Bovea, MD.; Ibáñez-Forés, V.; Perez-Belis, V. (2020). Repair vs. replacement: Selection of the best end-of-life scenario for small household electric and electronic equipment based on life cycle assessment. Journal of Environmental Management. 254:1-14. https://doi.org/10.1016/j.jenvman.2019.109679

REPAIR VS. REPLACEMENT: SELECTION OF THE BEST END-OF-LIFE SCENARIO FOR SMALL HOUSEHOLD ELECTRIC AND ELECTRONIC EQUIPMENT BASED ON LIFE CYCLE ASSESSMENT

María D Bovea, Valeria Ibáñez-Forés, Victoria Pérez-Belis,

Department of Mechanical Engineering & Construction, Universitat Jaume I, Castellón, Spain

ABSTRACT

This study presents a methodology designed for selecting, from an environmental point of view, the best end-of- life scenario for electric and electronic equipment which breaks before the end of its life span. To this end, the environmental impact of the life cycle of the equipment is evaluated for two different end-of-life scenarios: repair & reuse vs. replacement. As a case study, the proposed methodology is applied to a representative sample of nine categories of small household electric and electronic equipment (120 appliances). Repair & reuse scenarios consider the life span and the typical failures and repairs associated with each electric and electronic equipment category and the use of the repaired equipment until the remaining life span after its breakage. Replacement scenarios also consider the life span associated to each electric and electronic equipment category and the replacement of the broken equipment by an equivalent during the remaining life span after its breakage. The environmental impact obtained for both scenarios for each small household electric and electronic equipment category is compared in order to identify the best end-of-life scenario. To do so, the life cycle assessment methodology is applied, using CML and ReCiPe as midpoint- and endpoint-impact assessment methods, respectively. The results indicate that for all the analysed categories, the repair & reuse scenarios generally prove environmentally better than replacement scenarios, as Directive 2012/19/EU promotes. However, for some types of failure, e.g. those related to motors or printed circuit boards, if the failure occurs at the end of its life span, replacement is a better option than repair & reuse, since the environmental impact of the repair activities is not offset by the environmental benefits of extending the useful life until the end of the life span.

Keywords: EEE, Repair Replacement LCA, Environmental performance EoL, End-of-Life

1. Introduction

Reuse of products has become increasingly important within the framework of EU policies since its initial proposal in the Integrated Product Policy (IPP) (COM 68, 2001) until its incorporation into the Circular Economy Package (COM 33, 2017; COM 614, 2015) and the Ecodesign Working Plan 2016–2019 (COM 773, 2016). All these policies aim to encourage the reuse of products by preventing their disposal and by contributing to the extension of their life span.

In addition, Directive 2008/98/EC and Directive 2012/19/EU propose a waste management hierarchy, in which preparation for reuse is preferred to other waste management approaches, such as recycling or waste-to-energy, among others. Moreover, reuse also helps to prevent waste generation, the first option in the waste hierarchy.

According to den Hollander and Bakker (2012), options related to repair, refurbishment or remanufacturing boost the prevention and reuse of products. However, although repair & reuse have long been promoted as an effective way to extend product life span (Bocken et al., 2016) and to enhance resource efficiency (Milios, 2017), this depends on the product category and on the processes needed to return the product to a suitable state (Bovea et al., 2016a; Nußholz, 2017).

Regarding electric and electronic equipment (EEE), van Nes and Cramer (2006) stated that energy-using products should be replaced with more energy-efficient ones more often (even before they are broken) than those that belong to other product categories. In this line, Kim et al. (2006) and Pérez-Belis et al. (2017a) concluded that for refrigerators and vacuum cleaners, respectively, their premature replacement with more energy-efficient equipment could be an effective environmental choice.

