Preparation for reuse activity of waste electrical and electronic equipment: environmental performance, cost externality and job creation

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Abstract

The European Waste Electrical and Electronic Equipment system introduced measures to encourage both the reduction of the amount of electronic waste and its separation to prepare for reuse. The aim of this study is compare the environmental performance, external costs and social aspect of the whole life cycle of new and reconditioned electrical and electronic equipment by adopting Life Cycle Assessment methodology. Five electrical and electronic equipment categories were investigated and the data collection was made on an Italian context. The refurbishing of breakdown electrical and electronic equipment was assessed by considering different sets of faulty components (Scenario A and B) and a total of 25 scenarios were studied. Moreover, both *attributional* and *consequential* life cycle inventory modelling framework were adopted to represent the investigated scenarios. The outcomes highlighted that the preparation for reuse process leads to obtaining a sustainable electronic device than the new one, depending on which set of components are replaced. Adopting Scenario B with the attributional model, the environmental damage of reconditioned electrical and electronic equipment decreases compared to the new one. Conversely, the consequential approach determines an environmental credit for all repaired electronic devices except for one category; in particular, Scenario A produced the largest environmental advantage. The analyses of external costs and social aspects confirm that the preparation for reuse activity allows to obtain a more sustainable product than a new one. For these two latter aspects, the results showed a turnaround passing from attributional model to consequential one. Noting the variability in results adopting both different life cycle inventory modelling framework and set of replaced components, the Life Cycle Assessment practitioner, that conducted the study, should help the decision-makers to determine which scenario is more sustainable accomplishing an adequate choice.

Keywords

Life cycle assessment, WEEE, preparation for reuse, LCI modelling framework

1 Introduction

The growth of industrialization worldwide has resulted in an increase in electrical and electronic goods production in several markets. The acceleration rate of technological development effectively renders certain products obsolete almost as soon as they are purchased (Goodship and Stevels, 2012). These aspects have led to an inevitable increase in electrical and electronic waste, which has become a significant problem, particularly in environmental terms (de Oliveira Neto et al., 2017). Waste Electrical and Electronic Equipment (WEEE) is a complex mixture of materials and components, which because of their hazardous contents can cause major environmental and health problems if they are not properly disposed. Environmentally friendly recycling was extensively promoted by laws and regulations in recent years (Lu et al., 2018). European Directive 2002/96/EC, using the Extended Producer Responsibility (EPR) principle, ensures that producers can fulfil obligations either individually or collectively, and its aim is “as first priority, the prevention of WEEE and, in addition, the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste” (EU, 2008). In Italy, European Directive 2012/19/EU was implemented by Legislative Decree No. 49/2014 for EEE. This should contribute to the circular economy and enhance resource efficiency (González et al., 2017). The EU Directive stated, “where appropriate, priority should be given to preparing for reuse of WEEE and its components, subassemblies and consumables”. It also introduced a stepwise increase in the collection target, and from 2016, the annual collection target was defined as the ratio between the collected amount and the average weight of Electrical and Electronic Equipment (EEE) (2017/699/EU) put on the market (PoM) in the previous three preceding years, which will rise to 65% in 2019. Collection targets include both household and professional WEEE.

Today, there are different definitions of reuse and related concepts in the literature as detailed described by Lu and colleague (Lu et al., 2018). In this study, we referred to EU definition of *reuse* and *preparing for reuse* (EU, 2008), which identified these activities as crucial for WEEE management:

- ‘reuse’ means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived;

- ‘preparation for reuse’ means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused without any other pre-processing;

Life cycle assessment (LCA) is an environmental management tool for assessing environmental aspects and potential impacts associated with a product, process, or service. LCA follows a cradle-to-grave approach, taking into account the full life cycle of the product: from raw material acquisition to production, use, and end of life. It is regulated by ISO standards 14040 and 14044.

Moreover, LCA methodology is a powerful tool for decision-making and for the End of Life option (EoL), allowing for the identification of hotspots associated with a specific waste management policy and the eventual implementation of focused strategies to reduce environmental (Pini et al., 2018). The European Union has in recent years promoted recycling, reuse, and other forms of recovery in order to reduce the quantity of such waste to be disposed (Directive 2002/96/EC). The EU is also taking measures to restrict the use of hazardous substances in this type of equipment (Directive 2002/95/EC). Hence, in this context Europe was very active in carrying out LCA to support electronic waste management (Xue and Xu, 2017). The LCA methodology was thus selected in this study to compare environmental performance, external costs and social issue of the whole life cycle of the reused WEEE with the new WEEE.

In this study, the “preparation for reuse” (in the strict term of EU definition) was considered as the activity to recondition the faulty EEE and the resultant good is following called “reused EEE”. With the terms “repair” and “refurbish” we referred to all activities belonging to “preparation for reuse” treatment.

The comparison analysis of the life cycle of the reused electronic good and the equivalent new one was conducted through LCA methodology. The preparation for reuse was assessed by taking into account different sets of faulty components. Both attributional and consequential LCI framework modelling were adopted to model LCA of all scenarios. The obtained environmental results vary greatly considering these two different approaches leading to dissimilar results interpretations and therefore difficulty for the decision makers to take the adequate decision. From this perspective, is the LCA practitioner that conducted study that must to help the decision makers come to the appropriate decision.

The present study is part of a wider EU research project (WEEEN Models), the main purpose of which is to create a new sustainable model of WEEE management of an Italian context. In particular, the project was kicked-of considering the pilot city of Genoa.

The paper is organized as follows: Section 2 contains a literature review; Sections 3, 4 and 5 describe the LCA methodology step by step, from materials and methods to the LCA results; Sections 6 reports the discussion of LCA results and provide conclusions along with suggestions for further research.

2 Research background

This section reports relevant contributions that refer to the sustainability assessment of products and processes, with a special focus on WEEE treatment.

LCA represents a useful aid for waste management, and over the last decades it was applied in the waste management field (Soltani et al. 2015). Recovering metals from waste incineration (Boesch et al. 2014), organic fibres (Quirós et al. 2014), digestate (Vázquez-Rowe et al. 2015), and ash solidification and recycling (Di Gianfilippo et al. 2015; Margallo et al. 2014) are examples of waste materials and processes to which LCA was applied. Margallo et al. (2015) and Laurent et al. (2014) provide details of several LCA applications to waste treatment. Extensive recent scientific literature focuses on WEEE treatment. However, few LCA studies regarding the reuse/reconditioning of electronic waste were conducted. Recently, Rodriguez-Garcia and Weil (2016) proposed a literature review of environmental analyses conducted using LCA methodology in WEEE management and recycling. They investigated a time horizon from 1999 to 2015. They found that of the 47 LCA studies reviewed only 3 (Devoldere et al. 2009; Biswas & Rosano 2011; Biswas et al. 2013) focused on waste prevention and used new products as benchmarks. Lu et al. (2017) confirmed that only a few LCA manuscripts focus on the reuse activities of WEEE. They selected four LCA works concerning reuse strategy as EoL: Rose (2000), Schischke et al. (2003), Devoldere et al. (2009) and Zink et al. (2014). Xue and Xu (2017) published a review of the application of LCA on electronic waste management, but they only mentioned reuse issues in the chapter dedicated to the geographical distribution of LCA studies, without addressing this new WEEE management approach even within the gaps and challenges section.

