valuable products, loss of alloying elements, a different material system with no functional use, the need of additional virgin material. By expressing the material recovery rates and the purity and quality of secondary raw material, downcycling can be modeled and avoid the modeling of the material for the same type of use.

LCAs should express the recycling steps of hazardous components like PCB, PWB, or battery. ETSI standard and ITU-T 1410 recommendation do not detail these steps. Indeed, none of the studies inform about the considered recycling steps. After pre-processing, hazardous components are removed from the equipment and may be removed from the modeling scope. It seems essential to produce a comprehensive path for each hazardous component. If recycling is modeled for the hazardous component, LCAs should express the amount of secondary material production or the material recovery rates, the potential environmental impacts associated with the recycling steps, and the fate of the recycling residues.

LCAs should consider the informal flows. Providing the collection rate like (André et al. 2019; Ciroth and Franze 2011; Ercan et al. 2016) helps to model EoLT distribution and informal flows. When informal e-waste flows are considered, they are modeled as controlled landfills or as incineration with energy recovery. Controlled landfills modeling for informal flows modeling is far from reality. As Ciroth and Franze (2011); Heacock et al. (2016); Déportes et al. (2018); Leclerc and Badami (2023); Murthy and Ramakrishna (2022); Hibbert and Ogunseitan (2014); Alcántara-Concepción et al. (2016); Andeobu et al. (2023) show, informal flows can lead to informal recycling and therefore cause severe environmental damages. Controlled landfills as informal flows modeling underestimates environmental impacts. Incineration with energy recovery as informal flows modeling is also far from reality for the same reason. Only Ciroth and Franze (2011) model the informal flows as informal recycling in Guiyu (China), the Chinese centre for illegal recycling, but do not give environmental results due to lack of data. Heacock et al. (2016); Déportes et al. (2018); Andeobu et al. (2023) are a reminder of the extent of the unregulated WEEE impacts. Informal flows affect the populations and the environment (contamination of water, soil, dust, and severe health problems) from treatments carried out without proper sanitary conditions. This contamination comes from the hazardous substances contained in the digital equipment: bromine (Br), cadmium (Cd), copper (Cu), lead (Pb), yttrium (Y), and barium (Ba). Modeling informal recycling could be made by considering the share of non-collected WEEE and by collecting primary data. As 77.7% of e-waste is not properly collected at a global level (Balde et al. 2024), digital e-waste is likely no exception. Considering the collection rate and the informal treatments in the scenarios of EoL would be closer to reality. Huisman et al. (2015); Rochat et al. (2021) indicate the distribution of EoL informal treatments; it can be treated with residual waste bins, by the metal waste sector, illegally exported, unknown, etc. Informal recycling is performed with non-controlled treatment methods such as manual disassembly, open incineration, or acid baths (Ciroth and Franze 2011). In 2019, 66% of the PCBs e-waste have an unknown fate; they are unmanaged or taken care of by the informal sector (Balde et al. 2022). Hibbert and Ogunseitan (2014) model artisanal mining, informal recycling, in LCA of discarded cellphones and measure the concentration of seventeen metals of cellphone components for the ash of open incineration, to assess ecotoxicity and human health. They find that PCBs have the most significant ecotoxicity risks, followed by nickel and cobalt in batteries. Alcántara-Concepción et al. (2016) model open dumps in LCA of laptops and computers in Mexico and. They find major for human toxicity potential, abiotic depletion potential, stratospheric ozone depletion potential, photochemical ozone creation potential, and non-negligible GWP. The following impacts categories should be assessed for the EoL informal treatments: human toxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, abiotic depletion potential, stratospheric ozone depletion potential, photochemical ozone creation potential, and GWP (see Section 4.4.1,Alcántara-Concepción et al. (2016); Hibbert and Ogunseitan (2014); Andeobu et al. (2023)). In addition, illegal recycling is motivated by the recovery of valuable, non-hazardous substances and raw materials from electronic devices (Ciroth and Franze 2011). Laws are not applied. Severe social impacts are also present: child laborers, no trade unions, no minimum wage, no safety measures, or no regulation on working hours. We deeply encourage LCA practitioners to consider informal flow modeling by expressing the collection rate and model the informal treatments (Ciroth and Franze 2011).

