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

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Abstract

Purpose In the recent context of the Anthropocene and the ubiquity of ICT, the rise of digital e-waste should be tackled. In this paper, we study the environmental impacts of end-of-life (EoL) treatments of digital devices in life cycle assessments (LCA), a standardized methodology to perform a multicriteria environmental assessment of a product. We investigate how LCAs of digital equipment model the EoL.

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. We found twenty-eight references from academic and industrial sources corresponding to our research criteria.

Results and discussions We divided our review into two parts: system and assessment. Our first find is that EoL generally lacks a system description. Many elements are often missing for EoL modeling and research reproducibility, such

as bill of materials at a material level, primary data, collection and transport modeling, informal flows, hazardous components fate, e-waste stream, treatments description, type of loop, formulae assessment, list of materials recycled, material recovery rates, purity and quality of materials recycled, recycling residues fate. Secondly, EoL and LCA modeling lacks standardization for the impact category, LCIA method, computational tool, and environmental results. Thirdly, we observe that EoL is found to generate low environmental impacts. The choice of the substitution approach induces these low results. Human toxicity and ecotoxicity are the most critical impacts of digital e-waste.

Conclusion No clear consensus exists on modeling EoL in an LCA. Most studies employ a substitution approach with recycling and avoided impacts assessment. The substitution approach leads to several limitations: invisibilization of environmental impacts of EoL treatments and underestimations of potential environmental burdens. As the EoL of a digital device is highly uncertain, modeling needs to be more concise. We make several recommendations to improve EoL modeling: to detail the substitution approach, consider the informal flows, use primary data, and implement a hybrid methodology.

Keywords: digital equipment, end-of-life modeling, e-waste, LCA, LCA modeling, sustainable ICT

1 Introduction

Electrical and electronic equipment (EEE) have become ubiquitous and are vital across the globe [1], following a standardized technological lifestyle. In particular, there is an increasing production of digital EEE [2] and consequently at their end-of-life (EoL) cycle, a growth of waste of electrical and electronic equipment (WEEE) or e-waste. E-waste is one of the fastest-growing waste streams in the European Union (EU), which, if not properly treated, is hazardous [3]. At a global level, 53.6 Mt of WEEE were generated in 2019. Only 17% of this were from documented streams, i.e., collected e-waste that may be properly recycled, and 83% from undocumented streams [2]. WEEE from undocumented streams have an uncertain fate going from stockpiling, illegal exportation to sorting errors, etc.. [4–6].

In the context of the Anthropocene, digital e-waste can be viewed as a negative common [7], a non-biodegradable, hazardous waste created by the industrial society that becomes a heritage for our society and planet. The stakes on e-waste for producers are (1) the reduction of the environmental impacts due to the end-of-life treatments (EoLT) of e-waste and their irreversible effects on the environment and human health [8], (2) the understanding of the potential of urban mining, through e-waste recycling and recovery of precious metals, and (3) the development of low-tech or circular economy solutions for a sustainable future. These issues are just a small portion of the digital waste iceberg. Through environmental assessments, this review will look for answers concerning the environmental impacts of EoLT.

Several environmental assessment methodologies can be used to evaluate the potential environmental burdens and avoided impacts of digital e-waste, such as material flow analysis (MFA), LCA and environmental footprints. We choose to focus on LCA because the methodology is widely used for multi-criteria environmental assessment. Additionally, the system boundary is broader. Contrary to MFA, which is focused only on materials, LCA considers an exhaustive list of inputs (resources and energy consumed) and outputs (emissions and waste generated) for the entire life cycle. In LCA, EoL modeling is full of uncertainties because of the diversity of possible scenarios and the lack of reliable data [4, 9].

This review aims to understand how to model the end-of-life in LCA of digital equipment in order to reduce uncertainties related to the EoLT, and to understand the potential environmental burdens and the potential avoided impacts coming from EoLT of digital equipment. The following research question (RQ) is tackled: How do the 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 two sub-parts related to the system and the assessment. Section 5 highlights the limitations of the results and our methodological considerations. Section 6 concludes the review and opens perspectives for future research.

2 Methodology

Table 1: Research methodology

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/ IoT/ TV/ television device/ computer/ personal computer
Search process	- iterative search process - snowballing
Inclusion criteria	- scope: LCA studies of digital equipment including the end-of-life and multicriteria - type of research: LCAs or comparisons of LCAs - source: peer-reviewed journal articles and conference papers, OEM products, technical report, 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 CORE - reference: papers or articles written by the same author and for the same equipment, published on various sources

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 two exclusion criteria. The first criterion concerns scientific papers: the conference papers had to be referenced in CORE, and for journal papers, the journal had to be referenced in Scimago Journal & Country Rank with a Q3 ranking minimum. However, our expertise led us to integrate conference papers and journals that do not meet this criterion but had a clear scientific methodology and thus were considered relevant for our research. This exception concerns four conference papers [10–13] and one journal article [14]. The second criterion excludes scientific papers written by the same author, published on various sources, and analyzing the same equipment. We kept a single reference, the most exhaustive on the EoL. We apply this criterion for [11, 15].

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, VR. However, these searches did not bring any supplementary references. We firstly cutoff by practical screenings of titles and abstracts, which led to one hundred and fifteen papers remaining. We then applied the inclusion and exclusion criteria to the sample, drastically reducing the number of selected papers and articles to nineteen references.

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 fifteen references. OEM product reports can be a complete source of LCA because they represent the analysis from the ICT product manufacturers. Then, we applied the inclusion and exclusion criteria, which drastically reduced the selection to five EOM product reports and four references on Google Scholar.

We decided to keep the date of the document open because of this low number of documents remaining.

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 four new references.

The final sample of selected references consists of twenty-eight LCA studies.

Table 2: Summary information about the LCAs

Information	Statistics
Publication	International journals (14), EOM from equipment manufacturers or partners (5), conferences (5), technical report (2), master thesis (2)
Continent of origin	Europe (19), America (3), Asia (3) and mix of continents (3)
Date of the publication	In the last 5 years (9), between 5 to 10 years ago (12), more than 10 years ago (7)
EoL allocation procedures	Substitution approach (16), did not explain (7), allocation by economic flows (1), mix of 50/50 and substitution (1), mix of allocation by economic flows and substitution (1), cut-off (1), 50/50 (1)
Eol scenarios	Mix recycling with another(s) EoLT (16), 100% recycling (7), no description (2), 100% landfilling (1), mix landfilling and another EoLT (1), 100% incineration (1) (see details in Table 4)
LCIA method	ReCiPe (midpoints or endpoints) (7), mix of LCIA methods (7), CML (2001 or 2002) (6), did not explain (3), Eco-indicator 99 (2), PEF (2), their own method (1)
Computational tool	SimaPro (8), Gabi (7), did not explain (7), OpenLCA (2), mix software (2), their own software (2)
Data source for EoL	Secondary data (18), mix of primary and secondary data (8), did not explain (2)
Critical review	Highlight a critical review (4), did not highlight a critical review (24)
Conflict of interest	Performed with IT equipment manufacturers (12), fully academic (7), academic with governmental financial support (5), performed with academic and sustainability industrial (4)

3 Overview on the end-of-life in LCA studies of digital equipment

This section describes the criteria used in our review to understand the choices made for the EoL modeling of digital equipment. We first looked at the considered perimeters (studied system, geographical region) and general LCA methodology (computational tool and the life cycle impact assessment (LCIA) method(s) used). Then, we focused on the EoL modeling: firstly by looking at the EoL allocation methods, secondly by looking at EoLT scenarios. EoL allocation methods may be a substitution, allocation by physical or economic flows, cut-off, 50/50, etc.. EoLT scenarios modeling consider the share of recycling, recovery, landfilling, reuse, and incineration in each LCA. We also looked at the data sources for the EoL. Finally, we analyzed the potential environmental impacts of the EoL of digital equipment.

Table 2 references the main criteria to analyze the EoL modeling. To visualize the diversity of the LCAs found, we first looked at the LCA publisher, the LCA country of origin, and the publication date. Nineteen 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; twelve studies are performed with or from

the IT industry, seven LCAs are entirely academic, four are performed with the academic and sustainability industry, and five are academic with governmental financial support. We found nine recent studies published less than five years ago, twelve published between five and ten years ago, and seven published more than ten years ago. Because of the fast evolution of ICT devices, this criterion is significant to understand the studied system. LCAs are a long and drawn-up process; most often, equipment is already outdated when the LCA is performed. Most LCAs are from Europe (19 out of 28 LCAs), three are from America, three are from Asia, and three are from a mix of continents. None are from Africa or Oceania.

