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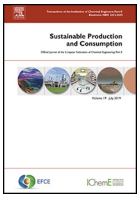

Research article

Life cycle assessment of repurposed waste electric and electronic equipment in comparison with original equipment

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ABSTRACT

Reuse is considered as a priority alternative for the management of Waste from Electrical and Electronic Equipment (WEEE). The reason is that it is thought that reuse always has a lower environmental impact. However, few studies have evaluated in detail the environmental impacts of reuse, and even fewer have analysed cases of reuse for a purpose other than the original one. In this study, life cycle assessment (LCA) following the ISO 14040 standard, was employed to assess the environmental impacts of two preparing for reuse processes of desktop computer considered as WEEE, whose results were repurposed products with industrial application: a programmable logic controller (PLC) and a perimeter security system (PSA). These scenarios were compared with other equivalents in which the products come from virgin raw materials. The results showed a worse environmental performance of repurposed PLC than one original, due mainly to differences in distribution and use stages. The greater weight, the shorter lifespan and mainly the higher operating power were responsible for the greater negative effects of the reuse scenario. However, repurposed PSA has a lower negative impact than original equipment in all environmental categories analysed. This was mainly due to its lower operating power and also not having demanding technical characteristics. Therefore, in this case, the usage profile, the composition and the lifespan can be considered as the main factors that determine the environmental advantage of repurposed products. The main conclusion of this work is that the environmental viability of the reuse of WEEE depends on the existing commercial alternatives for the application of the new product obtained; being one of the main factors the power consumption and the lifespan. This constitutes an important aspect to take into account when developing regulations, strategies and policies to prevent the implementation of WEEE management systems with environmental impacts greater than other alternatives. Further, the specific information about environmental performance of repurposing can contribute to the development of new processes of preparing for reuse. In this way, the commercialization of new products from these processes is favoured, which contributes to improving the environmental management of WEEE and the development of the circular economy.

1. Introduction

Waste electrical and electronic equipment is one of the fastest growing waste streams in the European Union. The proper prevention and management of WEEE are one of the main objectives of European environment policy (European Union, 2012). Computer waste is one of the most important groups of waste electrical and electronic equipment (WEEE), due to its quantity and high rate of generation (Eurostat, 2020; Jaiswal et al., 2015).

The current European policies and regulations on WEEE management prioritize direct reuse and preparing for reuse through the so-called waste hierarchy (European Union, 2008, 2012). In order to

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Abbreviations: ALO, Agricultural Land Occupation; CC, Climate Change; CPU, Central Processing Unit; EEE, Electrical and Electronic Equipment; EoL, End of Life; FE, Freshwater Eutrophication; FET, Freshwater Ecotoxicity; FD, Fossil Depletion; HT, Human Toxicity; IR, Ionising Radiation; LCA, Life Cycle Assessment; LS, Lifespan; MD, Metal Depletion; ME, Marine eutrophication; MET, Marine Ecotoxicity; NLT, Natural Land Transformation; OD, Ozone Depletion; PC, Power Consumption; PLC, Programmable Logic Controller (R-PLC is a repurposed PLC and O-PLC is an original PLC); PMF, Particulate matter formation; POF, Photochemical oxidant formation; PSA, Perimeter Security System (R-PSA is a repurposed PSA and O-PLC is an original PSA); TA, Terrestrial Acidification; TET, Terrestrial Ecotoxicity; ULO, Urban Land Occupation; W, Weight; WD, Water Depletion; WEEE, Waste Electrical and Electronic Equipment.

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achieve an effective application of this hierarchy, specific objectives have been established regarding the reuse and recycling of WEEE.

According to European Commission (2008), 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. Preparing for reuse is defined as 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. The reuse and preparing for reuse of WEEE can contribute to the reduction of environmental impacts, by saving resources and reducing the pollution associated with recycling or landfill of waste. In addition, from a social or economic point of view, they also have advantages by facilitating access to technology and contributing to the development of a sector that generates employment and wealth (MAGRAMA, 2014, 2015; O'Connell et al., 2013).

However, the application of reuse and preparing for reuse does not always have to be the best option from the environmental point of view (Cooper and Gutowski, 2015; Singhal et al., 2019). On the one hand, because the conditioning, logistics, diagnosis or repair involve an expenditure of energy, resources and materials with negative environmental impacts. On the other hand, because the resulting products can generate a negative impact during their use phase, greater than the equivalent products available on the market.

The aim of the present study is to evaluate the environmental impacts of repurposed products from WEEE and to identify the factors that limit the repurposing of WEEE to be an environmentally preferable alternative. To achieve this objective, a life cycle assessment (LCA) of two repurposed products of widespread use in companies and industries, a programmable logic controller (PLC) and a perimeter security system (PSA), was carried out. A comparative analysis with alternative final disposal scenarios and a sensitivity analysis with different parameters were also performed.

2. Literature review

The LCA has been used in several studies to determine the impacts linked to the end of life of WEEE and establish proposals for management improvement from the environmental point of view. Studies such as those of Biganzoli et al. (2015), Hischier et al. (2005) or Song et al. (2013) focus on evaluating the impacts on different environmental aspects and the benefits of the treatment and recovery of the materials. Other works show that recycling generally has a lower impact compared to other alternatives such as incineration or landfill (Hong et al., 2015; Wäger et al., 2011). Another aspect that has been studied is the collection and logistic of WEEE due to its high variability, which can compromise their environmental benefits (Caudill and Dickinson, 2004; Gamberini et al., 2010; Xu et al., 2013).

Some of these studies focus on WEEE from computers, mainly assessing recycling, incineration or landfill treatments. Most of these studies establish that even though recycling has negative environmental impacts, it is offset to a greater or lesser extent by the environmental benefits of the recovered materials (Andreola et al., 2005; Noon et al., 2011; Soares Rubin et al., 2014). Some authors, consider that there is a great potential to increase environmental benefits if recycling rates for WEEE were increased (Choi et al., 2006; Huisman et al., 2003) or changing the type of materials with which the equipment is manufactured (Mayers et al., 2005). In general, the results of these works show that the LCA is an adequate tool to perform a detailed and objective environmental assessment of final disposal scenarios.