LCAs should consider to develop a hybrid methodology based on material flow analysis (MFA) and LCA to assess the environmental impacts of EoL. Since allocation is based on weight, particularly material weight, using MFA can improve the accuracy of impact assessments by quantifying material flows in equipment through different EoLT scenarios. A few studies use firstly MFA to perform an environmental assessment of the EoL of digital equipment (De Meester et al. 2019; Clarke et al. 2019; Van Eygen et al. 2016; Soo and Doolan 2014). Soo and Doolan (2014) combine MFA with LCA to assess the environmental EoL impacts of smartphone printed circuit boards in Malaysia and Australia. De Meester et al. (2019) combine MFA and LCA to assess the benefit of WEEE recycling, whereas (Clarke et al. 2019) combine MFA with carbon footprint methodology to assess the quantities of greenhouse gases emitted by WEEE flows in the UK. Van Eygen et al. (2016) combines the MFA with the Cumulative Exergy Extraction from the Natural Environment method to assess the resources saved between two scenarios for desktops and laptops in Belgium. MFA helps to understand the quantity by EoLT, especially recycling. Including MFA would precise the distribution for materials at the EoL of digital equipment by treatment. From MFA, LCA assesses the environmental impacts for each treatment. Besides, few studies performed MFA to assess the amount of recovered material of discarded digital equipment in informal recycling sites (Borrirukwisitsak et al. 2023; Owusu-Sekyere and Aladago 2023; Tran and Salhofer 2018). These studies may help to model informal EoLT.

5.2 Temporal analysis

The publications of recommendations for ICT's LCAs, the ETSI standard and ITU-T 1410 recommendation, have not encouraged the publications of LCAs complying with our research criteria, as Fig. 1 shows. Five out of thirteen LCAs are on smartphones, two on laptops, two on TVs, two on computers, and two server (one is server + computer). Before the recommendations, other types of equipment were dominant in LCAs such as computer monitors and desktop computers. The systems studied in the LCAs reflect the general consumption of ICT users.

Regarding the publications, the five OEM from ICT manufacturers were released after the recommendations. Five publications are also from journals, one from a conference and one is a master thesis. One crucial recommendation for EoL modeling is not followed: expressing the distribution of impacts between system when recycling is modeled and the type of loop. This helps to understand the modeling choice, the EoL impact results, and the fate of recycled materials generated by the studied system.

ETSI and ITU-T 1410 recommend to collect primary data if possible for specific EoLT. LCAs do not follow this recommendation either. Only 3 out of the 13 LCAs collect primary data. There is no other information except the source.

Other recommendations are partly followed. Ten out of thirteen LCAs give a list of the most important recycled materials, indicating an improvement in modeling (see Section 4.1.3). LCAs published before ETSI and ITU-T 1410 share tend to provide less information on the list of materials recovered. The material recycling rates is a bit less shared (8 out of 13 LCAs), but it has been a large improvement. Before the recommendations, only two studies shared the material recycling rates. There is almost no difference for the treatment for hazardous and specific components. Six expressed it after ETSI and ITU-T 1410 and four before. Usually, the steps of the hazardous components treatments are not specified.

Concerning EoL transportation modeling, six out of thirteen LCAs share the information but it was not complete. Four do not share precise information but consider it and three do not consider EoL transportation. This recommendation is partly followed by LCAs.

In conclusion, it is unclear whether the ETSI standard and ITU-T are being followed in LCAs, as there are no noticeable changes except for the inclusion of a list of the main materials recycled.