EoL allocation procedure is a primary criterion for the EoL modeling. We found that sixteen studies used the substitution approach, seven did not explain the EoL allocation procedure, one used the allocation by economic flows combined with the substitution, one used the allocation by economic flows, one used cut-off, one used 50/50 and one used 50/50 with substitution.

To have a better overview, we define the main EoL allocation procedure. It determines the allocation of impacts to the system or co-systems. The substitution method, also known as avoided impact or extension of the system's boundary, is based on substituting virgin material for recycled material. The avoided impacts by not producing the material are removed from the system's life cycle [16]. Allocation by physical or economic flows method consists of the distribution of the impacts between the system that generates the recycled material and the system that uses it. Allocation is based on actual physical flows (taking into account the properties of the material and its successive uses) or economic flows (value of the material based on process based on process costs) [16]. The cut-off method is the assignment of the environmental impacts of the processes directly included in the life cycle of a system, which means that the LCA does not include processes beyond the system life cycle [17]. 50/50 is the equal share of the environmental impacts of the system using the virgin material and the system where the material is lost from the technosphere. "The environmental burdens of each recycling process are split equally between the product system supplying recyclable material and the product where the recycled material is used" [17].

EoL scenario distribution is a significant criterion because it determines the system's EoLT shares. We found that sixteen studies modeled a mix of recycling with another EoLT, seven modeled 100% recycling, two did not describe the distribution considered, one modeled 100% landfilling, one modeled a mix of landfilling with another EoLT and one 100% incineration. Table 4 shows the distribution of EoL scenarios in detail.

The LCIA method is critical for assessing the studied system's environmental impacts. Each LCIA method develops its characterization factors, which are used for the indicators of the impact category of the LCIA method. It determines the impact category. Seven LCAs used a mix of LCIA methods to perform the complete LCA. For example, the ILCD Handbook [18] recommends different LCIA method regarding the category impact. Therefore, if we follow the ILCD Handbook recommendations, we should mix different LCIA methods to use the most recommended method for each impact category assessed. Seven used ReCiPe (midpoints or endpoints) method, six studies used CML method (2001 or 2002), three did not explain, two used Eco-Indicator

99 method, two used Product Environmental Footprint (PEF) and one created their methodology.

The computational tool is an interface for modeling. Indeed, EoL modeling is based on the formulae of the tool. Proprietary software is mostly used; eight used SimaPro, seven used Gabi and two used a mix of software. Two studies used OpenLCA, which is an open source software. Seven studies did not specify the computational tool used, and two expressed that they used their software.

Regarding the data source for EoL, none of the studies performed a LCA with only primary data for this life cycle stage. Eighteen used secondary data only, eight used a mix of primary and secondary data, and two did not express their data source.

We also noticed that only four LCAs have been the subject of a critical review. Nevertheless, LCAs published in scientific journals and conferences are peer-reviewed, validating the process.

Table 3: Distribution of LCAs related to the EU-7 categories and the type of equipment

EU-7 category	Number of LCAs	Type of equipment (Number of LCAs)
2 (Displays)	11	Display (5), laptop (4), tablet (2)
4 (Large devices)	1	Server (1)
6 (Small IT devices)	17	Smartphones (8), desktop computer (3), IoT (2), small network equipment (2), VR headset (1) and server (1)

Note: One study has two equipment categories.

Table 3 shows the distribution of the LCAs related to the European EEE categories and the type of equipment. Seven electrical and electronic equipment (EEE) categories exist at the European level: 1/ Temperature exchange equipment, 2/ Screens, monitors, and equipment containing screens having a surface greater than 100 cm², 3/ Lamps, 4/ Large equipment, 5/ Small equipment, 6/ Small IT and telecommunication equipment, 7/ Photovoltaic panels [19]. Among the WEEE, digital e-waste emerges from devices like computers, laptops, smartphones, servers, etc., and so are included in the European categories 2, 4, 5 and 6. Extracting the share of digital e-waste in these categories is difficult except for category 6, which is 100% digital. We tried to find more LCAs of network equipment or more LCAs of categories 4 and 5, but we did not find them. The majority of LCAs is from category 6, with smartphones and desktop computers, and then category 2, with laptops, displays, and tablets. Table 7 lists the final selection of references considered in the review and a summary of the methodological considerations studied.

EoL treatment modeled	Tekwawa et al. (1997) [20]	Choi et al. (2006) [21]	Duan et al. (2009) [22]	Loubet et al. (2023) [23]	Ciroth et Franze (2011) [24]	Grzesik-Wojtyasiak et Kuklinski (2013) [25]	Herrmann et al. (2019) [26]	André et al. (2019) [27]	Grobe (2017) [11]	Kim et al. (2001) [28]	Hischier et al. (2010) [29]	Hischier (2015) [30]	Herrmann et al. (2019) [31]	Güvendik (2014) [32]	Moberg et al. (2014) [33]	Ercan et al. (2016) [10]	Proske et al. (2016) [34]	Proske et al. (2020) [35]	Sanchez et al. (2022) [36]	Wiche et al. (2022) [13]	Hischier et al. (2014) [37]	Andrae et al. (2017) [38]	Andrae et al. (2017) [14]	Socolof et al. (2001) [15]	Van Galen (2023) [6]	Song et al. (2012) [39]	Manz et al. (2021) [12]	Louis et al. (2015) [40]	Total	
Recycling		•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	23
Landfilling	•	•	•	•			•	•		•			•		•	•				•				•			•			13
Recovery							•				•		•								•			•						6
Incineration				•					•																		•			4
Reuse	•				•																									2
No description						•																					•			2

Table 4: Distribution of EoL scenarios by LCA

4 Results

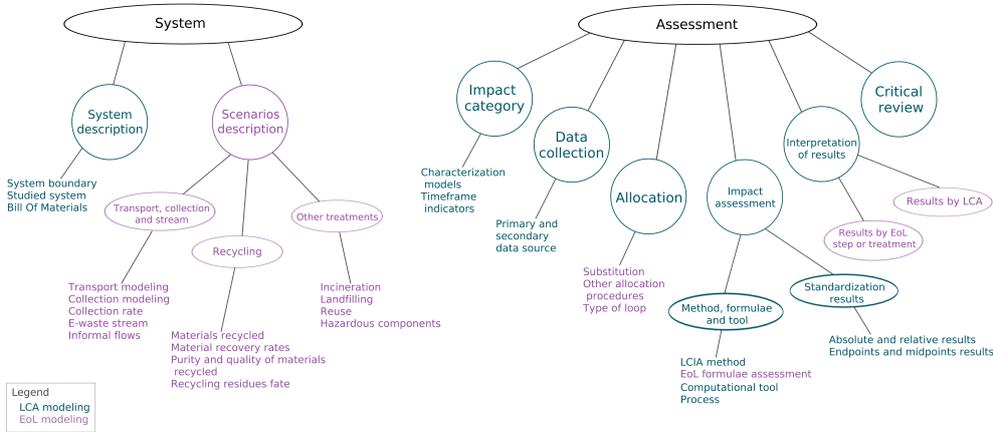


Fig. 1: Structure of the review

From the analysis of the LCA studies, we divide the review into two sections shown in figure 1: system and assessment. The first section concerns the system hypothesis, from the scope of the digital equipment to the scope of the EoL stage. The second section discusses about the assessment hypothesis. It considers the impact category, the data collection, the allocation, the impact assessment, the interpretation of results and the critical review.

4.1 System

The first part of the section concerns the system description. The second is about the scenarios description specific to EoL modeling.

4.1.1 System description

To understand the system, it is essential to describe it clearly. The system boundary and the studied system are two necessary points for LCA modeling. We also include the Bill Of Material (BOM) as an important piece of the system description.

The system boundary determines which unit processes shall be included within the LCA [41]. The system boundary influences the results to a large extent because it specifies all considered processes [33]. All LCAs analyzed are from cradle-to-grave, as it was a criterion of our literature review. Some differences in the system boundaries may appear with the inclusion of other stages like distribution, packaging, refurbishment and reuse. Some studies present the system boundary in a diagram [6, 15, 21–23, 25, 27, 29, 30, 32, 39], as recommended in the norm ISO 14044 [41]. Cut-offs and exclusions are also expressed clearly in [10, 26, 31]. For example, [10] precise to not consider the impact from material beyond the thirty most contributing materials.