The environmental performance of reuse of WEEE has been compared to other types of treatments more widely used today, such as recycling, incineration or landfill. Studies have shown that reuse is generally better than other alternatives from an environmental point of view (Bressanelli et al., 2020; Dowdell et al., 2000; Williams and Sasaki, 2003). Other works focus on certain types of electrical and electronic equipment (EEE). Thus, Zanghelini et al. (2014) which performed a comparison of three end-of-life scenarios for air compressors, considering their complete life cycle, showed that remanufacturing was the best treatment in all the impact categories studied. Lu et al. (2014) developed a case study related to mobile phones, using the Life Cycle Sustainability Assessment (LCSA) methodology. The results obtained showed that reuse generates greater environmental benefits and greater economic benefits than other scenarios. This study also concludes that the application of this methodology can contribute to a better development of public policies regarding WEEE management. Other studies focus on identifying the key aspects when determining whether reuse is a preferable management option in environmental terms. For this purpose, some authors compare management alternatives of different types of WEEE (Truttmann and Rechberger, 2006) and others study specific cases such as compressors (Biswas et al., 2013), computer screens (Lu et al., 2015), personal computers or mobiles phones (Quariguasi-Frota-Neto and Bloemhof, 2012; Sahni et al., 2010). These studies point to lifespan, energy efficiency and technological innovation as some of the most relevant aspects for a reused product presents fewer environmental impacts than a new one. Fatimah and Biswas (2016) showed that other criteria may also be relevant such as the quality of the materials, the existence of standardized processes or the involvement of specialized workers.

Many of these works focus on Information and Communication Technology equipment (ICT) and identify the lifespan as a key aspect in the success of reuse. However, these studies are relatively recent and have shown the need to expand knowledge regarding environmental aspects, the types of WEEE and the procedures to apply (Bovea et al., 2016).

The aforementioned studies are focused on direct reuse, i.e. for the same purpose as the product was originally intended. However, some authors indicate that the preparing for reuse can contemplate other applications, not necessarily equal to those that the products had in origin (Brezet and Van Hemel, 1997; Cole et al., 2018; Cooper and Gutowski, 2015). Although this type of process has received different denominations, in most cases it has been defined as *repurposing* (Abuzed et al., 2016; Rogers et al., 2013; Schofield et al., 2013). These studies propose the increase of different forms of reuse throughout the supply chain, showing some specific case studies from the technical point of view (Klausner et al., 1998; Kwak et al., 2011; Long et al., 2016). However, so far very few studies have performed a detailed environmental assessment of WEEE management by repurposing. Bobba et al. (2018) and Kim et al. (2019) showed by LCA that the use of repurposed electric vehicle batteries to photovoltaic self-consumption may have environmental benefits in certain circumstances. Zink et al. (2014) focused on mobile phones, concluding that repurposing represents a preferable management option to refurbishing for used smartphones. Among these studies, only one has been identified that studies the repurposing of computers, specifically notebook computers to be used as thin client computers (Coughlan et al., 2018).

3. Methods

In the present study, the LCA methodology has been applied according to the principles and requirements of ISO 14040 and ISO 14044 (ISO, 2006a, 2006b). The SimaPro 8.2 software and the Ecoinvent 3.2, included in this software version, have been used. In accordance with the standards guidelines, the following sections include the objective and scope of the study, the inventory analysis

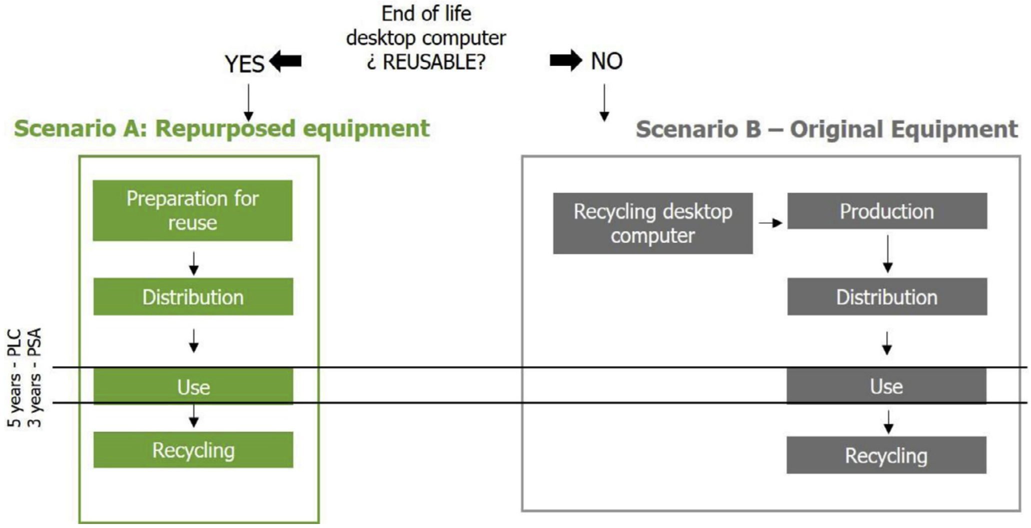

Fig. 1. System boundaries for scenarios A and B.

and the impact assessment method employed as well as its justification

3.1. Goal and scope

The aim of this study is to obtain an environmental impact assessment of two preparing for reuse processes of computers considered as WEEE, whose results are repurposed products with industrial application. Likewise, a comparative study has been carried out with alternative scenarios in which there is no reuse.

The results obtained will allow determining the environmental viability of repurposing of computers. Therefore, it is intended to establish the factors that determine the advantage or disadvantage of reuse scenario compared to other alternatives.

3.1.1. Product system

Two industrial application equipment were studied: a programmable logic controller (PLC) and a perimeter security system (PSA). For each of these products, two scenarios were established to be compared:

Scenario with reuse (Repurposed equipment): The office equipment considered as WEEE are repurposed in order to obtain a product of industrial application. Thus, the system includes the preparing for reuse process, the distribution of the resulting product, its use and the recycling treatment at the end of its lifespan.

Scenario without reuse (Original equipment): It is a system in which computers considered as WEEE is not reused, but is mainly recycled. Therefore, the system includes the manufacture, distribution, use and recycling of a product equivalent to that obtained by repurposing in scenario A, but made from virgin raw materials.

The definition of the system is based on the approach proposed by Zink et al. (2014) for the life cycle assessment of different reuse options. We do not use system expansion to reflect the benefit of reuse, since the objective is to compare it with a scenario in which this option does not exist. According to this approach, Scenario B includes the recycling of an amount of WEEE equivalent to that is repurposed in the scenario A, so that the conditions of scope are equivalent. The combination of both scenarios for the two equipment (PLC and PSA) is shown in Fig. 1.

3.1.2. Function, functional unit and reference flow

In the case of the PLC, the function of the system is to process WEEE and meet the needs of data acquisition and control mechanisms in a distributed system such as the lighting system, heating, etc., of a company or organization. The functional unit corresponds to obtaining a product that covers 5 years of data acquisition service and control of mechanisms in a distributed system and the processing of the WEEE necessary to obtain it by repurposing or recycling an equivalent amount. The reference flow corresponding to each scenario would be:

PLC scenario A: a repurposed equipment that acts as a PLC (R-PLC) and consists of a Central Processing Unit (CPU) that has, at least, a serial port, a network connection, 1 GB of RAM and a hard drive of 40 GB and wiring, with a lifespan of 5 years.