We identified four other publications that complete the picture of the application of LCA methodology to reuse/preparation of reuse of WEEE. Cheung et al. (2018) assessed the environmental impacts of lifetime extension versus energy efficiency for the product group of video projectors, based on three liquid-crystal display (LCD) projectors. Andrae et al. (2017) conducted a screening LCA study of a virtual reality (VR) headset in order to evaluate its potential environmental impacts under certain conditions, investigating different EoL treatments scenario among which the 5% reuse of entire product. Gonzàlez et al. (2017) analysed the economic and environmental convenience obtain from a reuse strategy versus the recycling treatment of computers in Spain. Lu et al. (2014) investigated the reusability of typical electrical and electronic products and components in China that used the merged Life Cycle Sustainability Assessment (LCSA). Only Cheung et al. (2018) considered the replacement of faulty parts in the reconditioning activities, while the other two studies regarded the reuse process simply as an extension of the appliance lifetime without taking into account the substitution of inoperative components.

Most of the above-mentioned studies only involved a single product, for example washing machines (Devoldere et al., 2009), computers (González et al. 2017 and Schischke et al. 2003), televisions (Rose 2000), compressors (Biswas et al., 2013), smartphones (Zink et al., 2014), mobile phones (Lu et al., 2014), video projectors (Cheung et al., 2018), until going to the newer VR headset (Andrae et al., 2017). Biswas and Rosano (2011) and Lu et al. (2017) considered two appliances: the former considered refrigeration and air conditioning compressors and the latter refrigeration and power supply units of desktops.

The focus of this study is on all WEEE categories, not only a single appliance. In Italy, WEEE is classified in five WEEE categories (DMn. 185 of the 25th of September, 2007): heaters and refrigerators (R1), large household appliances (R2), TV and monitors (R3), small household appliances (R4) and lighting equipment (R5). Following, WEEE categories will be called also "groups" or "product categories". Additionally, all operative processes to refurbish electronic waste (section, check, disassembly and replacement, and cleaning) and the life cycle of new components that can replace failed ones were considered.

As underlined in the introduction, LCA covers only the environmental dimension of the sustainability concept. To explore the sustainability of products and processes from a holistic perspective, economic and social impacts should also be assessed. In our project, only external costs were considered in the economic impact category. Chhipi-Shrestha et al. (2015) authored an extensive review of social sustainability, which provides a better understanding of the multidimensional nature of the social sustainability pillar. Their taxonomy allocates social stakeholders into five categories (workers, local community, society, consumers and value chain actors) that had been formalised earlier by UNEP/SETAC (2009), and six social categories (human rights, working conditions, health and safety, cultural heritage, governance and socio-economic repercussions) with their subcategories. Over 100 social indicators are also included in UNEP/SETAC (2013). In terms of WEEE treatment, to the best of our knowledge only Lu et al. (2014) addressed the reusability of typical electrical and electronic products and components by using the merged LCSA. In this study, one type of social impact was considered, namely job creation.

3 Materials and methods

The aspects dealt with in this study, the method used to evaluate them and the related sections in which they are summarized in the following table.

Table 1 Summary of the environmental, social and economic issues tackled

	Impact category	Evaluation method	Section
Environmental	Carcinogens Non-carcinogens Respiratory inorganics Ionizing radiation Ozone layer depletion Respiratory organics Aquatic ecotoxicity Terrestrial ecotoxicity Terrestrial acid/nutri Land occupation Aquatic acidification Aquatic eutrophication Global warming Non-renewable energy	IMPACT 2002+	3.2
Economic	External cost	EPS 2015	3.3
Social	Job creation	IMPACT 2002+ modified	3.4

3.1 Life cycle assessment

3.1.1 Goal definition

In the Italian context, WEEEs are classified into five categories (DM n. 185 of the 25th of September 2007): R1 – heaters and refrigerators; R2 – large household appliances; R3 – TVs and monitors; R4

– small household appliances; and R5 – lighting equipment. The aim of this study is to compare the environmental performance between the whole life cycle of reused WEEE and new WEEE. The LCA methodology was applied to achieve this (ISO 14040, 2006) (ISO 14044, 2006) and SimaPro 8.5.2 software calculation was used .

3.1.2 System and functional unit

The system study is the whole life cycles of both new EEE and reconditioned EEE obtained by preparation for reuse waste process, in particular different set of replaced faulty components were assessed. In agreements with the project partners, the lifetime of the reused products was assumed in first instance as equal to half that of an equivalent new product (e.g. if the lifetime of new R1 is equal to 10 years, then the lifetime of the reused R1 is equal to 5 years). Consequently, the functional unit (FU) chosen for representing the *entire* life cycle of the new EEE is 1 p (i.e. one new electrical product), whereas for the reused EEE's life cycle is 0.5 p.

Table 2 shows the representative product selected for each WEEE category and the relative weight.

Table 2 Representative product considered for each WEEE category and relative weight

Representative Product	Weight/FU
Refrigerator (R1)	44 kg
Washing machine (R2)	67,066 kg
LCD (R3)	5,1 kg
Laptop (R4)	3,12 kg
Fluorescent lamp (R5)	0,24 kg

3.1.3 System boundaries

The system boundaries of the life cycle of the new product (Fig. 1) considered the following steps: *i*) Production; *ii*) Use: consumption in terms of energy, water, etc.; and *iii*) Conventional EoL treatment (with recycling option). Those of the life cycle of the reused product (Fig. 2) considered: *i*) Transport to the collection centre of the decommissioned products; *ii*) WEEE selection to define what can be repaired; *iii*) Repair of reusable products; *iv*) EoL of the replaced components; *v*) Use of the reconditioned EEE; and *vi*) EoL of reconditioned EEE.