Regarding the EoL, the system boundary can also be explicit with a diagram. Three studies present a diagram to describe the EoL system boundary [21, 27, 39]. [27, 39] propose detailed diagrams, showing what treatment is modeled for each considered part of the digital equipment. [21] detail chemicals used for each EoLT of the desktop computer (for example, nitric, sulfuric, hydrochloric acid). These recycling processes require either much energy or the consumption of chemical resources, which can have a significant environmental impact regarding the environmental indicators considered. Presenting diagram helps to understand the modeling process, though it is not self-sufficient. For example, for recycling treatment, the allocation of the avoided impacts and the burdens of the production of secondary raw material must be also expressed.

For all studies, the studied system is the digital equipment only, as it was a criterion of our literature review. In three LCAs, the studied system includes the digital equipment and accessories like in [10, 22, 36]. For IoT, the studied system may include other digital devices required for the use of the IoT system, like in [40].

One primary piece of information is the description of the digital equipment. i.e. its components and materials details. The BOM condenses this information. The BOM is generally available at the component level (19 out of 28 LCAs, see Table 7) but not at the material level. Only [15] 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. [28] provide a material balance for each component of the studied equipment, omitting, however, to put the weights of each material in the component. Suppose the equipment manufacturer does not provide the BOM. In that case, LCA practitioners rely on the size and weight of the equipment components to estimate the material nomenclature after teardown (18 out of 28 LCAs, see Table 7) and/or use data from existing LCA databases. Extrapolation for the materials mapping is, therefore, a current practice. This extrapolation should impact the general results because environmental assessments are based on this information.

4.1.2 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 EoL treatments modeling.

Transport, collection and stream

Collection modeling is missing in the LCAs. Transportation is considered as collection. Thirteen studies share, or partly share, the EoL transport modeling (see Table 7). This generally refers to the transport between the collection point and the modeled treatment(s). The distances and transportation modes considered vary: 680 km by truck for recycling for [26, 31], 1500 km with 75% truck and 25% train for [32, 34–36], 1000 km by truck for [14], 300 km by heavy truck for [6], 30 km and 100 km for recycling and 50 km for reuse by truck for [20], the average distance from the German Federal Motor Transport Authority by lorry for [12], Ericsson internal conditions for recycling for [10], Swiss recycling system for [29], state of the art for [27]. [21] model the use of fossil oil in transportation. The authors found that the increase of fossil oil

consumption during collecting and transporting PCs to the recycling plants is a primary cause of environmental impacts. Indeed, in their study, PC recycling inhibits the environmental impacts of resource depletion, acidification, global warming and other environmental parameters.

The collection rate is not mentioned in most LCAs (20 out of 28 LCAs, see Table 7). However, this is significant information regarding WEEE management. 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 does not equal the recycling rate because not all the e-waste collected goes to 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, [6, 32, 34–36] 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. [32] 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%. [21] perform one LCA with two EoL scenarios. The first scenario has a collection rate of 46%, the 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.

Four studies perform several scenarios to model the EoL [10, 21, 22, 39]. This process allows us to visualize various EoLT distributions, which may consider optimistic and pessimist scenarios, as the EoL have significant uncertainties. Optimistic scenarios are modeled with the larger share of recycling, which can go to 100%, while pessimist scenarios consider a large share of landfilling. [39] compare four EoLTs: sanitary landfilling, hazardous waste incineration, recycling treatment by formal dismantling in China and EU recycling. They find that controlled landfilling generates low environmental burdens while incineration generates the most considerable burdens of EoLT. Recycling in China generates the most significant avoided impacts, and EU recycling generates low avoided impacts.

Seven studies perform several scenarios to consider the influence of repairing, refurbishment or modularity [6, 13, 27, 32, 34–36], which extends the life of the digital equipment but the scenarios are not modeled in the EoL disposal.

Other studies perform different LCA scenarios to compare other parameters: the geographical parameters [26, 31], the simplification of parameters [33], the life cycle parameters [14] or the products [23, 30, 37].

None of the authors share in which waste stream the studied EEE finished at its EoL, although the information is crucial for modeling the EoLT. Indeed, depending on the waste stream, EoLTs vary. [34–36] assume that the smartphone is discarded in the WEEE recycling stream with no material loss, without specifying the category stream.

Most LCAs do not consider informal flows even though they are part of the majority of e-waste at a global level [2]. Informal flows are non-documented e-waste which goes through non-regulated treatments. [37] model informal flows as incineration with energy recovery. [27] model informal flows as controlled landfilled. [10] 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 rate of recycling, EoL impacts are decreasing significantly for some impact categories. [39] estimate that informal sector in China represents 74% of discarded TV EoL. However, they do not consider informal flows due to a lack of data. [24] model informal flows as informal recycling in Guiyu (China). The authors perform the social LCA but could not the environmental LCA by lack of data.

Recycling

Describing EoLT is essential for understanding the system assessed in the EoL modeling. Nevertheless, EoLT steps often need to be better described. In most LCAs, the information is generally limited to the type of treatment (e.g. 22% landfill, 78% recycling), with no indication of the treatment steps. Consequently, the different treatment chains are invisible, leading to an oversimplification of the EoL modeling, which is far from reality. Depollution or dismantling is often outlined as a pre-treatment step and is generally manual or mechanical. [34–36] precise the following steps for the material recovery streamline of the smartphone: copper smelting, electrowinning, precious metal recovery. [32] models a pyrometallurgical process and a pyro-hydrometallurgical process for the recycling of the smartphone and the battery. [6] indicates to draw upon the following studies [32, 36]. [26, 31] explain that after manual depollution, the remaining parts are shredded and further processed to recover copper and precious metals. There is no indication of the recovery metals processes. [24] describe informal recycling for a laptop as manual disassembly, open incineration, or acid baths. Whereas formal recycling consists of hydrometallurgical, pyrometallurgical and mixed technology processes after manual and mechanical dismantling. [21] indicate four steps for recycling: collection, disassembly, pre-manipulation, and refinery processing. [22] model three EoL scenarios for a desktop computer. The variation for the two recycling scenarios is the release of toxic substances in the environment. [28] describe precisely the CRT pre-treatment. After manual depollution with a hammer, the broken glass is rinsed by hydrofluoric acid and water to remove fluorescent substances. Then, the broken glass is sent for recycling. [30, 37] assume a mechanical treatment in a shredder after depollution. [27] describe the recycling steps of a laptop through a diagram. After manual dismantling, it is mechanically shredded. After shredding, the different parts of the laptop go to incineration, refinery, and pyrometallurgical treatment. [39] use also a diagram to describe EoLT steps. [15] describe the recycling steps of CRT, disassembly and material recovery for three recycling companies.

Recycling is modeled in most studies (23 out of 28 LCAs, see Table 4). In seven LCAs, the modeling is 100% recycling. In sixteen LCAs, recycling is mixed with landfilling, recovery, incineration or/and reuse. Table 4 exhibits the distribution of EoL scenarios in which recycling is part. [32] 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.

As Table 5 shows, most of the studies detail the list of materials modeled for the recovery processes 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 rarely modeled as recovered. Some

studies do not detail the list of materials recovered and expressed only metals or electronics. For example, [10] 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 [29], and copper and cobalt or just cobalt from batteries [34–36]. Four studies do not fully specify the list of recycled materials modeled.

Plastic recycling is considered in seven LCAs and glass in five LCAs (see Table 5). Glass is recycled from the screen panel and avoid the production of sand [37]. Plastic recycled is generally recovered from housing or packaging [24]. In most EoL scenarios, glass and plastic are either incinerated or not indicated. [24] states that plastic packaging is recycled. Both LCAs that consider glass recycling perform a LCA on a tablet, digital equipment with a large screen. [37] indicate that glass goes to mechanical treatment and model sand is avoided production of primary raw production. [22] consider that all the plastic is recycled. [21] assume that plastic is recycled. [39] indicate in the EoL process diagram that plastic such as PP/PE and ABS and 30% of the panel glass go for reuse. [6] consider that mixed plastics have a recovery rate varying between 47,2% and 74,2%, the variation depends of the material type, and the packaging glass have a recovery rate of 74,2%.