PLC scenario B: an original equipment, manufactured with virgin materials, that acts as PLC (O-PLC), with technical capacity equivalent to the R-PLC and with a lifespan of 10 years.

In the case of PSA, the system has the function of processing WEEE and meeting the intranet protection needs of a company or organization, specifically, an electronic mail and network security system.

The functional unit consists in obtaining an equipment that complies during 3 years of service as a perimeter security system to protect the intranet of a company or organization that has 20 computers and the processing of the WEEE necessary to obtain it by repurposing or recycling an equivalent amount. The reference flow corresponding to each PSA scenario would be:

PSA scenario A: a repurposed equipment that acts as PSA (R-PSA), consisting of a CPU composed of, at least, one 300 W power supply, two network cards, 1GB of RAM, an 80GB hard drive and wiring, with a 3-year lifespan.

PSA scenario B: a combination of two equipment manufactured from virgin materials that act as PSA (O-PSA), with technical capacity equivalent to the R-PSA, consisting of a mail and network security system and with a lifespan of 14 and 20 years, respectively.

The repurposed products consist of prototypes, whose design and viability of application were developed as part of action B.4 of the ECORAEE project (ECORAEE, 2012). Their composition and lifespan were defined by its designers. In the scenarios without reuse (Scenario B), equipment available in the market is considered, manufactured from raw materials, which cover the same functions as the repurposed prototypes, without significantly exceeding them. For this, the technical and environmental information provided by manufacturers was considered.

3.1.3. Assumptions and limitations

The main assumptions and limitations of the study have been the following:

- The use of equipment (repurposed and original) and final disposal stages takes place in Spain. In scenario A, the spatial scope of obtaining equipment by repurposing is also Spain; while in scenario B the equivalent stage corresponds to European and Asian countries, according to the location of the main manufacturers.
- The environmental impacts of obtaining the materials from which the WEEE is composed is not considered, since this impact is attributable to the life cycle of the original equipment from which that waste comes from.
- The lifespan defined for each equipment (repurposed and original), is one in which there are no breakdowns, repairs or replacement of components.
- It is not possible to apply a second process of reuse to the components that have already been reused.
- When an equipment reaches the end of its lifespan and it is not possible to reuse it, all suitable materials are recycled and the rest goes to incineration or landfill.
- The components of WEEE for reuse that are obsolete or damaged are treated by recycling. The impact of their treatment is not taken into account because it is considered to belong to the life cycle of the equipment from which they come.
- The inventory data have been standardized by a factor that relates the lifespan of the repurposed products and the equivalent made with raw materials. In this way, the scenarios to be compared are equivalent. The factor that relates the lifespan of the R-PLC and that of the O-PLC is 0.5 and the factor that relates the lifespan of the R-PSA and that of the O-PSA is 0.2.

3.2. Life cycle inventory

3.2.1. Obtaining equipment

In scenario A, the equipment is obtained from the processing of WEEE from desktop computers, through preparing for reuse processes.

Based on the general requirements of preparing for reuses processes and the technical requirements of the prototypes, specific processes were developed that resulted in these products (ECORAEE, 2012, 2013; Pérez Martínez, 2018). These processes were reproduced on small scale (ECORAEE, 2014), which allowed the direct acquisition of inventory data (Table 1). Detailed data on this inventory can be found in the aforementioned bibliography. The inventory includes the inputs of material and the consumption of products and energy associated with each of the tasks that make up the process. The outputs included repurposed products, components that can be used as spare parts and material for recycling.

To complete the inventory of the manufacturing stage of equivalent equipment in scenario B, its main components and packaging have been considered, based on the information available in technical data sheets and environmental product declarations, which meet the criteria defined in the scope (Table 2).

3.2.2. Distribution

The transport of repurposed equipment to the final customer (scenario A) was established from transport data collected by a local company dedicated to the preparing for reuse of WEEE. According to the data provided, the transport is mostly by road in vans and the average distance traveled is 492 km.

Table 1
Inventory data of obtaining stage of R-PLC and R-PSA through preparing for reuse processes (values are per functional unit).

	R-PLC	R-PSA
INPUTS		
WEEE (kg)	43.4	47.2
Power consumption (kWh)	0.82	0.31
Labels (kg)	7.5×10^{-3}	6.2×10^{-3}
Cleaning material (kg)	1.8×10^{-2}	1.8×10^{-2}
Internet use (hours)	6.1×10^{-2}	0.107
OUTPUTS		
Repurposed(kg)	10.0	11.1
Spareparts(kg)	3.15	3.39
Recycling (kg)	30.25	32.67

Table 2
Type and quantity (kg) of components of O-PLC and O-PSA processes (values are per functional unit).

	O-PLC	O-PSA
Motherboards	0.202	1.43
Hard disks	-	0.575
Power supply and fun	-	3.09
Batteries	0.010	0.002
Wiring	0.060	0.675
Plastic	0.100	0.520
Metal	-	6.77
Paper and cardboard	0.154	3.44

Table 3
Energy consumption (kWh) of the equipment during its lifespan (values are per functional unit).

	R-PLC	R-PSA	O-PLC	O-PSA
Energy consumption	3063	1393	1095	1837

In scenario B, the distribution model is based on that proposed by OĆonnell and Stutz (2010) and Prakash et al. (2012), considering transportation from the main manufacturing sites in Asia and Europe to retailers.

3.2.3. Use

The impact during the use phase is due to the power consumption of the equipment. This consumption has been established based on the power demand, the patterns of use and the lifespan of each product (Table 3). Thus, by means of direct measurement in prototypes, it was determined that the average operating power for the R-PLC and the R-PSA is 70 W and 53 W, respectively. Due to the type of use of the device, the power supply (300 W) should be at full capacity during the workday and in idle or power down mode the rest of the day. The average working power of the O-PLC is 25 W and of the O-PSA is 70 W. These data were obtained from technical sheets and from the information reflected in IVF (2007). Taking into account the studies of Teehan and Kandlikar (2012), the estimated lifespan of the R-PLC is 5 years and that of the R-PSA is 3 years. In the scenario B (without reuse), the same period was considered so that the terms of the comparison were equivalent.

3.2.4. End of life (EoL)

This stage includes the treatment of the equipment at the end of its lifespan, separating the different materials of which the equipment is composed, the recycling of those suitable materials and the elimination of non-recoverable fractions.

Table 4
Types and quantity of materials to recycling, expressed as% of total weight.