Other aspects, apart from the energy efficiency, that can affect the decision on repair & reuse or replacement of EEE are related to the types of repair required by each product (Bovea et al., 2016a), the cost of the repair (Brusselaers et al., 2019; Monier et al., 2016; Kemna et al., 2005), the appearance of the final reused product (Dindarian et al., 2012), consumers' attitude towards repaired products (Bovea et al., 2018b). Iraldo et al., 2017; Perez-Belis et al., 2015, 2017b; Popoff et al., 2016), the existence of waste management policies and practices in the country (de Oliveira Neto et al., 2017; Lu et al., 2018; Morris and Metternicht, 2016; Zacho et al., 2018) or the efficiency of the reuse centres (Devoldere et al., 2006) or reuse networks (Cole et al., 2017), among others. In addition, the potential of repair & reuse of products also depends on the incorporation of disassembly properties in the original product design (Li et al., 2019; Vanegas et al., 2018, 2016).

Abbreviations

ACC	accessories
ANT	anti-slip parts
BLD	blades
CAB	cable
CDR	cable drum
COV	cover
D	distribution
DEPd	dust deposit
DEPw	water deposit
EEE	electric and electronic equipment
EI	environmental impact
EoL	end-of-life
FIL	filter
FILc	coffee maker filter
IPP	integrated product policy
LCA	life cycle assessment
LCD	liquid crystal display
LCI	life cycle inventory
M	mass
MOT	motor
PCB	printed circuit board
PIT	pitcher
PLU	plug
POC	power control
R&R	repair and reuse
REPLACE	replacement
HEA	heating element
SOL	soleplate
SWH	small wheel
SWI	switch button
THE	thermostat
TIN	temperature indicator
TSW	temperature switch
U	use
VEN	ventilator
VSP	vapour spray

Studies with special emphasis on assessing the environmental impact of activities involving the repair and/or reuse of EEE are limited in the literature (Bracquene et al, 2019; Bovea et al., 2018a; Cooper and Gutowski, 2017) and are mainly focused on analysing the environmental consequences of extending lifetime through its reuse by applying the life cycle assessment (LCA) methodology (ISO 14040, 2006; ISO 14044, 2006). Examples include Schischkeet al. (2003) and Gonzalez et al. (2017) for computers, Perez-Belis et al. (2017a) for vacuum cleaners, Baxter (2019) and Lu et al.

(2014) for domestic refrigerators, Devoldere et al. (2006) for washing machines, Zink et al. (2014) for smartphones, Cheung et al. (2018) for video projectors or Pini et al. (2019) for five EEE categories (refrigerator, washing machine, LCD, laptop and fluorescent lamp).

It is observed that, from most of these studies, the reuse process simply implies an extension of the appliance lifetime without taking into account the need for spare parts/components or maintenance/repair operations, which are only considered in Cheung et al. (2018) and Pini et al. (2019). In addition, little attention has been paid in the literature to comparing results between different EEE categories, with the exception of Pini et al. (2019).

By taking this context into account, our study presents a methodology designed for selecting the best end-of-life option, from an environ- mental point of view, for EEE which breaks down before the end of its life span. To this end, two different scenarios are compared: repair and continue using EEE until the end of its life span vs. replacing EEE with an equivalent appliance. Repair & reuse scenarios consider the life span and the typical failures and repairs associated with each electric and electronic equipment category and the use of the repaired equipment until the remaining life span after its breakage. Replacement scenarios also consider the life span associated with each electric and electronic equipment category and the replacement of the broken equipment by an equivalent appliance during the remaining life span after its breakage. The methodology is applied to nine product categories of small house- hold EEE, to observe similarities and differences and common behaviour patterns among them.

This methodology can be useful to facilitate the decision-making process for consumers since they will be able to easily and directly select the best end-of-life option by bearing in mind aspects related to the EEE category, the age of EEE when it breaks down or the type of repair required to fix it.

2. Methodology

The general objective of the proposed methodology is to improve the understanding of the environmental performance associated with different end-of-life scenarios of EEE. Specifically, this methodology is designed for selecting the best option, from an environmental point of view, between repair & reuse or replacing EEE which breaks before the end of its life span. To achieve this, the environmental impact of the life cycle of the equipment is evaluated, by applying the LCA methodology. Fig. 1 shows the proposed three-step methodology.