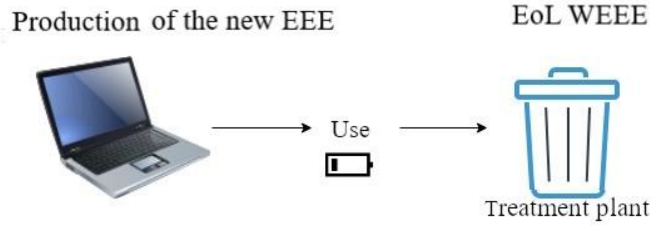

Figure 1 System boundaries of the life cycle of the new EEE

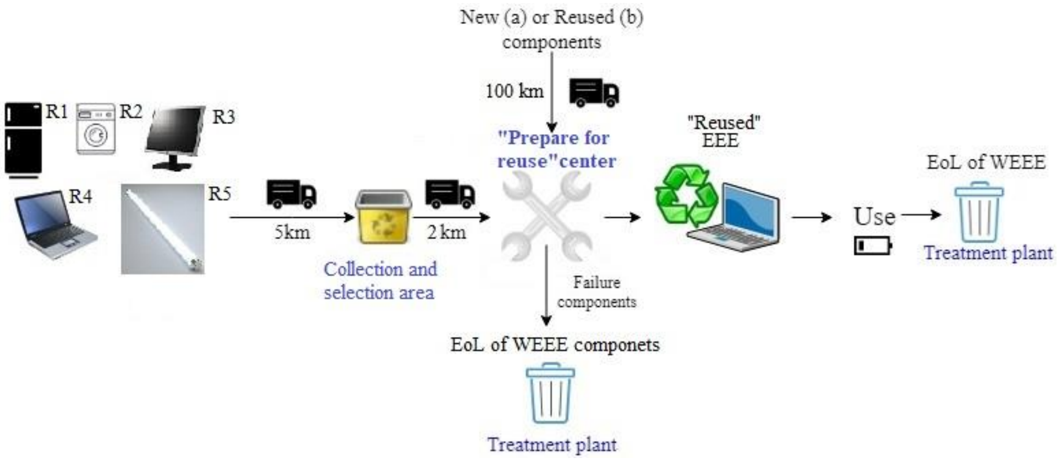

Figure 2 System boundaries of the life cycle the reconditioned EEE

A representative product was considered for each WEEE group (Table 2), assuming that it generates the same environmental damage as other products belonging to the same category. In the use phase, lower performance of reconditioned EEE was also considered for all appliances except for R5. A higher level of water consumption in the use phase of reconditioned R2 products was also assumed. Different sets of replaced components were evaluated to identify which determined the best solution. The definition of these alternative scenarios was conducted by distributing ad-hoc questionnaires addressed to expert technicians of the preparation for reuse center of the pilot city of the project:

- Scenario A represents the set of replaced components, which are damaged more frequently first, during the EEE lifetime,
- Scenario B represents a second group of replaced components, which have broken down more frequently, but in a time order following the previously defined set.

For each scenario, two sub-scenarios were evaluated: new (*a*) and reused (*b*) components, which were used to replace those that failed. In the reused components scenario, the faulty parts were replaced with still working parts of WEEE destined for the conventional EoL treatment.

The same lifetime assumption took for the entire life cycle of the reconditioned EEEs was made for the reused components as well. The environmental comparison thus involved five scenarios for each WEEE category, namely new EEE, reused EEE Scenario A-*a*, reused EEE Scenario A-*b*, reused EEE Scenario B-*a* and reused EEE Scenario B-*b*. Twenty-five scenarios were assessed per each LCI framework modelling, and more details are given in Chapter 4 “Life Cycle Inventory”.

3.1.4 Data quality

The data for the production of electric products belonging to R3, R4 and R5 categories were acquired from the Ecoinvent database v3.3 (Wernet et al., 2016). Data on the manufacture of electronic goods belonging to R1 and R2 categories are derived from previous LCA studies (Iezzi 2006; Ziosi 2000). The main parts for the replaced components were modelled through Ecoinvent database v3.3 processes (Wernet et al., 2016), with only data of those for the compressor (R1) and engine (R2) modules obtained from a previous study (Iezzi, 2006).

The primary data include *i*) reconditioning activities of WEEE that after the selection phase must be repaired; *ii*) transport for taking WEEE to the collection area; *iii*) average selection time and total repair time (reconditioning process) for checking, disassembly, replacing and cleaning; and *iv*) information on different replaced components options. This information was all obtained through direct interviews with retailers and technicians.

Since, this study started from a national context, the Italian mix electrical energy generated by Ecoinvent database v3.3 (Wernet et al., 2016) was taken into account to model the electricity employed in the study.

The background datasets were acquired from Ecoinvent database v3.3, in particular the system model “Allocation at the point of substitution” was used to model the Attributional LCA and “Substitution, consequential, long-“ was applied to the Consequential one.

3.1.5 Attributional and Consequential LCI modelling

The choice concerning the application of Attributional or Consequential LCI modelling framework is a key issue during an LCA study. Although the ISO standards (ISO 14040, 2006) (ISO 14044, 2006) and the ILCD manual (JRC-IES, 2010) provide recommendations on how to perform an LCA, there are still differences between the studies due to the different methodological approaches adopted (Thomassen et al., 2008) and, in particular, the LCI modelling framework substantially influences the LCA results (Ekvall et al., 2016). Recently, Ekvall et al. (Ekvall et al., 2016) analyzed the ILCD guidance on the structure of Attributional and Consequential LCI modelling by comparing the different statements in the handbook with each other and with previous research in this area. They concluded that the ILCD handbook is internally inconsistent, particularly when recommending choices between the two LCI models (Pini et al., 2018). Therefore, they indicate that the handbook needs to be revised. In addition, Weidema (Weidema, 2014) pointed to a criticism in the current ISO

14044 of which unit processes to include in a product system and how to link these unit process data sets together. He underlined that this causes different interpretations regarding LCI framework modelling (Pini et al., 2018).

The distinction between Attributional and Consequential modelling was developed in the process of resolving methodological debates on allocation issues and data selection (Thomassen et al., 2008).

Attributional modelling identifies the existing impacts generated by a system (Schrijvers et al., 2016) isolated from the rest of the technosphere. This approach quantifies the environmental impacts attributable to the functional unit of a product system on the basis of a mapping of the flows of resources and emissions (input and output) that accompany the product during its life cycle (Hauschild et al., 2017) and (Ekvall et al., 2016). The multifunctionality can be addressed by 'substitution', where the functional unit is expanded to include the co-functions (avoided products) of the process/product (Curran, 2018), or by 'partitioning', where inputs and outputs are allocated between the system function and the coproducts generated by the system (e.g. mass, energy, economic value allocations etc.). Furthermore, Attributional modelling uses as input data the average data representing the actual physical flows and describing the production system as a whole (Ekvall et al., 2016).