	R-PLC	R-PSA	O-PLC	O-PSA
Ferrous metals	12.4	12.4	22.0	22.0
Glass	3.0	3.0	0.08	0.08
Plastic	66.9	66.9	75.0	75.0

The criteria for the selection of processes in the Ecoinvent database that adequately represent the dismantling, segregation and disposal by incineration or landfill of non-recyclable material of WEEE, were those established by Hischier et al. (2007). Likewise, ferrous metals, plastic and glass are considered as potentially recyclable according to the proposal by Hischier et al. (2005, 2007) and MITECO (2019) (Table 4). To reflect the positive effect of this process, system expansion was applied for recycled materials, following the recommendations provided by Ecoinvent.

3.3. *Life cycle impact assessment (LCIA) method*

The ReCiPe at midpoint level methodology with a hierarchist perspective or Recipe Midpoint (H) was used as impact assessment method (European Commission - Joint Research Centre – Institute for Environment and Sustainability, 2010; RIVM, 2020) This method allows a broad assessment of the environmental effects of the different alternatives, which facilitates the analysis of the advantages and disadvantages of repurposing (Bobba et al., 2018). The impact categories analysed are Climate change (CC), Ozone depletion (OD), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Terrestrial ecotoxicity (TET), Freshwater ecotoxicity (FET), Marine ecotoxicity (MET), Ionising radiation (IR), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Metal depletion (MD) and Fossil depletion (FD).

4. Results and discussion

4.1. *Comparative analysis of programmable logic controller (PLC) case study*

The results of the comparison of the environmental impacts of the scenarios with reuse and without reuse (A and B) corresponding to programmable logic controller (PLC) are shown in Fig. 2. The results are expressed in percentage, corresponding 100% to the scenario that presents the highest impact value in each category. Figs. 3–8 also express the results in this way. As can be seen, the scenario without reuse (original-PLC) presents a lower environmental impact in all categories.

To determine the origin of the environmental advantage of scenario B, the differences between the main stages of each scenario were studied in detail (Table 5). The most significant differences were found in the distribution and use stages. The greater weight and the shorter lifespan seem to be the main responsible for the impact of the distribution stage of the R-PLC. The impact of distribution of R-PLC is between 71% and 98% greater than that of the O-PLC, even though the transport of this is international. On the other hand, the greater operating power of the R-PLC is responsible that the scenario with reuse presenting a 64% greater impact in the use stage, since the extension of the lifespan and the pattern of use of both equipment is the same. In the stages of obtaining equipment and end of life, a clear advantage of one scenario over the other is not identified, which seems to be related to the differences in the number and type of components of each equipment. The analysis of the contribution to the impact of the different stages of each scenario reveals that the use stage presents a greater relative contribution in both cases. Therefore, operating power is one of the main factors responsible for the environmental advantage of the scenario without reuse (O-PLC). In addition, its technical characteristics, such as its lower weight and longer life, reinforce the environmental advantage of this scenario.

4.2. *Comparative analysis of perimeter security system (PSA) case study*

The results of the comparative analysis between the scenarios with reuse and without reuse corresponding to the perimeter security system (PSA) are shown in Fig. 3. As can be seen, the scenario with reuse presents a lower environmental impact in all the categories analysed.

The obtaining and use stages of R-PSA have significantly lower impacts than the equivalent stages of O-PSA (Table 6). The components that are part of the R-PSA have no environmental burden, so the impact linked to their obtaining by repurposing it is only because of the processing of WEEE. On the other hand, since the R-PSA does not have demanding technical characteristics, most of the material processed is susceptible to being incorporated into an R-PSA and therefore a relatively small amount of non-reusable material is generated. In relation to the impact associated with the use stage, the parameter that conditions the observed differences is the operating power, being for R-PSA approximately 25% less than that corresponding to O-PSA. The distribution of the R-PSA presents an environmental incidence between 18% and 91% greater than that of the O-PSA. Considering that the weights of both equipment are similar, the longer lifespan of the O-PSA results in a lower impact of its distribution, even if it is international. On the other hand, the difference between the types and quantity of materials that make up each equipment would be responsible for the lack of a clear environmental advantage between the end of life stages of the two scenarios.

When studying the contribution to the impact of each stage, it is observed that the use stage is the most important in both scenarios. In the case of scenario B, manufacturing also has a significant relative contribution to the environmental impacts. This means that operating power and composition are the main factors responsible for the environmental disadvantage of the scenario B (original equipment).

4.3. *Sensitivity analysis*

The comparative analysis of the products under study in both scenarios shows that no option is clearly better in environmental terms. In the case of the PLC, scenario with reuse (scenario A) results in a worse alternative mainly due to the higher operating power. The differences of both products in terms of composition and lifespan also contribute to reinforce the environmental disadvantage of this scenario. In the case of the PSA, the lower operating power of the R-PSA together with the low negative impact of obtaining it, make scenario A the best alternative. This advantage occurs even tough O-PSA has a lifespan of almost six times longer.

Therefore, the usage profile, the composition and the lifespan can be considered as the three main factors that determine the environmental advantage of one scenario versus the other. Zink et al. (2014) have also pointed out these factors as some of the most important when establishing the environmental advantage of a specific reuse scenario. To reinforce this hypothesis and assess more specifically the influence of these three aspects, a sensitivity analysis was performed, as suggested by Bobba et al. (2018) and Kim et al. (2019).

Table 5
Results of environmental impact assessment of PLC case study scenarios, distributed in stages. Positive values represent negative environmental impacts and negative values represent environmental benefits (values are per functional unit).