The content of each stage is described below:

- **Stage I. Scenarios definition**

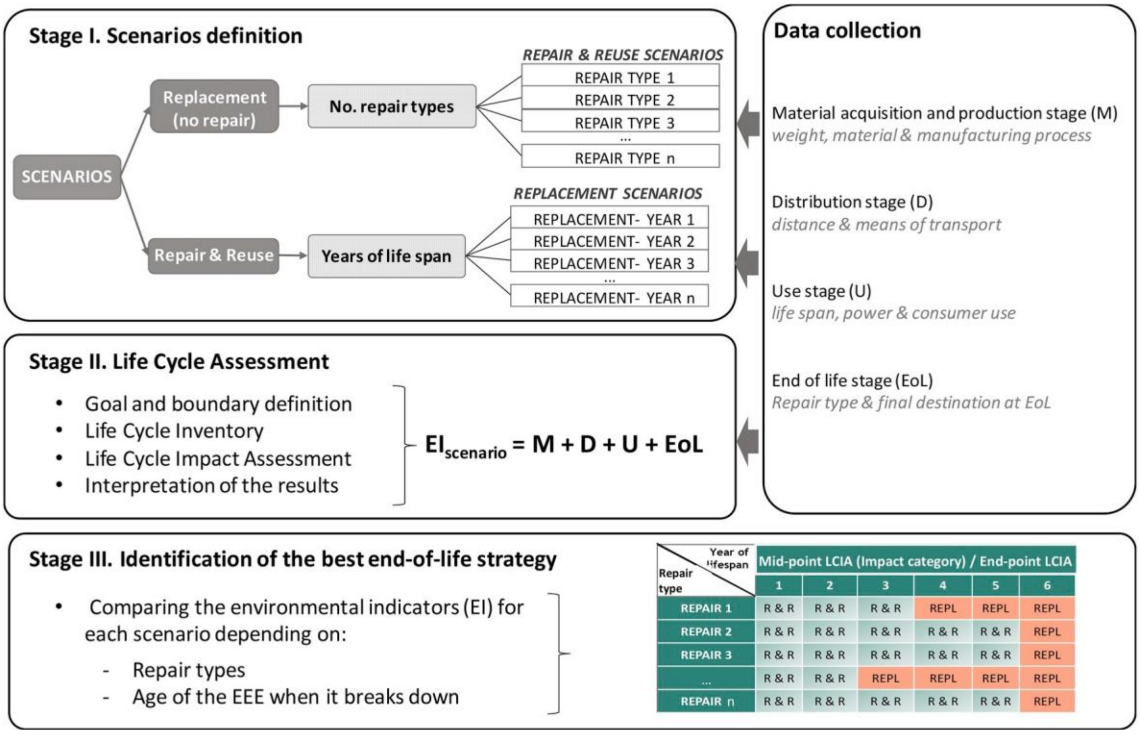
Two different end-of-life scenarios can be defined:

- Repair & reuse scenarios: repairing initial EEE when it breaks down and continuing to use it until the end of its life span. A different scenario will be defined for each potential failure and its corresponding repair operation.
- Replacement scenarios: replacing initial EEE when it breaks down with a new appliance that is equivalent to the replaced equipment. A different scenario will be defined for each year of the life span of the EEE by assuming that EEE can fail at different ages during its life span.

So, on the one hand, the number of replacement scenarios will be the number of lifetime years of the EEE category under study. On the other hand, the number of repair & reuse scenarios will be the number of types of repair identified for the EEE category under study.

- **Stage II. Life Cycle Assessment**

As suggested by Ardente and Mathieux (2014), Bobba et al. (2016), Ciantar and Hadfield (2004) or Socolof et al. (2005), LCA is the recommended methodology for evaluating the environmental performance of each scenario.