Consequential modelling describes how environmentally relevant physical flows will change in response to a possible decision and reflects the consequences of a change in production (Weidema, 2014). Usually, this approach solves the multifunctionality through 'substitution' by identifying the co-products generated by the system and crediting the avoidance of those co-products and their associated impacts that are supposed to be a consequence of the decision taken. Consequential approach uses marginal data to model consequences. Marginal data are only used to model changes large enough to have a direct and large-scale effect on the production capacity of the system (Ekvall et al., 2016). The unavailability of marginal data is a problem when performing Consequential LCA. Further research is needed to identify marginal processes.

As the choice of LCI modelling framework is still an open and complex issue to be discussed (Pini et al., 2018), this work adopted both models to assess the environmental burdens associated with the life cycle of reused EEEs.

The way in which the LCI modelling frameworks were applied for the 'preparation for reuse' activity is reported in the paragraph 4.2 (Life Cycle Inventory of reused EEE).

3.2 Environmental assessment

The Life Cycle Impact Assessment (LCIA) was conducted using the Impact 2002+ method (Jolliet et al., 2003). This method takes into account continental emissions diffusion (Europe) covers more impact categories than other methods and includes more substances. Moreover, it combines midpoint and endpoint approaches. The midpoint indicators link the cause-effects chain of an impact category (Pini et al., 2017). Endpoint indicators are considered to be linked to the cause-effect chain for all categories of impact (e.g., human health impacts in terms of disability adjusted life years (DALY) for carcinogenicity, climate change, ozone depletion, photochemical ozone creation or impacts in terms of changes in biodiversity) (Bare et al., 2000).

As impact categories (mid-point) IMPACT 2002+ considers: Carcinogens, Non-carcinogens, Respiratory inorganics, Ionizing radiation, Ozone layer depletion, Respiratory organics, Aquatic ecotoxicity, Terrestrial ecotoxicity, Land occupation, Terrestrial acid/nutri, Aquatic acidification, Aquatic eutrophication, Global warming, Non-renewable energy and Mineral extraction. At the end-point level the impact categories converge into the relative area of protection, therefore the damage categories for this LCIA method are: Human Health, Ecosystem Quality, Climate Change and Resources. Additions and modifications, however, were implemented to provide a more representative index of the system considered as reported in Pini et al. (2014).

3.3 Economic assessment

The economic issues were evaluated as the *external costs* analysis, derived from the EPS 2015 LCIA method (Steen, 2015). The external cost represents *the monetized costs imposed on society of direct and indirect damage caused by pollutants emitted during the manufacture of a product or rendering of services, which are not paid by the producers or the consumers nor considered in production or consumption decisions* (NRC, 2010). The cost externality is the only economic assessment performed in this study.

3.4 Social assessment

A new “social” category *Job creation* was added to the LCIA method IMPACT 2002+, to consider the number of new jobs that will be created by the new preparation for reuse activity. Therefore, a new social substance defined as “number of employees” was included in the social category and the characterization factor was set equal to 1 p/p. This allowed for the consideration of benefits generated by the reconditioning activities along with the environmental analysis. The calculation of the number of the new job positions created is reported in the chapter 5.2.

The reconditioned EEEs create a new business opportunities allowing job creations throughout the product lifecycle in terms of, maintenance, repair, upgrade, and reuse (Vasilev, 2015) and not changing the traditional market demand of new electronic products.

4 Life cycle inventory

4.1 New EEE

In assessing the life cycle of the new EEE, the following phases were considered:

Production

The fabrication of new EEE involves the production of main components, auxiliaries, packaging materials, energy consumption, infrastructure, land use and emissions. For the production of LCDs (R3), laptops (R4) and fluorescent lamps (R5) the Ecoinvent datasets v3.3 (Wernet et al., 2016) were used, while as mentioned refrigerator and washing machine manufacture were built ad hoc by considering previous LCA studies.

Use

The electric energy consumption throughout the lifespan of each group of EEE was calculated. Additionally, for the R2 category water consumption was considered. Table 3 reports the lifespan and the use pattern of each electronic product considered in this study.

Table 3 Lifetime and energy consumption per year during the use phase

Product	Life time	Energy consumption	Data Source
Refrigerator (R1)	10 years	270 kWh/year*	(ENEA, 2018)
Washing machine (R2)	6 years	196 kWh/year* Water consumption§: 165 wash cycle/year * 48 l/wash cycle= 7920 l/year	(ENEA, 2018) (Hustvedt et al., 2010); (Szann, 2017)
LCD (R3)	10 years	155 kWh/year	(CNET, 2018)
Laptop (R4)	4 years Average annual day worked by laptop: 240 days/year	Activation mode (office use): Off 16,5 h/day Active 5,5 h/day Stand-by 2 h/day	(Hischier et al., 2007)
Fluorescent lamp (R5)	5 years	29,2 kWh/year	(Hischier et al., 2007)

*Energy class A+; § Wash programme: Cottons 40°C intensive

Final disposal

Conventional EoL treatment of WEEE was evaluated along with the recycling of all valuable materials (metals, precious metals, plastic, glass, etc.). Open-loop recycling modelling was used, which means that recovered secondary materials are used for different applications. Thus the products do not return to the original producer but will be used in other industries (Fleischmann et al., 1997). Table 4 reports the Ecoinvent datasets v3.3 (Wernet et al., 2016) used to model the EoL treatment of each WEEE group.

Table 4 Ecoinvent dataset v3.3 used to model EoL treatment

Product	Dataset
Refrigerator (R1)	*Used industrial electronic device {CH}| treatment of, manual dismantling*
Washing machine (R2)	*Used industrial electronic device {CH}| treatment of, manual dismantling*
LCD (R3)	*Used liquid crystal tube display {CH}| treatment of, manual dismantling*
Laptop (R4)	*Used laptop computer {GLO}| treatment of*
Fluorescent lamp (R5)	*Used fluorescent lamp {GLO}| treatment of*

4.2 Reused EEE

The life cycle of the reused EEE considers the following steps:

Waste collection

In this life cycle step, transport of WEEE from consumer or distributor to the collection centre was assessed. The average distance between these actors was set equal to 5 km. The transport typology is represented by 25% small van (Transport, passenger car, EURO 5 {RER}) and 75% lorry (Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}). Moreover, the average distance from the collection/selection area to the preparation for reuse center was taken of 2 km and lorry was considered as the unique type of road vehicle.

Selection

WEEE selection was assumed to take place in the collection area. This activity concerns 1) the functionality testing of WEEE and identification of the faulty components that have to replaced, 2) the conveyor belt for moving the WEEE during the section activity and 3) the plant and land occupation. Table 5 reports the duration of the selection process for each WEEE category.