Impact categories	Units	Repurposed PLC (Scenario A)				Original PLC (Scenario B)					
		Production	Use	Transport	EoL	TOTAL	Production	Use	Transport	EoL	TOTAL
CC	kg CO_2 eq	31.0	1435	10.46	−9.35	1467	15.55	513	2.85	−9.48	522
OD	kg CFC-11 eq	$5.2 \bullet 10^{-6}$	$2.0 \bullet 10^{-4}$	$1.8 \bullet 10^{-6}$	$2.9 \bullet 10^{-7}$	$2.0 \bullet 10^{-4}$	$1.8 \bullet 10^{-6}$	$7.0 \bullet 10^{-5}$	$5.2 \bullet 10^{-7}$	$3.0\ 0 \bullet 10^{-7}$	$7.3\ 0 \bullet 10^{-5}$
TA	kg SO_2 eq	0.13	8.93	0.04	−0.03	9.07	0.11	3.19	0.01	−0.03	3.27
FE	kg P eq	$6.4 \bullet 10^{-3}$	0.45	$2.1 \bullet 10^{-3}$	$-6.4 \bullet 10^{-5}$	0.45	0.07	0.16	$7.5 \bullet 10^{-5}$	$7.3 \bullet 10^{-5}$	0.22
ME	kg N eq	$6.8 \bullet 10^{-3}$	0.30	$2.3 \bullet 10^{-3}$	$-6.6 \bullet 10^{-4}$	0.31	$7.9 \bullet 10^{-3}$	0.11	$5.1 \bullet 10^{-4}$	$-6.4 \bullet 10^{-4}$	0.12
HT	kg 1,4-DB eq	9.45	418	3.09	5.97	436	105.9	149.6	0.12	5.98	262
POF	kg NMVOC	0.18	4.67	0.06	−0.05	4.86	0.07	1.67	0.01	−0.05	1.70
PMF	kg PM10 eq	0.07	3.14	0.02	−0.02	3.22	0.06	1.12	$3.9 \bullet 10^{-3}$	−0.02	1.17
TET	kg 1,4-DB eq	$3.7 \bullet 10^{-3}$	0.10	$1.2 \bullet 10^{-3}$	$3.8 \bullet 10^{-3}$	0.11	$4.6 \bullet 10^{-3}$	0.04	$1.2 \bullet 10^{-4}$	$3.9 \bullet 10^{-3}$	0.04
FET	kg 1,4-DB eq	0.39	66.11	0.12	4.67	71.3	2.15	23.63	$3.8 \bullet 10^{-3}$	4.69	30.5
MET	kg 1,4-DB eq	0.37	57.72	0.12	3.89	62.1	2.03	20.63	$3.8 \bullet 10^{-3}$	3.90	26.6
IR	kBq U235 eq	2.91	621	0.93	0.72	625	1.97	222	0.20	0.37	224
ALO	m^2a	13.34	120.8	0.19	0.07	134	0.99	43.18	$9.2 \bullet 10^{-3}$	0.13	44.3
ULO	m^2a	1.09	10.2	0.34	$2.1 \bullet 10^{-3}$	11.6	0.51	3.63	0.01	$2.1 \bullet 10^{-3}$	4.16
NLT	m^2	0.01	0.19	$3.7 \bullet 10^{-3}$	$6.4 \bullet 10^{-5}$	0.21	$3.4 \bullet 10^{-3}$	0.07	$1.1 \bullet 10^{-3}$	$7.4 \bullet 10^{-5}$	0.07
WD	m^3	0.16	8.89	0.05	−0.19	8.91	0.21	3.18	$5.4 \bullet 10^{-3}$	−0.20	3.19
MD	kg Fe eq	2.66	51.0	0.89	−1.08	53.4	17.80	18.22	0.02	−1.13	34.98
FD	Kg oil eq	10.7	401	3.60	−9.9	4.03	143	0.98	−10.0	138	

Table 6

Results of environmental impact assessment of PSA case study scenarios, distributed in stages. Positive values represent negative environmental impacts and negative values represent environmental benefits (values are per functional unit).

Impact categories	Units	Repurposed PSA (Scenario A)				Original PSA (Scenario B)					
		Production	Use	Transport	EoL	TOTAL	Production	Use	Transport	EoL	TOTAL
CC	kg CO_2 eq	33.5	653	11.59	−10.37	687	66.0	860	8.77	−13.49	921
OD	kg CFC-11 eq	$5.7\bullet10^{-6}$	$8.9\bullet10^{-5}$	$2.0\bullet10^{-6}$	$3.3\bullet10^{-7}$	$9.7\bullet10^{-5}$	$8.0\bullet10^{-6}$	$1.2\bullet10^{-4}$	$1.6\bullet10^{-6}$	$3.7\bullet10^{-7}$	$1.3\bullet10^{-4}$
TA	kg SO_2 eq	0.14	4.06	0.05	−0.04	4.21	0.45	5.35	0.03	−0.05	5.79
FE	kg P eq	$6.7\bullet10^{-3}$	0.20	$2.3\bullet10^{-3}$	$-7.1\bullet10^{-5}$	0.21	0.24	0.27	$2.6\bullet10^{-4}$	$-2.6\bullet10^{-4}$	0.51
ME	kg N eq	$7.3\bullet10^{-3}$	0.14	$2.5\bullet10^{-3}$	$-7.3\bullet10^{-4}$	0.15	0.03	0.18	$1.6\bullet10^{-3}$	$-8.4\bullet10^{-4}$	0.22
HT	kg 1,4-DB eq	9.98	190	3.42	6.63	210	393	251	0.53	7.53	652
POF	kg NMVOC	0.20	2.12	0.07	−0.06	2.33	0.32	2.80	0.04	−0.07	3.09
PMF	kg PM10 eq	0.07	1.43	0.03	−0.02	1.51	0.25	1.89	0.01	−0.02	2.12
TET	kg 1,4-DB eq	$4.0\bullet10^{-3}$	0.05	$1.4\bullet10^{-3}$	$4.2\bullet10^{-3}$	0.06	0.02	0.06	$6.7\bullet10^{-4}$	$5.1\bullet10^{-3}$	0.08
FET	kg 1,4-DB eq	0.40	30.1	0.13	5.19	35.8	8.02	39.7	0.02	5.55	53.2
MET	kg 1,4-DB eq	0.39	26.3	0.13	4.32	31.1	7.70	34.6	0.02	4.61	46.9
IR	kBq U235 eq	3.04	282	1.04	0.80	287	7.89	372	0.61	−0.52	380
ALO	m^2a	14.31	54.9	0.21	0.07	69.5	4.77	72.5	0.04	0.34	77.6
ULO	m^2a	1.18	4.62	0.37	$2.3\bullet10^{-3}$	6.17	2.43	6.09	0.07	$-1.2\bullet10^{-3}$	8.58
NLT	m^2	0.01	0.09	$4.1\bullet10^{-3}$	$7.1\bullet10^{-5}$	0.10	0.02	0.12	$3.4\bullet10^{-3}$	$9.4\bullet10^{-5}$	0.13
WD	m^3	0.17	4.04	0.05	−0.21	4.05	1.03	5.33	0.02	−0.30	6.08
MD	kg Fe eq	2.84	23.2	0.98	−1.20	25.8	82.0	30.6	0.09	−1.78	111
FD	Kg oil eq	11.6	182	3.99	−10.97	17.2	240	3.05	−13.74	247	