Repair type \ Year of lifespan	Mid-point LCIA (Impact category) / End-point LCIA					
	1	2	3	4	5	6
REPAIR 1	R & R	R & R	R & R	REPL	REPL	REPL
REPAIR 2	R & R	R & R	R & R	R & R	R & R	REPL
REPAIR 3	R & R	R & R	R & R	R & R	R & R	REPL
...	R & R	R & R	REPL	REPL	REPL	REPL
REPAIR n	R & R	R & R	R & R	R & R	R & R	REPL

Fig. 1. Methodology.

The goal of this stage is to quantify the environmental impact of each scenario defined in the previous stage of the methodology. The entire life cycle of the EEE for each scenario should be considered, taking into account the following life cycle stages: raw material acquisition, production, use, end-of-life option (repair& reuse vs. replacement) and final treatment/disposal.

The complexity of defining a functional unit when the durability of products is involved has been considered by different authors (Ardente and Mathieux, 2014; Bobba et al., 2016, 2015). According to Bovea et al. (2018a), the functional unit has been defined as the use of an item of EEE during its average life span.

The life cycle inventory (LCI) model consists in a detailed tracking of all in and out flows, including raw resources or materials, energy by type, water, and emissions of specific substances to air, water and land, for each stage of the product system under study (ISO/TS 14048, 2002). As the quality of the LCA study results largely depends on the quality of the LCI data (Bovea et al., 2010; Ibanez-Forés et al., 2011), the use of primary data to define the LCI model combined with the use of secondary data collected from the literature or from public/commercial LCI databases is highly recommendable. Primary data can be obtained from product sample characterisation processes, interviews with manufacturers or repair companies, etc. LCI databases, such as Ecoinvent Data- base (2017), European Life Cycle Database (ELCD, 2017) or the other LCI databases included in LCA software such as SimaPro (2019) or GaBi Software (2019), among others, can be applied to complete the LCI model.

The environmental impact can be obtained by applying life cycle impact assessment (LCIA) methods to the LCI model. According to guidelines ISO 14040 (2006) and ISO 14044 (2006), environmental impacts need to be expressed mandatorily by impact categories using mid-point LCIA methods (IMPACT 2000 (Jolliet et al., 2003), CML (Guinee et al., 2002), EDIP (Potting Hauschild,, 2004; Wenzel and Hauschild, 1998), among others) and, optionally, using end-point LCIA methods (Eco-Indicator’99 (Goedkoop and Spriensma, 2000), Ecological scarcity (Frischknecht et al., 2009), ReCiPe (Goedkoop et al., 2009), among others). For this purpose, an LCA software package (i.e. SimaPro (2019), GaBi (2019), etc.) can be applied.

As a result, different environmental indicators will be obtained for each scenario as the sum of the environmental impact of each stage of the life cycle of the product under study:

- Replacement scenarios: the environmental impact of replacement scenarios (EIREPLACEx) has to consider the environmental impact of the life cycle of initial EEE until it breaks down and the environ- mental impact of replacing EEE, which is proportional to the years left until its life span ends, according to the following equation:

$$EI_{REPLACEMENTx} \text{ ¼ } M_{initial} + D_{initial} + U_{initial} \cdot x + (M_{replacing}/ls)\cdot(ls-x) + D_{replacing} + U_{replacing}\cdot(ls-x) + EoL_{initial}$$

where:

x =1, 2, ..., is the year of the life span when EEE breaks down

ls = average life span (years) of EEE

$M_{initial}/M_{replacing}$ environmental impact of the purchasing raw material & production stage for initial and
replacement EEE $D_{initial}/D_{replacing}$ environmental impact of the distribution stage for initial and replacement EEE
$U_{initial}/U_{replacing}$ annual environmental impact of the use stage for initial and replacement EEE
$EoL_{initial}$ environmental impact of the end-of-life treatment of initial EEE (including the avoided burden that derives from recovering recyclable materials in EEE and the impact of the disposal (landfill) of the remaining materials)