5.3 EoL regarding the other life cycle stages

As explained in the introduction, EoL is often less described, neglected, with lower impacts than the other life cycle stages. Several factors may influence these low results for the EoL: the choice of scenarios for EoLT, the EoL allocation procedure with the use of the substitution and avoided impacts approach, the distribution of impacts between the system for the recycled materials, and the choice of the impact categories.

This stage, compared to others, starts with a hypothesis for EoLT scenarios, often based on the computational tool, the database, or the literature. These modeling hypotheses may be arbitrary and depend on the LCA practitioners. For example, modeling a scenario with 100% recycling seems very optimistic when there is more than 77% of undocumented WEEE at a global level in 2022 (Balde et al. 2024) or around 47% in France in 2021 (Deprouw et al. 2022). A few studies try to comply with reality, either by providing the collection rate Choi et al. (2006); André et al. (2019); Ciroth and Franze (2011), or describing the distribution of EoLT scenarios (Socolof et al. 2001, 2005), or by modeling different EoL scenarios in which there is always one closer from reality (Duan et al. 2009; Song et al. 2012). To continue on the collection importance, it might be also far from reality to model that all collected e-waste is going to be recycled. For instance, in France, on the 53% of e-waste collected, around 75% are recycled, 12% are incinerated with energy recovery, 11% are disposed and 2% reused (Deprouw et al. 2022).

It is also crucial to assess multiple environmental impacts to understand the EoL compared to other life cycle stages. Table 4 shows the burdens and avoided impacts by EoLT. Bhakar et al. (2015) is a great example. The authors found major EoL relative and absolute impacts, that are not assessed in any other studies, for freshwater sediment ecotoxicity potential, malodorous air, marine aquatic ecotoxicity potential, marine sediment ecotoxicity potential. These impact categories and freshwater aquatic ecotoxicity are more important for the EoL than the use stage. Choi et al. (2006) find that human toxicity has the largest impact for the EoL regarding all other stages. In this study, ecotoxicy is the second largest contributor after the pre-manufacturing. Duan et al. (2009) find that the EoL dominates the impacts for freshwater aquatic ecotoxicity. However, these LCAs do not share their EoL allocation procedure. In most LCAs, EoL is either invisible, with impacts close to zero (Tekwawa et al. 1997; Güvendik 2014; Hischier 2015; Grzesik-Wojtysiak and Kukliński 2013; Moberg et al. 2014; Subramanian and Yung 2017; Loubet et al. 2023; Van Galen 2023; Ercan et al. 2016), or reduces the burdens of the associated impact categories with the avoided impacts approach. This is obvious for the depletion of resource in Hischier et al. (2014); Proske et al. (2016, 2020); Sanchez et al. (2022); André et al. (2019), for human toxicity in André et al. (2019); Song et al. (2012). In these last twelve studies cited, most LCAs employed the substitution with the avoided approach impacts and only two of them explain the modeling choice for the distribution of impacts between systems and the type of loop. A large proportion of the studies also do not share the EoL allocation procedure. We are not able to estimate the relative impacts of the EoL with the substitution approach and no explanation on the point of substitution and distribution of impacts.

5.4 Limits of the study

We have identified several methodological and results limits for this review.

Regarding the methodological limits, we have identified a few key points. Firstly, to perform the search process, we used only our knowledge and a limited number of keywords on a limited number of platforms (scopus and Google Scholar) and search engines (ecosia, duckduckgo, google). Keywords for digital equipment were limited to the most used and known digital devices and keywords for environmental impacts were limited to the synonym of LCA. Based on this, we conducted a snowballing search. This method may have caused us to overlook some LCAs. Regarding the LCIA methods, there is no study using PEF, which is the European method recommended since 2021, with another approach for EoL modeling. We believe it is a limitation to not have found LCAs using PEF and complying with our research criteria.