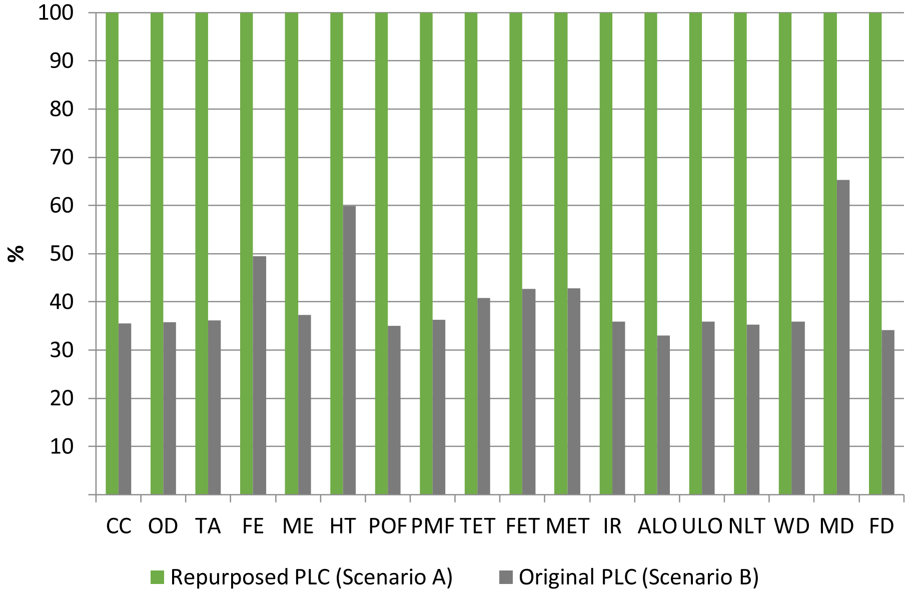

Fig. 2. Comparative environmental impact assessment of PLC case study scenarios. Recipe Midpoint (H), characterization.

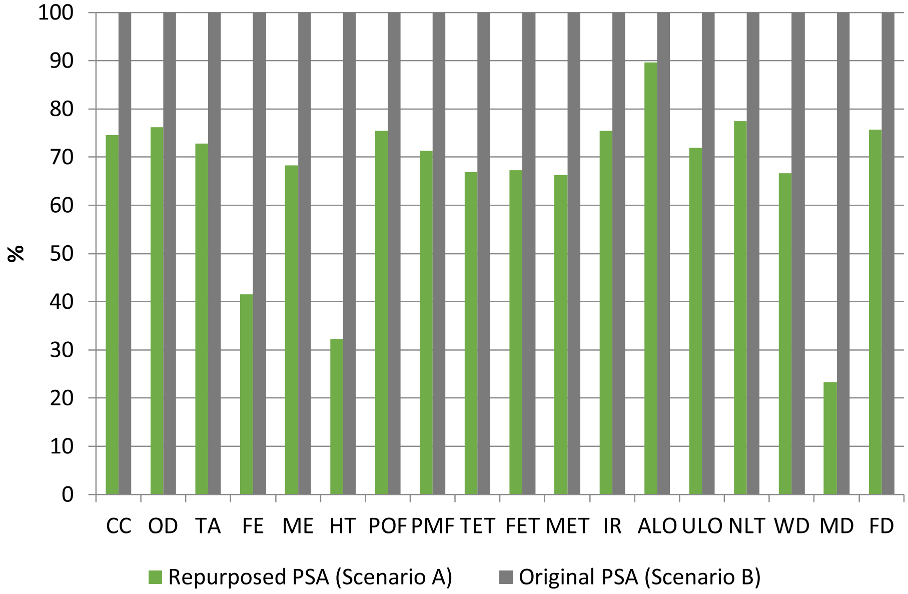

Fig. 3. Comparative environmental impact assessment of PSA case study scenarios. Recipe Midpoint (H), characterization.

First, to evaluate the influence of the lifespan (LS) it has been considered that repurposed products have a lifespan as long as that of the original products (Figs. 4 and 5; Table S1 and Table S2). Under this assumption, there is an increase in the negative effects derived from manufacturing, distribution and final disposal in scenario B, while scenario A remains constant. In the case of the PLC, this alternative slightly reduces the differences between the environmental impacts of scenarios, although the scenario that includes reuse remains the one with the greatest impact. In the case of the PSA, the equalization of the lifespan supposes a slight increase of the environmental advantage of the scenario with reuse.

Second, to assess the effect of the usage profile, the power consumption (PC) of the repurposed product is assumed to be equal to the original equipment (Figs. 6 and 7; Table S3 and Table S4). This situation implies a lower impact of use stage of the PLC in scenario A, but a greater impact in the case of the PSA for this scenario. The results of sensitive analysis show that when the consumptions of the equipment are equal, the differences between the environmental impacts of both scenarios are significantly reduced. In particular, there is a significant decrease in the negative impact in scenario A of the PLC, becoming the least negative impact in many categories, however, in the case of the PSA, the opposite occurs.

Finally, to assess the effect of the composition, a situation is proposed in which the weight (W) of the reused product is equal to that of the original one. This premise is already fulfilled in the PSA case of study, so only its influence has been studied in the case of the PLC (Fig. 8; Table S5). The results show that, when the weight of the products is similar, the environmental advantage of the scenario without reuse decreases, although slightly.

The usage profile is the one that seems to have the greatest influence among the three factors analysed. Therefore, when the energy consumption of the repurposed product is similar to the original, the scenario with reuse significantly reduces its impact. The composition and lifespan can reinforce the environmental advantage, but their contribution is not so significant. Other authors have

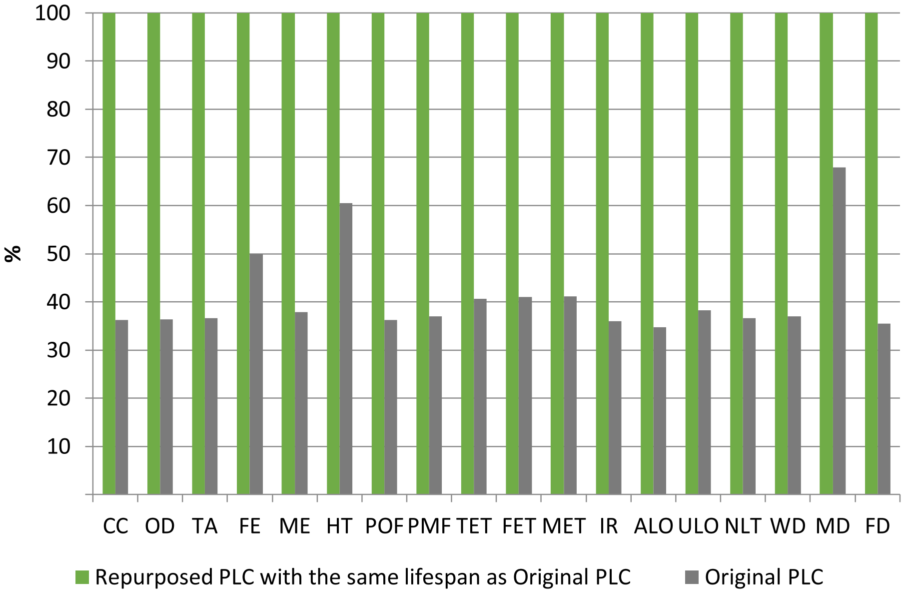

Fig. 4. Sensitivity analysis results when considering the lifespan of the R-PLC equal to that of the O-PLC. Recipe Midpoint (H), characterization.