The material recovery rate is important for material recycling modeling. The material recovery rate is the percentage of material recovered after recycling. Twelve LCAs share their assumptions of the material recovery rates modeled for recycling (see Table 7). The material recovery rates are crucial for assessing the avoided impacts and knowing what is actually recycled in the digital equipment. If the material recovery rates are not expressed, we understand that there is no material loss from the input and output of the recycling process. The material recovery rate would be modeled at 100%. Thus, the material recovery rate significantly affects the environmental impact results for the EoL. [34–36] model the material recovery rates at 95%. [27] 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. 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. [10] model the UNEP recycling rates. In terms of material recovery rates, [6] is the most precise study; the author share in detail different recovery rates regarding the ecoinvent material type and the waste treatment. Material recovery rates vary from 47,2% for mixed plastics and PET (plastics as well) to 78,8% for aluminum, chromium and copper.

Additionally, the purity and quality of the secondary material (obtained after recycling) are rarely given (5 out of 28 LCAs, see Table 7). We do not know whether it differs from non-recycled materials and whether these recycled materials can be reused for the same type of equipment. When there is a decrease in quality between the secondary material and the primary, it is called downcycling. [11] assumes that the purity of recycled materials is close to 100%. [28] indicate that the recycled plastic from the monitor’s cabinet produces plastic toys or other low-grade plastic products. [35] specify that there is no loss in quality in gold and copper recycling. [26, 31] 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 (10 out of 23 LCAs modeling recycling, see Table 7). Recycling residues may undergo incineration, recovery, or landfilling. These residues are the materials that are not recycled during the recycling process and remain. [34–36] assume that recycling residues are lost and do not consider them. [26, 31] indicate that the recycling residues go to landfilling and generate minor impacts because they are inert. [28] assume that they go either to landfilling or incineration, [37] assume either landfilling or recovery. [29] indicate that lead and copper cables and plastic goes to incineration. [39] assume that they go to incineration. [6] 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.

Material	Choi et al. (2006) [21]	Duan et al. (2009) [22]	Loubet et al. (2023) [23]	Ciroth et Franze (2011) [24]	Herrmann et al. (2019) [26]	André et al. (2019) [27]	Grobe (2017) [11]	Kim et al. (2001) [28]	Hischier et al. (2010) [29]	Hischier (2015) [30]	Herrmann et al. (2019) [31]	Güvendik (2014) [32]	Moberg et al. (2014) [33]	Ercan et al. (2016) [10]	Proske et al. (2016) [34]	Proske et al. (2020) [35]	Sanchez et al. (2012) [36]	Hischier et al. (2014) [37]	Andrae et al. (2017) [38]	Andrae et al. (2017) [14]	Socolof et al. (2001) [15]	Van Galen (2023) [6]	Song et al. (2012) [39]	Total		
Al (aluminum)	•				•	•	•		•	•	•							•					•	•	10	
Ag (silver)						•	•		•	•		•		•	•	•			•							10
Au (gold)						•	•		•	•		•		•	•	•			•		•					11
Co (cobalt)														•	•	•										4
Cr (chromium)																							•			1
Cu (copper)					•	•	•		•	•	•	•		•	•	•		•	•				•	•	•	14
Fe (iron)																					•		•			2
Ni (nickel)						•			•	•		•														4
Pb (lead)									•	•																2
Pd (palladium)						•	•		•	•		•			•	•		•								8
Pt (platinum)							•												•							2
Sb (antimony)												•														1
Sn (tin)						•						•							•							3
Cardboard																						•				1
Electronics					•						•															2
Glass										•								•				•		•		4
Metals		•					•																			2
Plastics	•			•				•															•	•		6
Steel	•				•		•		•	•	•		•					•				•	•	•		10
Undefined			•											•					•		•					4

Table 5: List of materials modeled for recovery in recycling

Note: Each dot means that the reference takes the material into account.

Other treatments

After recycling, landfilling is the second modeled EoLT (13 out of 28 LCAs, see Table 4). Some LCAs model a sanitary landfill or controlled landfill i.e. infrastructures minimize the release of toxic substances into the environment: [27, 39]. Some other studies model a worst case scenario landfilling, in which there is no control of the release of toxic substances: [22]. The following LCAs do not describe the landfilling scenario: [10, 13, 15, 20, 21, 23, 26, 28, 31, 33].

Preparation for reuse is rarely estimated LCAs (2 out of 28 LCAs, see Table 4), as this treatment is very limited. For example, in France, reuse (life extension by repairing) represents 1% of WEEE tonnages processed in France [42]. Two studies consider the reuse of digital equipment or components of the digital equipment as part of the EoL disposal scenario [20, 24]. [24] model that 20% of the laptops are reused in China. They assume that the reuse takes two years.

Furthermore, eight studies consider reuse as part of the life cycle, and not in the EoL modeling [6, 13, 15, 32, 34–36]. Five out of the eight studies consider repair scenarios (changing components) and compare the repair scenario to the main EoL disposal scenario [27, 32, 34–36]. [34–36] find that production of the spare parts generates most of the impacts, strongly depending on the replaced components. Repair scenario reduces overall emissions, except for the integrated circuit on the PCB replacement that produces most of the impacts. In the refurbishment stage of [13], only the replaced parts (components and packaging) are considered. [6] performs a case study by creating different user profiles to examine the environmental benefits of reusing a smartphone. [15] consider the reuse in the use stage.

There are two types of incineration: incineration without recovery and incineration with recovery. We call recovery, incineration with energy recovery, and incineration, incineration without recovery. Recovery is modeled in six LCAs and incineration in four LCAs (see Table 4). [37] describe two types of incineration plants: heat only boiler plant and combined heat and power plant. [37] model 65% of the e-waste go to combined heat and power plant and 35% go to heat only boiler plant. [26, 31] model incineration with recovery only for packaging (paper and plastic). [14] model energy recovery from incineration of plastic. The following studies do not describe the incineration with recovery [15, 29].

[39] model hazardous waste incineration, in which the incineration plant is equipped with a pollution system control and meet national emissions standard. The following studies do not describe the incineration without recovery [11, 15, 23, 40].

Some studies (12 out of 28 LCAs, see Table 7) indicate that specific and hazardous components (like a printed wiring board (PWB), printed circuit board (PCB), batteries, SSD or HDD, etc.) have different treatments. Information is generally limited, and the treatment steps are not detailed. [39] describe the fate of PWB. PWB is divided in electric components and PCB. Electric components go to incineration whereas PCB is shredded, separated for copper and nonmetallic material recovery. [12] share in their supplementary materials the modeling of inputs and outputs for the disposal and waste scenario of alkaline batteries and the waste scenario for the smart home controller, containing the PWB. [28] specify that the PCB is reused in China and goes out of the scope. [40] indicate that PCB and hazardous parts, such as the LCD screens, are

separated and sent for material recovery or treatment. [6, 32, 34–36] indicate that the battery goes to recycling but does not indicate specific treatment for the PCB. [26, 29, 31] indicate that PWB and electronics parts are shredded to recover precious metals and do not specify the fate of the battery. [37] state that the battery and PCB are recycled.

PCBs are not fully recyclable; raw materials are never recycled at 100% due to process losses [43].

4.2 Assessment

This section covers points relating to the environmental assessment. We analyzed the impact category, the allocation, the impact assessment, the data collection and the critical review.

4.2.1 Impact category

Each environmental impact is called an impact category, representing a specific alteration in the environment. The indicator for the impact category is calculated by multiplying the mass of each elementary flow by the characterization factor. The characterization factor gives the contribution of the elementary flow to the impact category assessed. For each impact category, a reference substance is chosen. For example, CO₂e is the reference substance for global warming potential (GWP) indicator and its characterization factor equals to 1. Characterization models describe the environmental mechanism to convert an assigned life cycle inventory result to the standard unit of the category indicator [18]. The characterization models are a set of characterization factors. By lack of international consensus and scientific publications, there may be several characterization models for a single impact category. 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.

Another point for 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. These time horizons refer to the time measurements in which the elementary flow is observed. Indeed, according to [33], 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 [16].