The diversity of devices is also limited due to the lack of studies found; eight types of digital devices do not represent the diversity of digital devices nowadays by neglecting networks, data centers and Internet of Things (IoT) devices. Professional ICT equipment is still missing of the LCAs landscape. Data centers and telecommunication networks are the other ICT's pillars (Bieser et al. 2023; Malmodin et al. 2024), and there is no public LCAs for these devices.

In addition, one other limitation is the geographical perimeter. We did not restrict the location of the LCAs, but yet fifteen of our studies are European. It is a significant limitation because many EoL modeling criteria vary according to the country or continent: the WEEE system, the collection rate, the recycling rate, the computational tool, the data source, etc. For example, there is a clear difference in EoLT between developed and developing countries, and the same is true for the collection rate. Data usually considers geographical and temporal perimeters. Therefore, it is essential to respect these conditions.

6 Conclusion

This review provides an overview of the EoL modeling of digital devices in full LCAs. We began by summarizing the main findings on the LCAs analyzed. Then, we focused on findings related to EoL modeling. Next, we identified the criteria that influence the EoL environmental results. Following this, we highlight the missing elements of EoL modeling. Finally, we propose recommendations for further research.

We reviewed eight types of digital devices, with mostly household items (smartphones, laptops, displays, desktop computers, IoT, etc.) and one professional item (server). The majority of LCAs analyzed are from Europe and describe rather poorly the EoL. EoL data are mainly secondary (from the LCA database or LCA computational tool) and outdated (Loubet et al. 2023).

This paper examined the EoL modeling and choices. There is no clear consensus on how to model the EoL stage in an LCA, neither in the guides nor in the standards (Ekvall et al. 2020). The majority of studies employ a substitution approach with recycling and the avoided impacts approach. The substitution approach leads to several limitations: invisibilization of environmental impacts of EoLT and an optimistic scenario for EoL with underestimations of potential environmental impacts. The lack of data and the high uncertainties of what may be the final disposal for the digital equipment (Arushanyan et al. 2014) induces an over-simplification of the EoL scenarios. Moreover, the uncertainties are also influenced by variations in human behaviors and/or variations according to the geographical perimeters (Suckling and Lee 2015). Furthermore, as the EoL environmental results are usually assessed as low or very low, it is hard to detect which criteria influence the environmental results. As the EoL is the only life cycle stage where avoided impacts are input into the model, this can vastly reduce the environmental burdens of this stage. This reversal of consequences is due to the choices made in allocating the EoL. Nevertheless, we can express a few criteria that have an influence: the allocation method with the implementation of the substitution approach, the distribution of EoLT scenarios, the list of materials recovered during recycling and their material recovery rates, and the transport modeling.

ETSI standard and ITU-T recommendations propose guidelines to model the EoL. One primary EoL modeling criterion is not systematically applied: the type of loop and distribution of impacts between systems when recycling is modeling are rarely given. Collecting primary data is also not followed. Transport modeling is partly applied, as the treatment of specific and hazardous components and the list of materials recycled and their recycling rates. Missing elements in ETSI standard and ITU-T 1410 recommendations and these studies are (1) purity and quality of the recycled materials, (2) fate of recycling residues, (3) informal flows modeling, (4) clear and transparent reporting when substitution is used, with the expression of environmental burdens and avoided impacts and the formulae for the EoL impact assessment, and (5) detailed description of the fate of specific components containing hazardous materials.

Section 5 mentions most of our leads for EoL modeling improvements in LCAs of digital equipment. Our first recommendation is detailed reporting when the substitution approach is employed. We then recommend including the environmental impacts of the non-collected digital equipment, also called informal flows. We also highly recommend performing an LCA with primary data for the EoL and opening it. Lastly, we recommend developing a hybrid methodology based on MFA and LCA to assess the environmental impacts of EoL. Such studies to evaluate the environmental impacts of digital WEEE are still rare today.

Supplementary information

Supplementary data to this article can be found online.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-024-02367-x.

Declarations

Conflict of interest The authors declare no competing interests.

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