- Repair & reuse scenarios: the environmental impact of the repair and reuse scenarios (EIR&Ry) has to consider the environmental impact of the life cycle of initial EEE until it breaks down, and of the spare parts/components and operations needed for the repair process, according to the following equation:

$$EI_{R\&Ry} = M_{initial} + D_{initial} + U_{initial}\cdot ls + R_y + EoL_{initial}$$

where:

y =1, 2, ..., n– types of repair

Ry = environmental impact of the spare parts/components and operations needed for the repair process

- **Stage III. Identification of best end-of-life scenario**

For specific EEE, the environmental impact of a repair & reuse scenario (EIR&Ry) may be lower or higher than the environmental impact of replacement scenarios (EIREPLACEx), depending on the years of the life span already consumed by the EEE (age of EEE when it breaks down) and the repair type. Hence, to identify the best end-of-life scenario for each EEE, the following comparison needs to be made:

- If the environmental impact of replacing broken EEE in year "x" (IREPLACEx) is higher than the environmental impact of repair type "y" (IR&Ry), repairing the initial EEE and using it until the end of its life span would be the preferable option.
- If the environmental impact of replacing broken EEE in year "x" (IREPLACEx) is lower than the environmental impact of repair type "y" (IR&Ry), replacing the EEE with a more energy-efficient appliance would be the preferable option.

This can be represented in a matrix for each impact category/end- point LCIA method applied, where each row represents the number of types of repair of a specific appliance category and each column represents each year in the life span of that specific appliance category. In this way, selecting the best end-of-life scenario becomes a quick and easy process. For example, from Fig. 2 we observe that if EEE breaks down during year 4 of its life span and the repair type needed is #1, the best end-of-life scenario is Replacement. However, if EEE breaks down during year 3 of its life span and the repair type needed is #2, the best end- of-life scenario is Repair & Reuse.

- **Data collection**

To apply the methodology shown in Fig. 1 to a specific case study, first we should previously collect the information needed to configure the scenarios and to apply the LCA methodology. Specifically, it is necessary to obtain information about the following aspects that cover the life cycle stages of EEE:

- Purchasing material and the production stage (M). It is necessary to identify the weight, material and manufacturing process for each component of the EEE under study.

Distribution stage (D). It is necessary to identify the average distance from the manufacturing location to the point of sale, and the means of transportation used for each journey.
Use stage (U). It is necessary to identify the energy use and the consumables needed while EEE is being used. For this purpose, in- formation about the electric power and the consumer use of EEE is required.
End-of-life stage (EoL). It is necessary to identify the commonest types of repair of the EEE under study, the resources needed for such repairs, and the final destination of the spare parts and the product when its life span ends.

3. Case study

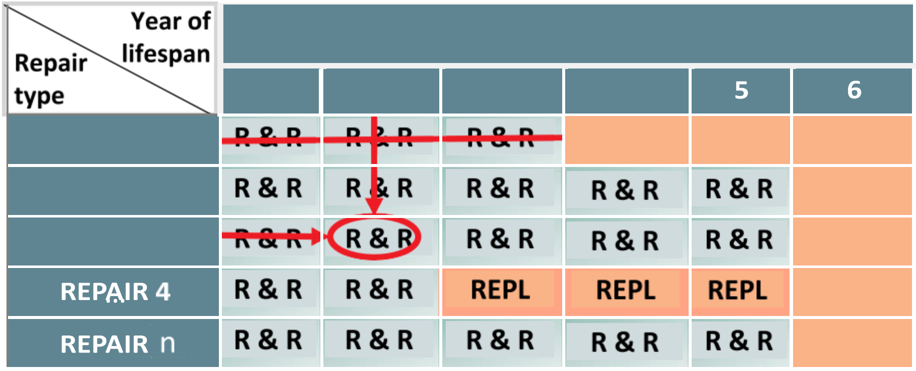
The proposed methodology was applied to a representative sample of nine categories of small household EEE, obtained from a collection campaign designed and implemented in the city of Castellón de la Plana (Spain) (Bovea et al., 2016b). For this case study, 120 of the collected appliances were analysed, from the following nine categories: Vacuum cleaner (7 appliances), Hand blender (17), Coffee maker (13), Heater (7), Juicer (8), Iron (30), Sandwich maker (7), Hair dryer (17) and Toaster (14).