4.2.2 Data collection

Regarding the data collection, a minority of studies use primary data for EoL modeling combined with secondary data (8 out of 28 LCAs, see Table 7). Primary data are not necessarily field data; they can be collected from the recyclers. If primary data are used in the EoL modeling, there is no specification of which data is collected. Only [21] state that they use specific-site data to collect, disassemble and pre-manipulate a waste computer provided by Korea Computer Recycling. [39] indicate that they use field surveys to reference the EoLT processes in order to know the current practice in professional dismantling enterprises. [15] use primary data for most of the life cycle inventory of the LCA and partly for the EoL. The authors collect primary data from three companies for CRT recycling facilities, particularly the CRT shredding-and-materials-recovery process. 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. In other studies, recyclers cited for primary data are Umicore [34–36], Boliden [10, 33], Wisetek [26, 31], Korea Computer Recycling [21] and Stena Recycling [27]. Data from EoL stakeholders (recyclers, equipment manufacturers, eco-organizations, etc.) are not open and available. In order to obtain data on EoLT and their environmental impact, it is necessary to work with recycling facilities, eco-organizations and recyclers, and any stakeholders who have visibility of the inputs and outputs of their processes. LCAs are commonly carried out by equipment manufacturers, who do not necessarily have access to this information themselves.

Most of EoL data are secondary data. Eighteen 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 [22, 29] for secondary data.

4.2.3 Allocation

Allocation solves the problem of multi-functionality by partitioning the amounts of inputs and outputs of a process or a product system between the product system under study and one or more other product systems [44]. As the line "EoL allocation procedures" in Table 2 shows, there is no standard for the EoL modeling. Several types of allocation can be used (cut-off, substitution, allocation according to the market, with economic or physical flows, etc.). Allocation of the EoL is a primary factor which is not systematically explained. Seven LCAs did not describe their allocation procedure which prevents reproductibility of research. Substitution is the most employed approach in the LCA studies (16 out of 28 LCAs). As a result, the EoL often generates environmental credits on all the impact categories assessed, which represents the avoided impacts. [12] express that they use a cut-off. However, it does not fit with our definition; we therefore consider it a substitution. [32] uses an allocation with economic flow for recycling, according to the price of the recovered materials obtained from the recycling company. [6] applies a cut-off allocation. The author defines the cut-off when the smartphone enters the recycling facility. In this way, there is no environmental burdens and avoided impacts assessed from the production of the secondary materials. [38] use a 50/50 allocation, as modeled in the PEF. [10] apply a mix of 50/50 and

substitution. The 50/50 allocation is only modeled for gold recycling. [27] 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.

In most cases, when the substitution approach is employed, only the final results are visible (12 out of 18 LCAs, in which the substitution is used). There is no highlighting of the estimated share of the environmental burdens of the treatments and the estimated share of the environmental avoided impacts. The potential burdens of EoLTs are invisible in most of the LCAs. Three studies highlight the environmental burdens of the treatments: [29, 30, 37]. In one case, EoL results are entirely invisible because they are directly included in the extraction phase [10]. [27] 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 onecoinvent.

Moreover, it is essential to specify which system will consider the avoided impacts and burdens and to which share. For example, [27] express that they input the net avoided impacts from the recycled material to the input production. The authors make it clear that the avoided impacts from the secondary material production are used to produce the same type of equipment, and it is a closed-loop system. Nevertheless, we do not know how is the distribution of the environmental burdens and the avoided impacts. In most LCAs (19 out of 23 LCAs, in which recycling is modeled), there is no explanation of the type of loop (open or closed) allocation for the recycling system (see Table 7). Only three LCAs mention the closed-loop system [13, 27, 28]. This means when a material is recycled into the same product system, or when it is recycled into another product system, there is no changes in the properties of the material [45]. [15] express that depending on the type of material recovered, it can be an open-loop or a closed-loop.

4.2.4 Impact assessment

Impact assessment step determines the choice of LCIA method(s), in which several impact categories are assessed. Results *Method, formulae and tool*

The choice of the LCIA method generates differences in the results of potential environmental impacts and is, therefore, a determining factor in modeling. [27] compare the results of seven LCIA methods for the metal resources used and avoided metal resources used. The shares of the different metals differ significantly between LCIA methods. For example, the authors normalize the characterization factors for abiotic resource depletion of metal according to zinc. In the case of gold, it varies from 510 (EcoSc method) to 189352 (CExD method). This variation is quite significant for the metals modeled. A notable difference may also appear among variations of an LCIA method; for example, CML has three variants depending on the kind of resource type

considered. Each CML variant uses different characterization factors, and the results vary broadly in the study. Furthermore, a mix of several methods can be used for a LCA, depending on the impacts to be characterized and the robustness of the methods. The most commonly used methods are ReCiPe (midpoints or/and endpoints), a mix of LCIA methods, CML (2001 or 2002), Eco-indicator 99 and PEF (see Table 2). [38] specify that PEF proposes a default EoL scenario that does not emphasize improving EoL modeling. In the EU, PEF is the recommended method for a harmonized display of the environmental footprints. One study is an exception among the others, [15] develop their own LCIA methodology. The authors attempt to consider chemical toxicity often ignored in LCIA methods. To do so, they collect and gather chemical substances information for the entire life cycle. EoL is the only stage with low to moderate quality data because of the dominance of secondary data or no data available. [15] 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.

As the line "Computational tool" in Table 2 shows, there is no standard in the choice of the software used. The computational tools are mostly private applications requiring a license, like Gabi and SimaPro. Only OpenLCA is an open-source and free software, used in two LCAs. Seven studies did not share the choice of the computational tool, thus, the research reproducibility is not possible.

Nine LCAs partly share the processes chosen in the LCA data sets or in the software to model the EoL process. The processes are either share in the reports or appendixes [12, 23, 24, 26, 27, 30–32, 40]. Sharing these features helps to understand EoL modeling choices.

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. Endpoint level characterizes the environmental impacts at the Areas of Protection level i.e. natural environment's ecosystems, human health, resource availability [46]. Midpoints level characterizes the environmental interventions of cause-effect chain between emission or resource consumption towards endpoint level [46]. Midpoint results are more accurate and precise compared to the endpoint assessments [44]. Midpoint impacts are the most common assessment (25 out of 28 LCAs, see Table 7) because it is recommended that the LCIA method provide characterization factors on midpoint level [44]. Six LCAs assessed the midpoints and the endpoints impacts and three LCAs share only the endpoints.

The presentation of results varies for each study. Sixteen LCAs present both absolute and relative impacts. Relative impacts are EoL impacts according to the overall result presented in percentage. Absolute impacts are the estimated potential impacts amount in the unit (for example, in kg CO₂e for the GWP). Eight studies present only relative impacts, and three only 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, [30] 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.

4.2.5 Interpretation of results

Interpretation of results is divided into two sections: the results by EoL step or treatment and the results by LCA. This section analyzes the findings on the environmental impacts, burdens and avoided impacts, of the LCAs.

Results by EoL step or treatment

Table 6: 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 sources	Impacts
Collection	No data	-	Not relevant	-	-
Transport	Rather low or relatively high, depending on the studies	Consumption of fossil oil	Not relevant	-	-
Recycling	Possibly high for human toxicity and ecotoxicity. 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	Possibly important for resource depletion, human health	Recovery of materials during recycling.	Mainly from gold, tin, copper and other metals
Controlled landfilling	Rather low for human health	Minimum leak of toxic substances in the ecosystems	Not relevant	-	-
Non controlled landfilling	Possibly high for human toxicity and ecotoxicity	Leak of toxic substances in the ecosystems	Not relevant	-	-
Recovery	No data	-	No data	Recovery of energy during incineration	-
Incineration without recovery	Possibly high for ecosystems quality	Emissions into water, air and soil	Not relevant	-	-
Reuse	No data	Production of the spare parts	Relatively high for GWP	Avoid the production of another equipment	-
Informal recycling	Possibly high for ecotoxicity and human health	Leak of toxic substances in the ecosystems (copper, lead, tin, nickel, cadmium)	No data	-	-

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 6 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 [21]. [21] highlight that transport can have important environmental burdens with the fossil oil consumption. Whereas [35] find low environmental burdens for EoL transport for all impact categories.