Table 5 Selection time spent to investigate the functionality of WEEE

Product	Selection time [hours]
Refrigerator (R1)	0,5042
Washing machine (R2)	0,5042

LCD (R3)	1,0025
Laptop (R4)	2,0025
Fluorescent lamp (R5)	0,101

Production

The reused EEE manufacture is simply the by-product of the preparation for reuse activity necessary to get it working. After the reconditioning activity, the electronic waste is referred to as "reused EEE". Therefore, the multifunctionality of the reconditioning process was solved by using both attributional ("partitioning" approach) and consequential ("system expansion" approach) LCI modelling frameworks. For the former modelling the economic value-based allocation was used to allocate the boundaries between system function and by-product. The economic value associated with the functional unit are all the costs related to the repair activities, namely transport, electric energy, new components, waste disposal (broken components that have to replaced) and labour costs. The economic value correlated to the by-product is the estimated selling cost of the reused EEE. This information was acquired from interviews with technicians and Table 6 reports the economic value allocation adopted in this work.

Attributional LCI modelling with partitioning as basis of allocation returns an environmental damage albeit reduced of the allocation share associated to the generated co-product.

Table 6 Economic value allocation adopted in the Attributional LCI modelling with partitioning approach

Product	***Scenario A*** **allocation related to preparation for reuse activity**	***Scenario A*** **allocation related to reused EEE**	***Scenario B*** **allocation related to preparation for reuse activity**	***Scenario B*** **allocation related to reused EEE**
R1	33%	67%	26,3%	73,7%
R2	41,6%	58,4%	43,4%	56,6%
R3	40,8%	59,2%	36,4%	63,6%
R4	34,4%	65,6%	34,4%	65,6%
R5	41,4%	58,6%	42,7%	57,3%

Additionally, the study was modelled adopting Consequential LCI approach in order to solve the multifunctionality identifying the co-products generated by the analyzed system (i.e. reused EEE). There is currently no production chain in Italy and therefore no legitimate market for reconditioned EEEs. In fact, 'preparation for re-use' is the activity promoted by European directive 2008/98/EC (Directive that establishes the order of priority of regulations and policy on waste management and prevention) that immediately follows the 'prevention' that has the absolutely priority. Directive 2008/98/EC was adopted by Italy with Legislative Decree n. 205/2010, but this law still has no practical effects due to the lack of implementing decrees. Consequently, it was no possible to assess any changes in this market demand (no marginal data were available).

Therefore, the environmental credit was assessed taking into account only the avoided production of the new equivalent electronic devices and their relative impacts. No allocation was considered but a system expansion (avoided products) was applied. In particular, the 'preparation for reuse' activity produces the avoided manufacture of new EEE but with a lower energy efficiency as described below in the "Use" section.

The preparation for reuse process consists of 1) the manual disassembly of broken components, 2) a functionality test for each WEEE component, 3) cleaning with compressed air, 4) transport and installation of the new components that replace the broken ones, 5) the plant and its land use and 6) the EoL treatment of broken components.

As for the set of replaced components, two different scenarios were considered. Table 7 reports the sets of replaced components considered in scenarios A and B.

Table 7 Components replaced in the five representative products

Product	Replaced components Scenario A	Replaced components Scenario B
Refrigerator (R1)	Compressor Refrigerator liquid gaskets	1 PWB[*] Resistor Thermostat
Washing machine (R2)	1 PWB[*] engine belt	1 PWB[*] Water pump Filter
LCD (R3)	1 Video interface	12 Capacitors
Laptop (R4)	Li-ion battery NiMH battery 4 PWB[*]	Power pack Hard disk
Fluorescent lamp (R5)	2 Capacitors	2 Resistors

* Printed Wiring Boards

The details of the time duration for each reconditioning step are reported in Table 8.

Table 8 Repair time spent for preparing for reuse of WEEE

Product	Check + Disassembly and Replacement (Scenario a/b)+ Cleaning [hours]
Refrigerator (R1)	0,5 + 1,504/1,5 + 0,25
Washing machine (R2)	0,5 + 1,504/1,5 + 0,25
LCD (R3)	0,5 + 0,503/0,5 + 0,25
Laptop (R4)	1,5[§] + 0,503/0,75 + 0,033
Fluorescent lamp (R5)	0,0833 + 0,501/0,5 + 0[*]

[§] This time considers check, formatting and installation of new operating system (e.g. Linux).

[*] For this product category no clean operation was assumed.

The durations for check and cleaning of WEEE were assumed the same in both scenarios.

Use

In accordance with the results obtained by data collection in the reuse center located in the pilot city of Genoa, lower performance was taken into account for the use phase of reused EEE by assessing higher energy and water consumption levels. The electric energy consumption increased by 10% for R1 and R3, while in R2 electricity and water consumption increased by 40%. R4 and R5 maintained the same energy performance as the new EEE.

Final disposal

After their regular usage period, the same EoL treatments, i.e. the recovery and recycling of precious materials such as metals, were applied to both new and reused EEE. An equal recycling rate for new EEE and reused EEE were considered.

5 Results

5.1 Life Cycle Assessment

To study the variations in environmental performance of the life cycles between new and reused EEE, 25 scenarios were assessed for both attributional and consequential LCI modelling. Different strategic choices were taken in the reconditioning phase in terms of replacement component options (Scenarios A and B), and different natures of the replaced components, i.e., new or reused (Sub-scenario *a* and *b*) were considered. The influence on the environmental results determined by the LCI modelling approaches was investigated.

The environmental comparison was made per each EEE category and among the different scenarios, since it is not possible perform the results comparison among the different EEE groups; indeed the analysed electronic devices have different function.

The Life Cycle Impact Assessment (LCIA) was conducted using the IMPACT 2002+ modified method. Following are described the main single score environmental results achieved. Single score results were obtained aggregating the four-damage oriented impact categories (human health, ecosystem quality, climate change, and resources) and using a default weighting factor of one (Jolliet et al., 2003). The single score allows to obtain the overall environmental trend of each of the scenarios studied. The detailed mid-point and end-point outcomes were reported in the Supporting Information.

5.1.1 Attributional LCI modelling results

Figure 3 and Table 9 show the single score environmental outcomes. For all EEE categories, *Scenario B-b* determined the more “greener” scenario. *Scenario New* produced the worst case for R1 and R3 groups, whereas *Scenario A-a* becomes it for R2, R4 and R5 categories.