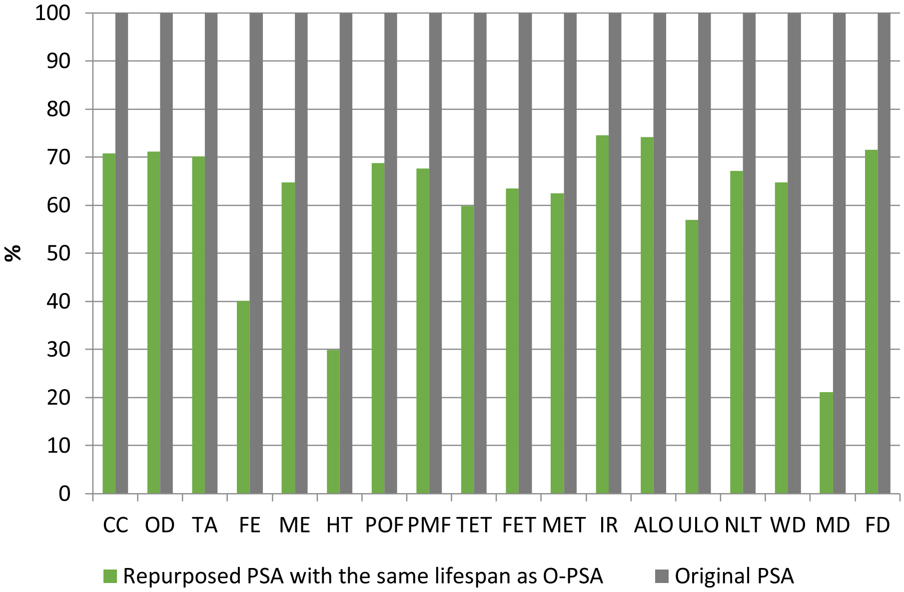

Fig. 5. Sensitivity analysis results when considering the lifespan of the R-PSA equal to that of the O-PSA. Recipe Midpoint (H), characterization.

already highlighted the importance of the lifespan and the energy consumption during use stage when determining whether reuse is the best alternative for the final disposal of WEEE (Biswas et al., 2013; Devoldere et al., 2009; Williams and Sasaki, 2003). However, these works have studied the reuse for the same purpose that had the equipment in origin and only one of them was made for computers. Coughlan et al. (2018) carried out a repurposing study to produce thin client computers using different components from used laptops. Although their work focuses mainly on technical aspects, they carried out a simplified LCA to determine the environmental benefits of this alternative. For this purpose, they analysed only the stages of use and manufacturing and evaluating a single category of impact (Cumulative Energy Demand). The results obtained showed that, although the use is the stage with the greatest effects, the manufacturing phase is where the main environmental benefits of the repurposed products are identified. In this case, the manufacturing of the commercial equipment had an important environmental load in comparison with the repurposed ones and its power consumption is also greater, in a similar way to the studied PSA. Bobba et al. (2018) and Kim et al. (2019) studied by means of LCA the environmental feasibility of the use of repurposed components from WEEE in obtaining solar energy systems; they also identified the profile of use and lifespan as two of the most influential aspects in the environmental advantage of repurposed scenarios.

Taking into account the results of this study, several recommendations can be drawn so that repurposed products are a preferable alternative from an environmental point of view.

In the first place, the product resulting from this type of processes must not have a high energy consumption compared to the alternatives existing in the market, either because they present low intensity usage patterns or because of the inclusion of components that do not have high energy consumption. The repurposed equipment should also have a similar lifespan than its market counterparts, following the proposal of Quariguasi-Frota-Neto and Bloemhof (2012). In this sense, in addition to the application

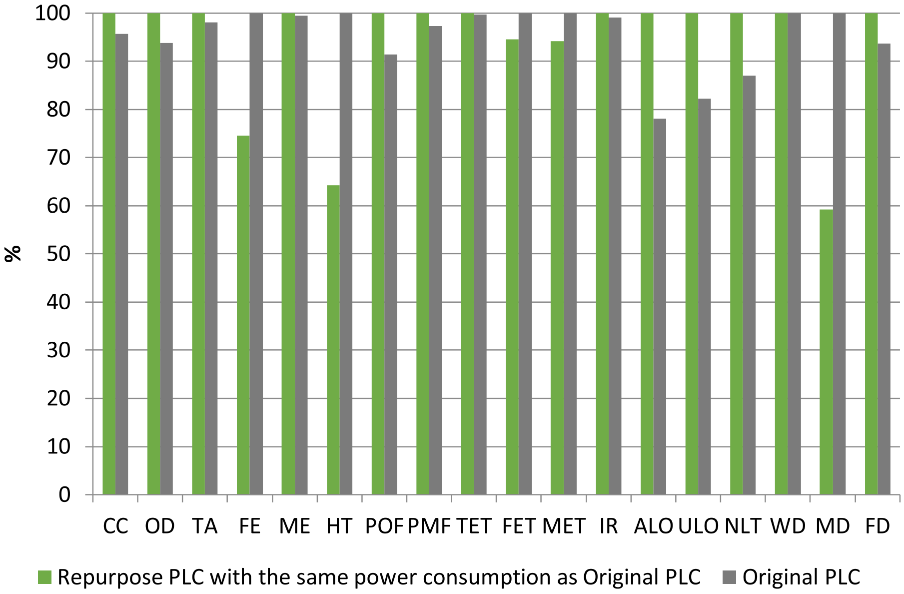

Fig. 6. Sensitivity analysis results considering that the power consumption of the R-PLC is equal to that of the O-PLC. Recipe Midpoint (H), characterization.

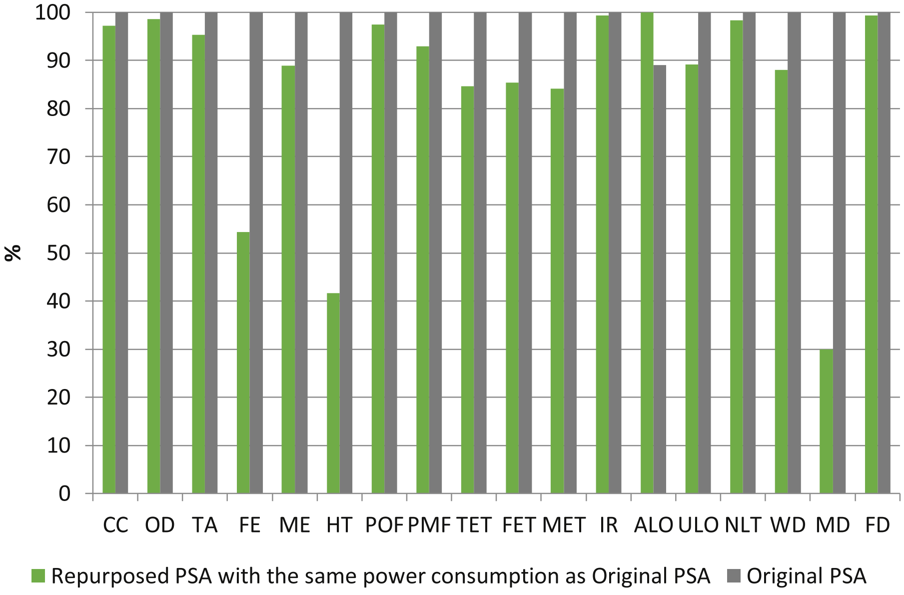

Fig. 7. Sensitivity analysis results considering that the power consumption of the R-PSA is equal to that of the O-PSA. Recipe Midpoint (H), characterization.