As [21] highlight, recycling has a significant contribution for human toxicity and ecotoxicity because of the consumption of substances during refinery (nitric acid, sulfuric acid, hydrochloric acid and deoxidating agent). [21] indicate that the EoL is the most impactful of all phases for human toxicity, followed by impacts on ecotoxicity (the second contributory phase after pre-manufacturing). Results [24] recall that recycling has environmental impacts due to dust, metals, gases and dioxins emissions, water use, or waste generation. In some countries, like Belgium, geographical localization of their study and modern technologies in recycling plants, such as de-dusting plants, specific filters, wastewater treatment plants, and sprinkling plants, limit the environmental impacts. [24] find high burdens for terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity (between 3 to 7 % of the results), for the disposal stage which is recycling in Belgium. In the recovery process, [35] find high environmental burdens for battery recycling and copper smelting.

[24] 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. [27] 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 coming from gold recycling [10, 26, 27, 31, 35, 36], followed by tin and copper [27]. Indeed, the impacts associated with gold extraction are extremely polluting due to low environmental concentrations and extraction processes with sometimes irreversible consequences. According to [47], gold is one of the complex and/or refractory ores, which means that processes are becoming more complex as they become more and more complex. Processes with the increase and diversity of ore treatments (numerous chemical reagents with increasingly sophisticated processing facilities), are necessarily associated with large quantities of effluent and mining waste. They recycle it and avoid its extraction to limit environmental and health impacts. [27] 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.

[39] 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, [21] 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. [22] 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. [27] 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.

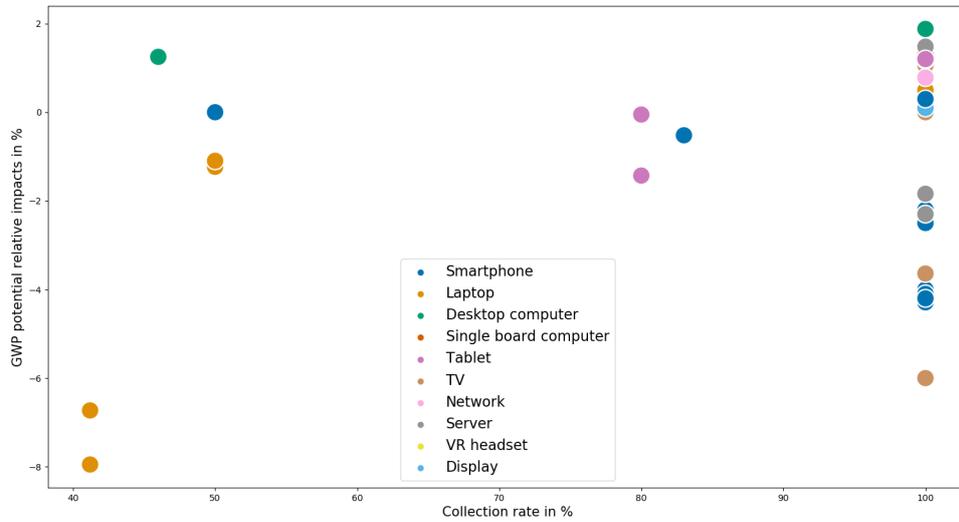
[24] argue that informal recycling happens in non-controlled conditions where workers apply crude methods such as acid baths with sodium cyanide, burning plastics, or manual disassembly of components. The authors model informal recycling in the Guiyu region (China), for a social assessment but not for 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.

Results by LCA

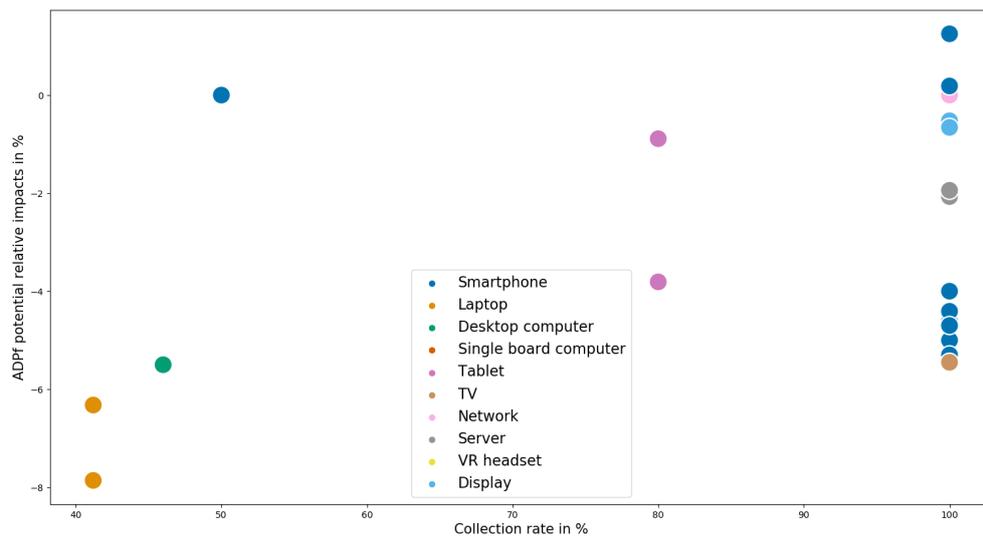
To understand the potential environmental impacts of the digital devices, we collected information on each LCA analyzed. To this end, we gathered relative and absolute impacts data from each study for the following impact indicators: global warming potential (GWP), abiotic depletion potential fossils (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 28 LCAs). We could not extract EoL impact data for seven studies [12, 14, 20, 22, 28, 39, 40]. Some studies make comparisons of digital devices [23, 27, 30, 37]. In this case, we gathered environmental impacts for all the devices analyzed in the LCA. For four studies, we could extract only GWP impacts even if all the LCAs are multicriteria [10, 11, 23, 33]. 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. We assumed that if the collection rate is not provided in the LCA, the collection rate equals 100%. Our collected data is presented in Figure 2 and 3.

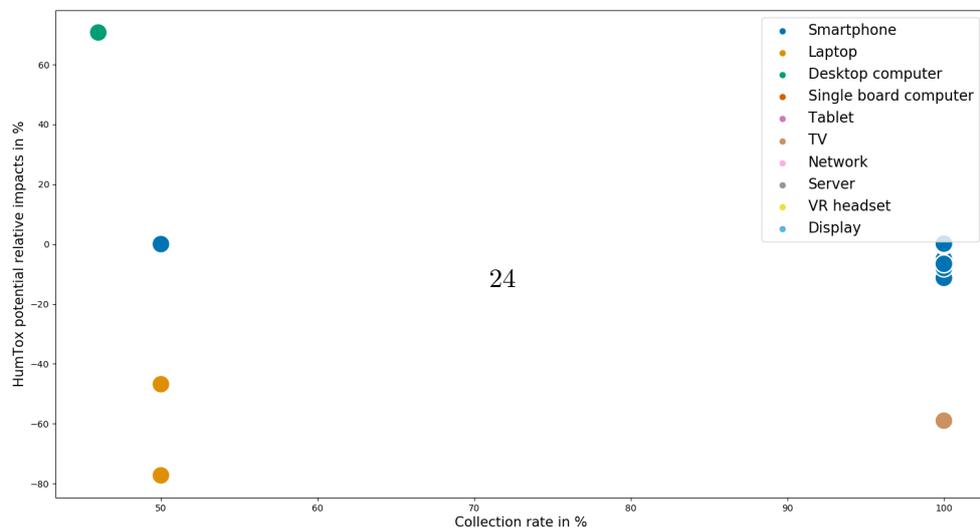
Figure 2 presents the EoL relative environmental impacts for each LCA. The three sub-figures present the distribution of the EoL relative impacts according to the collection rate: Figure 2a for GWP, Figure 2b for ADPf and Figure 2c for HumTox. We choose to present GWP, ADPf and HumTox because we found more data for them



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



(b) Distribution of the EoL ADPF fossils relative impacts according to the collection rate



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

Fig. 2: Results of relative environmental impacts according to the collection rate of the LCAs