Table 9 Environmental results for each EEE category - Attributional LCI modelling

Single score	R1	R2	R3	R4	R5
New	0,5521	0,4320	0,3992	0,1601	0,0256
Reused - Scenario A-a	0,5505	0,4352	0,3058	0,1734	0,0285
Reused - Scenario A-b	0,5087	0,3656	0,2934	0,1383	0,0265
Reused - Scenario B-a	0,4725	0,3193	0,2931	0,1158	0,0250
Reused - Scenario B-b	0,4702	0,3063	0,2869	0,1092	0,0247

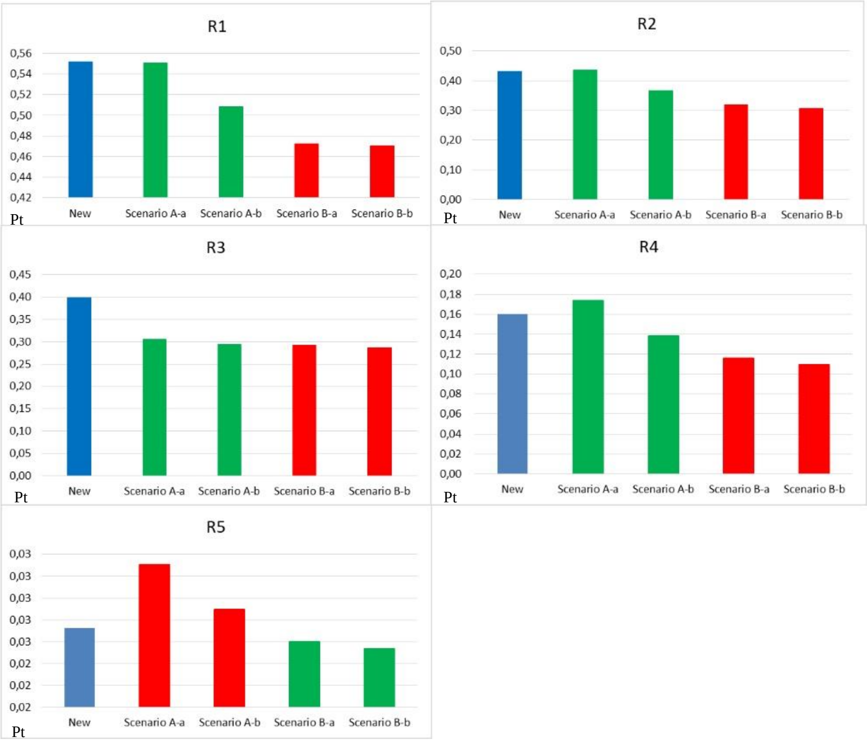

Figure 3 Environmental performance of the five EEE categories - Attributional LCI modelling

5.1.2 Consequential LCI modelling results

As before mentioned the consequential approach typically returns an environmental credit. Figure 4 and Table 10 report the single score environmental outcomes. The environmental results obtained by this LCI approach vary widely among the different EEE categories. Indeed, *Scenario A-b* determined the main environmental credit for R1 and R2 thanks to the reduction of damage associated to the compressor adopting the sub-scenario b (reused components), *Scenario B-b* produced the more “greener” scenario for R3 and *Scenario B-a* is the most advantageous for R4 mainly thank to the avoided environmental burdens associated to the hard disk materials. Instead, for R5 the environmental performance of all reused scenarios produced a damage (positive values); this is mainly due to the lower energy performance in the use phase. For this electronic device, the best case is resulted to be *Scenario A-b*. *Scenario New* produced the worst case for all EEE categories.

Table 10 Environmental results for each EEE category – Consequential LCI modelling

Single score	R1	R2	R3	R4	R5
New	0,2364	0,1660	0,2721	0,1013	0,0189
Reused - Scenario A-a	-5,6220	-0,3996	-0,6195	-0,1315	0,0136
Reused - Scenario A-b	-5,6908	-0,5312	-0,6483	-0,1959	0,0088
Reused - Scenario B-a	-5,6860	-0,4496	-0,6521	-0,2231	0,0115
Reused - Scenario B-b	-5,6890	-0,4862	-0,664	-0,2214	0,0091

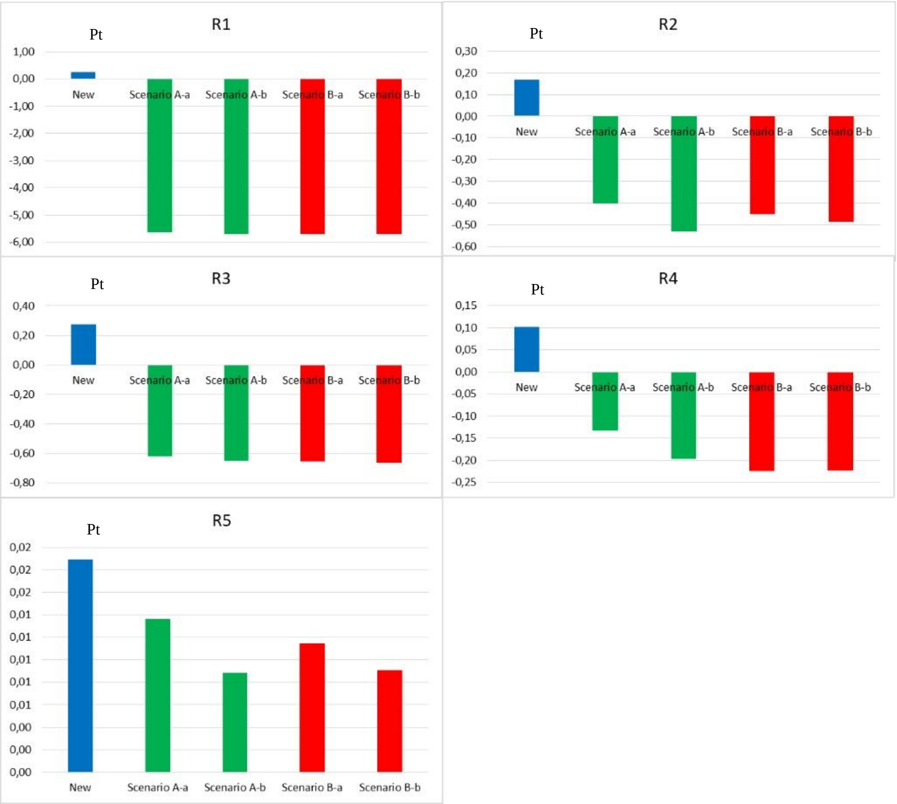

Figure 4 Environmental performance of the five EEE categories - Consequential LCI modelling

5.2 External costs

5.2.1 Attributional LCI modelling

Table 11 and Figure 5 report the external cost for new and reused EEEs. The results highlight that *New* and *Scenario A-a* determine the mainly contribute in all EEE categories. *Scenario B-b* produces a lower external cost and therefore the best economic performance.