3.1. Data collection

As described in Section 2, it is necessary to collect some information to apply stages I and II of the proposed methodology to the case study. Specifically, the following information is needed to define both scenarios and the LCI model in order to apply the LCA methodology:

- Raw material acquisition and production stage. It is necessary to identify the average weight of material and the manufacturing processes for the components of each EEE category under study. For this case study, the sample came from a selective collection campaign organised in Castellón de la Plana (Spain). A total of 833.7 kg (749 units) of small EEE was collected, of which 23.3% by weight and 22.4% by units belonged to the subcategory small household EEE. After disassembling and characterising a representative sample of the material collected, the data reported in Table 1 were obtained (Bovea et al., 2016b).

- Distribution stage. In relation to the transport of small household EEE from the manufacturing location to the point of sale, for this case study the data reported in Table 2 were assumed: small household EEE is manufactured in Asian countries and is transported to Europe by freighters and then distributed nationally by lorries.



Year of lifespan / Repair type					5	6
	~~R & R~~	~~R & R~~	~~R & R~~			
	R & R	R & R	R & R	R & R	R & R	
	R & R	R & R	R & R	R & R	R & R	
REPAIR 4	R & R	R & R	REPL	REPL	REPL	
REPAIR n	R & R	R & R	R & R	R & R	R & R	

Fig. 2. Matrix representation of results.

Table 1. Average composition of the small household EEE categories (kg) (Bovea et al., 2016b).