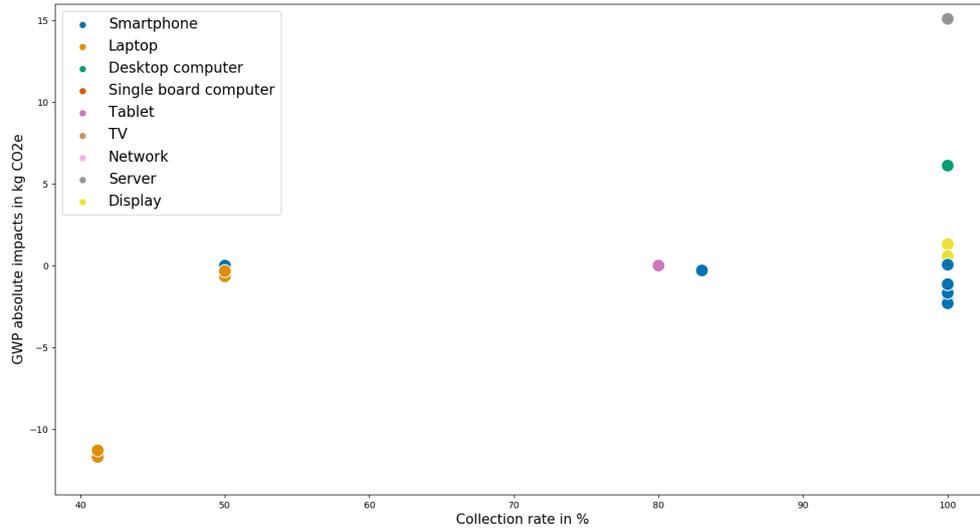


Fig. 3: Results of absolute GWP impacts according to the collection rate of the LCAs

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. Most of the relative impacts are assessed with avoided impacts from the substitution approach, and we do not know the shares of the EoLT and the material and/or energy recovery. We can observe a slight variation in the relative results of the studies for two environmental impact indicators: in Figure 2a GWP varies between $-7,95\%$ and $+1,9\%$ and in Figure 2b ADPf varies between $-7,9\%$ and $+1,25\%$. We observe a significant variation of results for three environmental impact indicators: in Figure 2c 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 Figure 2, we did not see a significant difference in EoL impacts depending on the collection rate or the type of digital equipment.

Figure 3 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. 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.

4.2.6 Critical review

The ILCD Handbook (p.341) [44] formulates that the critical review is a one of the key features that assures 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 [15] share the list of the fifty-six stakeholders involved in the critical review. [26, 31, 33] specify that a critical review was performed on their studies. [26, 31] precise the academic reviewer and share the critical review statement in the appendixes. The other twenty-four studies do not highlight a critical review.

Analysis	Tekwawa et al. (1997) [20]	Choi et al. (2006) [21]	Duan et al. (2009) [22]	Loubet et al. (2023) [23]	Ciroth et Franze (2011) [24]	Grzesik-Wojtyasiak et Kuklinski (2013) [25]	Herrmann et al. (2019) [26]	André et al. (2019) [27]	Grobe (2017) [11]	Kim et al. (2001) [28]	Hischier et al. (2010) [29]	Hischier (2015) [30]	Herrmann et al. (2019) [31]	Güvendik (2014) [32]	Moberg et al. (2014) [33]	Ercan et al. (2016) [10]	Proske et al. (2016) [34]	Proske et al. (2020) [35]	Sanchez et al. (2022) [36]	Wiche et al. (2022) [13]	Hischier et al. (2014) [37]	Andrae et al. (2017) [38]	Andrae et al. (2017) [14]	Socolof et al. (2001) [15]	Van Galen (2023) [6]	Song et al. (2012) [39]	Manz et al. (2021) [12]	Louis et al. (2015) [40]			
Substitution approach is used as EoL allocation procedure	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
The substitution approach is mixed with another type of allocation								•								•															
EoL allocation procedure is not available	•					•			•			•									•			•					•		
The type of loop is not available	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
BOM is available at a component-level				•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Materials BOM is extrapolated after teardown and weighting the components (or partly)	•			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Transport modeling is (or partly) available	•						•	•			•		•	•		•	•	•	•				•		•			•	•	•	
Metal recycling rates are (or partly) available		•			•		•	•			•		•	•			•	•	•	•		•			•						
Purity and quality of secondary raw materials are (or partly) available							•		•	•			•						•					•							
Primary and secondary data are used for the EoL		•					•	•					•		•	•								•			•				
Only secondary data are used for the EoL			•	•	•	•				•	•	•		•			•	•	•	•	•	•	•		•			•	•	•	
The collection rate is not mentioned	•		•	•		•			•	•	•	•	•		•					•	•	•	•	•			•	•	•	•	
Information on the treatment of the specific and hazardous components is available							•			•	•		•	•				•	•		•				•	•	•	•	•	•	
Information on recycling residues are (or partly) available							•			•	•		•				•	•	•		•	•			•						
Midpoint impacts are given in the study		•		•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Endpoint impacts are given in the study	•		•		•			•				•									•			•			•				
Relative impacts are given in the study		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Absolute impacts are given in the study	•			•	•	•	•	•	•				•	•	•	•	•	•	•	•	•		•	•	•	•			•	•	•

Table 7: Results of our analysis of the LCAs for the criteria considered: each dot means that the reference takes the criterion into account.

5 Discussion

Our review raises several points for recommendations to perform a LCA of a digital equipment. Recommendations concern EoL modeling, data accessibility, EoL treatments and potential environmental impacts. Then, we will explore the limitations of our methodological considerations and results.

5.1 EoL modeling

There is almost no description of the EoL stage, which leads to high uncertainties in the EoL modeling. This lack of description is explained by the uncertainties of the fate of digital equipment at its EoL [4]. However, several considerations could reduce uncertainties associated with EoL modeling: expressing the collection rate, considering the informal flows, obtaining primary data, expressing the technologies employed for each EoLT and their potential environmental impacts, expressing the material recycling rates, highlighting the system boundary of EoL and making explicit the type of loop for recycling.

LCAs should detail the share of the potential burdens and the potential avoided impacts, when the substitution approach is used. Most studies employ substitution for the EoL allocation. The substitution approach leads to the invisibilization of EoL environmental impacts because the EoL results are displayed as final results only (potential burdens - potential avoided impacts). Therefore, we cannot get answers on the potential environmental burdens of EoLT or the avoided impacts. Two studies highlight the potential burdens and avoided impacts of the EoLT for each substance/ emission/ material used in the life cycle inventory [29, 30]. In their LCA results, only the final result for EoL is visible. By contrast, [27] share the calculation for the net result of the avoided impact approach. To do so, the authors calculate the avoided impacts of secondary material generated in recycling to which they subtract the avoided impacts of primary material used in the production stage. For each recycled material, the net results are: secondary input - primary input. Sharing the calculation helps (1) determine to which the avoided impacts of EoLT recycling for each material modeled is assessed, and (2) for future research.

LCAs should express the distribution of impacts between the systems, when the recycling is modeled with the substitution. 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 [17, 48]. However, the LCAs selected are 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) [44]. Furthermore, 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. [28] express the 100% recycling as an optimistic scenario. With the substitution approach

and the avoided impacts calculation, one risk is to count twice the "benefits" generated by the production of secondary material. In the LCAs, there is no information on the distribution of these avoided impacts. The avoided impacts are fully accounted for in the LCA system studied. Therefore, it cannot go to a system that will use this secondary material. Expressing the system that will use the secondary material is essential for EoL modeling. Only when LCA practitioners used the 50/50 allocation procedure, the distribution of burdens and avoided impacts between the systems is clear. *LCAs should express the type of loop, when recycling is modeled.* Few studies mention the closed-loop system and one mention the distinction between open and closed loop by material. For closed-loop, if the avoided impacts of the studied system are fully accounted for, the avoided impacts cannot go to the system that will use this secondary material. This signifies that the studied system may consider the avoided impacts either in the raw extraction phase (production stage) or in the EoL stage.

If it is an open-loop system, the avoided impacts should be shared appropriately between the system that will use the recycled materials and the system studied that produces like NegaOctet require payment.

LCAs should indicate the material recovery rates and the fate of the recycling residues. Regarding the material loss during recycling, few studies share the material recovery rates with the list of materials modeled for the EoL. Both of these information are essential because they offer a comprehensive way for the impact assessment. The material loss and recovery vary regarding the type of recycling processes [49] or the type of material [6]. Furthermore, recycling rates for certain metals used in digital equipment manufacturing can be less than 1% [50]. It is therefore necessary to provide the list of materials recycled and their recovery rates. To complete the information, sharing the EoLT potential environmental burdens and the potential avoided impacts is essential. Another important neglected point in the EoL modeling is the recycling residues fate. Few LCAs express it and model the residues as landfilled or incinerated or recovered. By doing so, the recycling residues fate modeling is explicit.