Table 11 External cost of the life cycles of new and reused EEE per each EEE group - Attributional LCI modelling

External cost K€	R1	R2	R3	R4	R5

New	1,129	2,189	1,131	1,192	0,099
Scenario A-a	1,022	1,426	0,606	1,915	0,125
Scenario A-b	0,845	0,929	0,439	1,017	0,082
Scenario B-a	0,732	1,33	0,392	0,303	0,094
Scenario B-b	0,703	0,877	0,328	0,211	0,066

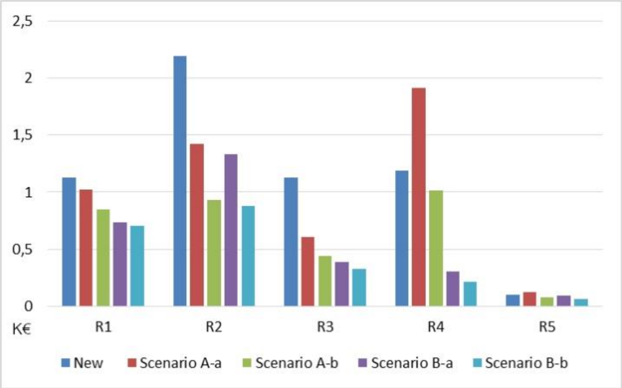

Figure 5 External cost of the life cycles of new and reused EEE per each EEE group - Attributional LCI modelling

5.2.2 Consequential LCI modelling

The results (Table 12 and Figure 6) highlight that *Scenario A-b* determined a slight higher credit than other scenarios for R1. *Scenario A-a* produced a higher advantage for R2, R3 and R5 and therefore the best economic performance. *Scenario B-b* instead positively influenced R4 group.

Table 12 External cost of the life cycles of new and reused EEE per each EEE group- Consequential LCI modelling

External cost K€	R1	R2	R3	R4	R5
New	-0,720	-0,226	0,234	0,361	-0,026
Scenario A-a	-9,506	-2,108	-4,213	-0,455	-0,099
Scenario A-b	-9,566	-2,057	-4,034	-0,909	-0,070
Scenario B-a	-9,398	-2,021	-3,689	-1,227	0,001
Scenario B-b	-9,408	-1,820	-3,781	-1,236	-0,019

Figure 6 External cost of the life cycles of new and reused EEE per each EEE group - Consequential LCI modelling

5.3 Social aspects - Job creation

The benefit derived from new jobs created by the preparation for reuse activity is carried out for each EEE category introducing into all different reconditioning processes modelled in Simapro (i.e. selection, check, disassembly and replacement, and cleaning) the duration (Ti, where *i* is the specific reconditioning process) necessary to perform each refurbishment activity. Considering, one work shift equal to eight hours per worker, it obtained the number of new jobs generated by the refurbishment activity as following reported:

$$\sum_i Ti/8$$

The number of new jobs were introduced in the calculation software through a new social substance defined as "number of employees", which converges in the "Job creation" social category of the impact assessment method.

The life cycle of new EEEs had no positive contribution, as it does not account for reconditioning and therefore no job growth was considered.

5.3.1 Attributional LCI modelling

The benefit derived from the *Job creation* category increases in *Scenario B* for the three EEE categories R1, R3 and R4. *Scenario A* is advantageous only for R2 and R5 (Table 13 and Figure 7). These results mainly depend on the different duration of the "Disassembly and Replacement" process and the calculated allocation share.

Table 13 Evaluation of job creation increase adopting the reuse approach for both considered scenarios - Attributional LCI modelling

Job creation [p*]	R1	R2	R3	R4	R5
Scenario A (a-b)	0,504	0,455	0,436	0,834	0,111
Scenario B (a-b)	0,541	0,444	0,449	0,916	0,109

* 1 p corresponds to 1 job create by reuse activities

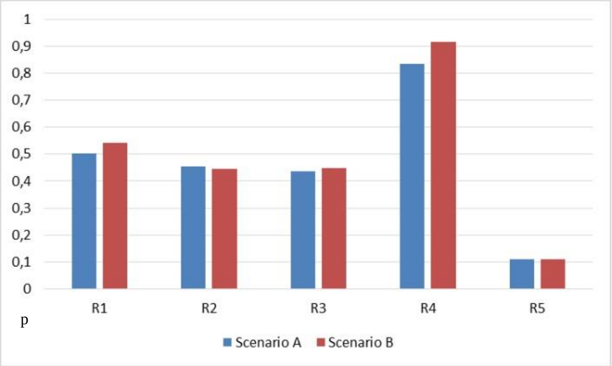

Figure 7 Evaluation of job creation for Scenario A and B - Attributional LCI modelling

5.3.2 Consequential LCI modelling

The benefit derived from the *Job creation* category increases in *Scenario A* excepted for R4, mainly because of the longer replacement activity duration of *Scenario A*, the duration of "Disassembly and Replacement" process also depends on the weight of replaced components (Table 14 and Figure 8).

Table 14 Evaluation of job creation increase adopting the reuse approach for both considered scenarios - Consequential LCI modelling

Job creation [p*]	**R1**	**R2**	**R3**	**R4**	**R5**
Scenario A (a-b)	0,690	0,690	0,626	1,010	1,296
Scenario B (a-b)	0,689	0,689	0,563	1,134	1,1

[*] 1 p corresponds to 1 job create by reuse activities

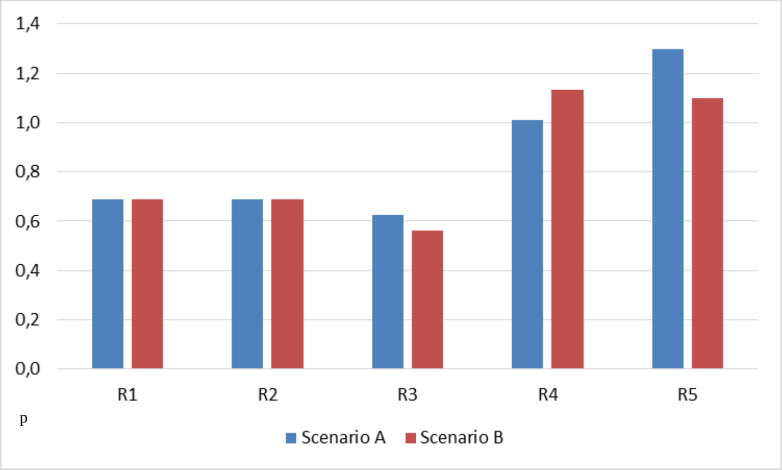

Figure 8 Evaluation of job creation for Scenario A and B - Consequential LCI modelling

Table 15 highlights the scenario that main determines the best environmental, social and economic performance achieve with attributional and consequential LCI modelling framework.