of the reused product, the useful life of the device from which its components come should also be evaluated (Kim et al. (2019); Yoshida and Terazono (2010)). It would also be convenient that their technical characteristics (weight, number and type of components) were similar or less demanding than those of commercial alternatives. Zink et al. (2014) studied the environmental performance of repurposed smartphones for use as parking meters. These authors observed that when solar charger was used instead of a conventional battery, the repurposing supposed a greater impact, despite having no negative effects in the use stage. This is due to the important negative impacts associated with the manufacture and transport of the solar charger. Lu et al. (2015) and Sahni et al. (2010) also determined that reuse is effective when market products have characteristics similar to those reused. Additionally, obtaining repurposed products with little demanding technical requirements implies a lower impact of preparing for reuse processes, since the amount of non-reusable material would be reduced. The availability of high quality WEEE could contribute to this objective through specialized selective collection and procedures to preserve the reuse potential of equipment and components (Dindarian and Gibson, 2011; Kissling et al., 2013; Zacho et al., 2018). Other aspect of special interest is that reused products have more functions than market products, since then, to cover the same functions, more than one commercial product would be necessary. This fact would increase the environmental advantage of the repurposed product.

The equipment studied are examples of repurposed equipment widely applied in industry and services sector. PLCs are devices that are used to control processes of various kinds, and their use is widely extended in all those sectors in which process automation and data monitoring are necessary. Second, antivirus, antispam, content control and firewall systems can prevent breakdowns in computer systems that in many cases involve serious losses for companies. Therefore, the perimeter defense system for networks or PSA, are today essential for companies. The results of this study show that it is possible to obtain devices with these applications

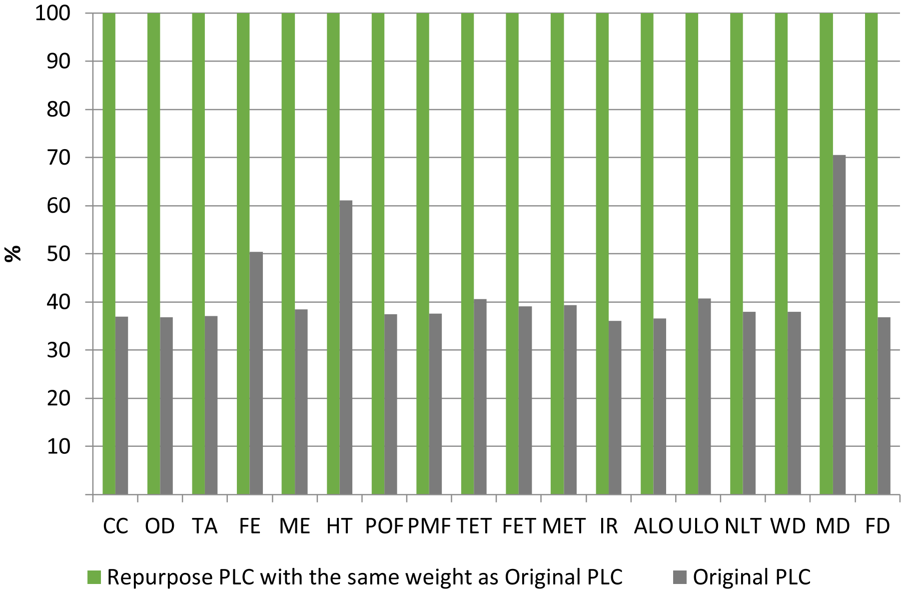

Fig. 8. Sensitivity analysis results when contemplating that the weight of the R-PLC is the same as that of the O-PLC. Recipe Midpoint (H), characterization.

from WEEE repurposing. This obtaining may be environmentally preferable to commercial alternatives manufactured from virgin raw materials if certain factors are taken into account. Thus, the results of this study may be of interest to a wide spectrum of companies and waste management entities, by providing proven information that contributes to expanding their market and possibilities for business improvement.

5. Conclusions

The life cycle assessment of two repurposed products with industrial application and the comparison with alternative scenarios in which there is no reuse has shown that repurposing is not always the best environmental option. This constitutes an important aspect to take into account when developing regulations, strategies and policies in the area of WEEE management since, at present, these instruments always give priority to reuse.

The environmental feasibility of repurposing of WEEE depends on the new application of the product and the alternatives that exist in the market. Mainly it should be taken into account that the usage profile is similar or less intense. Additionally the lifespan should be equivalent or longer and its composition (quantity and complexity of components) similar or lower.

The results of the PSA case study show that a repurposed product from WEEE with lower energy consumption, together with a similar lifespan and composition as the original equivalent product, could present an environmental impact between 25% and 80% less than in scenario without reuse.

The data derived from this work can contribute to optimizing preparing for reuse from an environmental point of view, taking into account the characteristics that the resulting equipment must meet. This can prevent the implementation of WEEE management systems with higher negative environmental impacts than other possible alternatives. On the other hand, we believe that it constitutes a source of information that public institutions can use to develop strategies, plans and regulations that contribute to the efficient use of resources and also to reduce the environmental problems related to the generation and management of WEEE. Finally, it provides specific information of repurposing, a kind of reuse little studied from the environmental point of view. This can encourage the development of new preparing for reuse processes and the placing on the market of new products. In this way, the environmental management of WEEE could be improved and the development of the circular economy is promoted.

Preparing for reuse is a WEEE management alternative that has been little studied, particularly for obtaining repurposed products. Therefore, it would be necessary to expand knowledge regarding the environmental viability of products resulting from processes of preparing for the reuse of WEEE, considering a greater diversity of application alternatives. The results have also shown that these systems can cause significant negative effects in several impact categories. Therefore, another question of interest would be the in-depth study of the main environmental problems and the specific associated processes. Additionally, the development of this reuse sector could also bring economic and social advantages. Therefore, it would be interesting to carry out complementary studies to the LCA, which evaluate the possible contribution of the expansion of the reuse market in these aspects, and thus carry out a complete assessment from the perspective of sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.03.017.

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