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. [15] collect primary data for the entire life cycle stage of the CRT and LCDs, except for the EoL stage in which they mix primary and secondary data. When they performed the LCA, data only existed for CRT recycling, and none existed for LCD as the technology was too recent. The fast evolution of technology makes it difficult to use primary data collection. Recyclers have to adapt their processes to the speed of technology. EoL is seen as a stage with no relevant impacts in most LCAs. Even [33] explicitly propose to focus on extraction, use and manufacturing stages where the environmental hotspots are mainly found. Nevertheless, [23] point out that secondary data from ecoinvent for electronics may be outdated as they were produced in the 2000s. With this in mind, collecting primary data for this stage seems essential nowadays. On the eight LCAs that use a mix of primary and secondary data for the EoL, only one study details which primary data is collected (collection, disassembly and pre-manipulation processes) and its data source (Korea Computer Recycling). Sharing both information, data and its source, is essential to understand the extent of the primary data collection for the LCA.

5.2 EoL treatments

[24] recall that the central issue of illegal recycling focuses on the cheap recovery of valuable, non hazardous substances, raw materials from electronic devices. Due to this, non-controlled treatment methods such as manual disassembly, open incineration, or acid baths are applied, and have severe environmental impacts on human health and ecotoxicity. Moreover, 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.

LCAs should consider the informal flows. Providing the collection rate like [10, 24, 27] 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 [8, 24, 51–53] 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 [24] 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. [51, 52] 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). Therefore, modeling informal recycling could be made by considering the share of non-collected WEEE and by collecting primary data [54].

LCAs should consider the collection process. 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 can be reduced to transportation from the collection point to the EoLT location. To model the transportation, [21] model a quantity of light oil consumption without the distance. However, in six other studies, a distance is modeled without the use of the resource [20, 26, 31, 32, 34, 35]. In [32, 34–36], the authors model two type of transportation, train and truck. Depending on the type of transportation, the environmental impacts broadly vary. In [20], the authors model two average distances. Transport modelling is often neglected, as is the collection. To have a complete view of transportation modeling and assess the environmental impacts, it is essential to share information on the quantity of resources used and the transportation distance. [55] 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. However, the transport impacts can be relevant for a few environmental categories, such as air pollution, acidification and terrestrial eutrophication.

LCAs should express the recycling steps of hazardous components like PCB, PWB or battery. Indeed, none of the studies inform about the considered recycling steps. After pre-processing, hazardous components are removed from the equipment and

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.

5.3 Potential environmental impacts

This review is a starting point for understanding the EoL environmental impacts of digital devices.

LCAs should share the absolute impacts. Understanding the impacts is difficult when the absolute results are not shared. With absolute results, we can compare them with other systems. [25, 29] use ReCiPe points to display the environmental impacts, limiting the understanding and comparison of environmental impacts. ReCiPe points can give information in terms of relative impacts rather than absolute. As we observe in Figure 2, we have seen that relative impacts do not seem to depend on the equipment category/type.

LCAs should assess multiple environmental impacts. Ecotoxicity and human toxicity are the impact categories with the most significant burdens for the EoL of digital equipment [21, 22]. Nevertheless, these LCIA methods remain to be consolidated [56]. The authors recommend three human toxicity indicators for LCIA, considering different severity for ‘cancer’, ‘reproductive/developmental’, and ‘other non-cancer’ effects [56]. They highlight that for ecotoxicity, only a consensus on freshwater ecotoxicity exists in LCIA. The characterization methods of the effects of chemical substances on terrestrial and marine ecosystems are largely based on extrapolation of effect data from freshwater ecosystems [56]. We still encourage the LCA practitioners to employ various LCIA methods to have data for the EoL stage. In addition, only two studies employ the PEF for European environmental labelling [14, 38], recommended by the EU since December 2021 [57]. The publication date of the studies can explain this. PEF is still criticized for some indicators and its implementation process is lengthy due to data collection of each material involved in the equipment (emissions and resources consumed by process). [38] specify that PEF modeled a default EoL i.e. if no better data are available, the PEF method proposes default values.

5.4 Limits of the study

We notice several methodological and results limits for this review.

Regarding the methodological limits, we distinguish a few highlights. 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. From this, we did the snowballing. However, we know that this part of the method limits the number of LCAs found. Another limit was the limitation to LCA with several impact categories and LCA of digital equipment or comparison. After reviewing the papers, GWP was the only environmental indicator

present in all studies. Other environmental impacts are not systematically provided. Consequently, it could have brought more results and elements of analysis to use Product Carbon Footprint, or monocriteria LCA (mostly with GWP indicator).

We also chose to exclude LCAs of digital services. Nevertheless, it could also have been a source of information.

Regarding the results limits, one limitation of our approach is the number of LCAs analyzed. We could not find more studies that comply with our inclusion criteria, which were multicriteria studies, taking into account the entire life cycle and focused on one or a comparison of digital equipment. The diversity of devices is also limited due to the lack of studies found; eleven types of digital devices do not represent the diversity of digital devices nowadays by neglecting networks, data centers and Internet of Things (IoT) devices.

In addition, one other limitation is the geographical perimeter. We did not restrict the location of the LCAs, but yet nineteen of our studies are European. It is a significant limitation because many EoL modelling 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 aims to provide an overview of the EoL modeling of digital devices. We first recall the main findings on the LCAs analyzed. Then, we focus on EoL modeling findings. Next, we make explicit the criteria that influence the EoL environmental results. Following this, we specify the missing elements of EoL modeling. Finally, we propose recommendations for further research.

We reviewed eleven types of digital devices, with mostly household items (smartphones, laptops, displays, desktops computers, IoT, etc.) and two professional items (server and network equipment). The majority of LCAs analyzed are from Europe and describe poorly the EoL. The data sources of the EoL are mainly secondary (from the LCA database or LCA computational tool), comply with a geographical perimeter and are outdated [23]. All the allocations are based on the equipment, components or material weights instead of other parameters (age, geographical perimeter, product range, etc.). This paper examined the EoL modeling and choices. No clear consensus exists to model the EoL in a LCA neither in the guides nor the norms [17]. 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 [4] induces an over-simplification of the EoL scenarios. Moreover, the uncertainties are also influenced by variations in human behaviours and/or variations according to the geographical perimeters [9].

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. Missing elements in these studies are: (1) transport and collection modeling, (2) purity and quality of the recycled materials, (3) fate of recycling residues, (4) material recovery rates, (5) informal flows modeling, (6) primary data collection and the expression of which data is collected for the study, (7) EoLT potential impacts, (8) expression of both potential burdens and avoided impacts (when the substitution is employed), (9) EoL system boundary with the expression of the type of loop, (10) modeling formulae for the EoL impact assessment, and (11) detailed description of the fate of specific components containing hazardous materials. Unfortunately, given the small number of studies, we cannot detect which criteria do not influence these missing elements.

To detail the first recommendation, when the substitution approach is employed, sharing more information and details is required. The expected information are the type of loop (closed or open), the list of materials sent to recycling with their recovery rates, the purity and quality of the recycled material obtained, and the share of the potential burdens of the EoLT and of the potential avoided impacts.

We then recommend including the environmental impacts of the non-collected digital equipment, also called informal flows. A large proportion of WEEE passes through informal flows, whose lack of information makes it impossible to model their environmental impacts [10]. However, several studies highlight the severe potential environmental and social impacts that can arise from this scenario [24, 51, 52] and future research should be implemented in this direction.

We also highly recommend performing an LCA with primary data for the EoL and opening it. It could be from a bottom-up or a top-down approach. In both cases, collecting primary data needs further collaborations with actors from the whole of a country's WEEE chain. Primary data could be the WEEE stream, the scenario distribution for the WEEE stream or the studied equipment, collection rates, the material recovery rates by material, etc..

Lastly, we recommend to develop a hybrid methodology based on MFA and LCA to assess the environmental impacts of EoL. As allocation is based on weight, particularly material weight, leading MFA would help to quantify materials flows of an equipment through the different EoLTs. Few studies use firstly MFA to perform an environmental assessment of the EoL of digital equipment [58–61]. Such studies for assessing the environmental impacts of digital WEEE are still rare today.

Supplementary information. Supplementary data to this article can be found online.

Declarations

The authors declare no competing interests.

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