Table 15 Summary table of the best scenarios obtained

	Environmental	**Social issue**	**External cost**
		Attributional	
Best case	*Scenario B-b* (EEE all category)	*Scenario A* (R2, R5) *Scenario B* (R1, R3, R4)	*Scenario B-b* (EEE all category)
		Consequential	
Best case	*Scenario A-b* (R1, R2) *Scenario B-a* (R4) *Scenario B-b* (R3)	*Scenario A* (R1, R2, R3, R5) *Scenario B* (R4)	*Scenario A-a* (R2, R3, R5) *Scenario A-b* (R1) *Scenario B-b* (R4)

6 Discussion

The LCIA results adopting attributional LCI modelling (Tables 1-5, Supporting Information) show that taking the *New* scenario as the baseline, the obtained outcomes indicate that all scenarios exhibit better environmental performance than the baseline. The only exception is in *Scenario A-a* (new replacement components) and for the R2, R4 and R5 groups, where the environmental damage is higher than the baseline scenario. In these groups and in this scenario, therefore, there is no environmental convenience in repairing an appliance and it is preferable to buy a new one. However, simply by substituting the set of new replaced components (*Scenario A-b*) with reused components, the environmental damage is reduced and the environmental performance is in line with all other scenarios, becoming advantageous compared to the baseline. *Scenario B* demonstrates a net environmental reduction with respect to the *New* one. Here, the reduction also increases when reused replaced components are used. Regarding job creation, *Scenario B* is advantageous for three categories out of five (i.e., R1, R3 and R4), while *Scenario A* benefits only the R2 and R5 groups.

The external cost assessment illustrates that the economic trend of each group is similar to that related to the environmental assessment. All scenarios determine a better economic performance than the *New* scenario, with the exception of R4 and R5 groups.

The analysis of results obtaining by consequential LCI modelling (Tables 6-10, Supporting Information) determined, as for attributional approach, that all scenarios are better than the baseline. Even because the *New* scenario generates for all groups an environmental damage (contrarily the *Reused* scenarios produced an environmental credit), in fact the life cycle of new EEEs does not consider the avoided production of the electronic devices since they are disposed to EoL treatments after their lifetime use. The environmental outcomes do not create a specific best performance scenario this depends on the different avoided environmental burdens associated to the new EEE production (avoided product). In particular, *Scenario A* rewards the large household appliances (R1 and R2) whereas *Scenario B* is the best scenario for the smaller device categories such as R3 and R4. In this latter scenario, R5 category does not achieve an environmental credit due to the energy consumption in the use phase that does not balance the benefit generated by the avoided production of the new R5.

Compared to the attributional LCI approach, it is possible observe a job creation trend reversal, which determines *Scenario A* advantageous for all categories except for R4 group. The external cost evaluation produced an economic trend different to that related to the environmental assessment. *Scenario A* is advantageous for all groups except for R5. The environmental, job creation and external cost assessments generated moderately different trends. Therefore, a univocal results interpretation is rather difficult to develop.

It is worth noting that the choices of the set of components that must be replaced and the LCI modelling framework adopted to conduct the LCA study are crucial issues.

Indeed, the attributional LCI modelling conducted to the conclusion that *Scenario A* represents the more frequent setting but not the more sustainable and *Scenario B* represents the set that can actually result in a decrease in environmental damage and external costs and an increase in social benefits. However, according to the direct interviews with retailers and technicians, this latter scenario occurs less frequently than Scenario A.

Consequential LCI modelling generated diversified outcomes varying with the EEE category, therefore the best-case scenario that conduct the higher environmental credits is not possible defined. Although, for external costs and job creation *Scenario A* showed to be the set of components having the best performance.

This highlights the importance of LCA in decision-making and the influence of the results interpretation given by the LCA practitioner that conducts the LCA study.

Therefore, taking into account that the consequential LCI modelling enlarges the boundaries of the study until embracing the consequences that the analysed system might cause on market avoiding the production of that specific resource and consequentially changing the market demand, it is possible conclude this LCI approach is unsuitable for this LCA study. In fact, the final market of reused EEEs is not the same as for new EEEs. Currently, as aforementioned, no legitimate market exists. Therefore, reconditioned EEEs could create a new business opportunity, not changing the traditional market demand of new electronic products. Therefore, we suggest to implement the cause-oriented attributional modelling, firstly because this model allows to obtain a snapshot of the understudied system meeting the requests of who commissioned the study (Pini et al., 2018) and secondly for the lack of marginal data concerning the 'preparation for reuse' activity, in the Italian context, necessary to model consequential LCA.

In conclusion, the Attributional LCI approach carried out that the preparation for reuse activity could lead to obtaining a greener EEE than the new one, but this depends on the components replaced. Nevertheless, through the LCA study the decision-maker can ensure that adopting the scenario is more sustainable.

7 Conclusions and further research agenda

Electrical and electronic equipment is of increasing importance in our daily work and life. In fact, we are now dependent on appliances such as laptops, tablets, mobile phones, washing machines and televisions. The current short lifetime and the widespread use of these devices lead to an inevitable accumulation of WEEE, which at their EoL must be managed in a responsible and conscious way. The present work provides an environmental comparison, through the LCA methodology, between the reused EEE (WEEE reconditioned after the preparation for reuse treatment) and the new one for the *whole* life cycle. For reused EEE, to investigate how the choice of the set of replaced components affects the LCA results, different scenarios were analysed. This research is the first to consider all WEEE categories (i.e., R1, R2, R3, R4, R5), and not only a singular group or just one of its components (e.g., printed wiring boards, engines, capacitors, projectors, etc.). Few LCA studies have to date investigated reuse. Our work is therefore of value, and we believe that future research should focus attention on the environmental assessment of reuse by expanding the analysis to different WEEE groups. This would allow the environmental convenience of the preparation for reuse and traditional EoL treatments of electronic waste to be compared and assessed for a broader range of devices. Indeed, by prolonging the lifetime horizon of electrical and electronic products it may be possible to avoid the production of new goods and the use of materials that those recuperated through conventional WEEE treatment. Alongside the environmental evaluation, the social benefit derived from job creation, the external cost engendered by preparation of reuse activity were assessed. Therefore, the sustainability assessment was thus greatly enriched. Finally, further research should focus on the integration of a multicriteria decision-making approach (MCDM) to LCA analysis, in order to collect others social sustainability measures which will be carried out through a Fuzzy Promethee model group, able to integrate objective (e.g. environmental) criteria with subjective (e.g. social). Moreover, a sensitivity analysis considering different lifespans of the reused EEE and different energy performance in the use phase is worth to be accomplished.

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