			Vacuum cleaner	**Hand blender**	**Coffee maker**	**Heater**	**Juicer**	**Iron**	**Sandwich maker**	**Hair dryer**	**Toaster**
MATERIALS	Plastics	PP	2.1E+00	3.3E-02	4.2E-01	2.7E-01	-	2.0E-01	-	7.0E-04	4,0E-01
		PS	-	-	-	-	-	-	-	-	4,0E-04
		PVC	-	-	-	-	-	3.6E-04	-	2.5E-03	-
		PET	-	-	-	-	-	1.2E-02	-	-	-
		ABS	1.0E+00	1.4E-01	4.1E-03	3.3E-01	4.8E-01	4.0E-02	4.1E-03	6.8E-02	3,3E-03
		PA 6	4.6E-02	3.6E-03	-	-	-	1.3E-03	1.9E-01	-	8,0E-04
		PC	1.9E-02	9.5E-03	-	6.0E-04	2.0E-04	1.9E-02	1.8E-01	6.4E-02	4,8E-02
		POM	-	-	-	1.2E-02	-	1.7E-05	4.2E-05	-	-
		PBT	-	-	-	-	-	7.7E-02	3.9E-02	-	-
		PF	-	-	-	-	-	2.5E-02	1.3E-01	-	-
		TPE	1.5E-03	-	-	-	-	-	-	-	-
		PMMA	6.3E-02	-	-	-	4.4E-02	2.7E-04	-	1.1E-02	1,9E-03
		Others	1.7E-01	3.7E-03	-	-	-	2.6E-03	-	1.2E-03	-
	Ferrous metal		0,00771	7.7E-03	1.3E-02	4.9E-02	4.2E-02	5.6E-03	2.3E-01	6.0E-01	5.7E-03
	Non-ferrous metal		0	-	9.1E-02	-	4.8E-03	-	-	7.9E-01	-
	Paper & cardboard		0,00286	2.9E-03	-	-	1.3E-02	-	-	-	1.8E-03
	Electronic components	Thermostat	-	-	-	1.9E-02	-	5.2E-02	-	-	-
		Plug	2.7E-02	1.8E-02	5.0E-02	3.0E-02	1.7E-02	5.4E-02	5.6E-02	2.4E-02	4,4E-02
		Cable	3.2E-01	4.7E-02	5.0E-02	1.1E-01	4.5E-02	1.1E-01	1.1E-01	5.3E-02	6,6E-02
		Switch	-	-	-	-	-	-	-	-	-
		PCB	4.9E-02	1.1E-02	-	1.9E-02	-	-	-	1.8E-02	5,3E-02
		Engine	1.7E+00	4.4E-01	-	3.0E-01	6.1E-01	-	-	8.4E-02	-
		LED	-	-	-	-	-	-	-	-	-
		Heating element	-	-	8.9E-02	3.8E-01	-	2.8E-01	1.2E-01	1.6E-02	2,7E-02
		Lead	-	-	-	1.3E-03	-	4.3E-03	8.0E-04	-	-
		Power transformer	-	-	-	-	-	-	8.4E-03	-	-
		Relay	-	-	-	-	-	-	-	-	-
		Others	-	-	-	-	-	-	-	-	8,0E-04
	Rubber		-	-	5.9E-04	9.0E-04	-	1.9E-03	6.1E-03	6.4E-03	1.6E-03
	Glass		-	-	-	-	-	-	-	-	-
	Others		0,11571	1.2E-01	-	-	-	-	2.7E-02	-	-
		Total weight	**5,62E+00**	**8,05E-01**	**6.60E-01**	**1.53E+00**	**1.20E+00**	**1.14E+00**	**2.25E+00**	**3.52E-01**	**1.32E+00**
PROCESSES	Injection moulding		3,77884	3.8E+00	1.9E-01	4.2E-01	6.1E-01	5.2E-01	4.0E-01	5.5E-01	1.5E-01
	Shell moulding		-	-	9.1E-02	-	4.8E-03	-	2.2E-01	1.4E+00	-
	Ferro metal extrusion		-	-	-	-	-	-	-	-	-
	Plastic extrusion		-	-	-	9.0E-04	-	1.9E-03	6.1E-03	6.4E-03	1.6E-03
	Paper cutting, folding and gluing		0,00286	2.9E-03	-	-	1.3E-02	-	-	-	1.8E-03
	Screw machining		0,00771	7.7E-03	1.3E-02	4.9E-02	4.2E-02	5.6E-03	1.1E-02	1.6E-02	5.7E-03

Table 2 Data for the distribution stage.

Distribution type	Distance (km)	Means of transport
International	10000	Lorry - 40 t
National	500	Freighter

- Use stage. It is necessary to identify the energy use and consumables needed while small household EEE is being used. Thus, information about the electric power of the equipment and how consumers use it is required. For this case study, the data reported in Table 3 were obtained after conducting a survey with users of small household EEE which aimed to identify current habits and practices as to its use and disposal in Spain (Pérez-Belis et al., 2017b).
- End-of-life stage

It is necessary to identify the end-of-life practices related to the repair & reuse and replacement of small household EEE. Hence, information about the commonest repair types needs to be identified for each small household EEE category analysed. For this case study, the data were obtained after conducting a survey which aimed to examine the awareness and perceptions of reusing small household EEE from the viewpoint of the different stakeholders involved in its end of life: repair centres and second-hand shops. After contacting 222 EEE repair centres in person and by telephone, the data reported in Table 4 was obtained (Bovea et al., 2017).

For each repair type reported in Table 4, Table 5 indicates the material composition and manufacturing processes required for each spare part and repair operation. More details about the specific data for each repair operation can be consulted in Bovea et al. (2018a).

3.2. Scenario definition

After collecting all the information needed to apply the methodology (Fig. 1) to the case study, the repair & reuse scenarios and replacement scenarios can be defined:

- Repair & reuse scenarios can be defined after identifying the commonest repair types for each small household EEE category (Table 4). The number of repair & reuse scenarios will equal the number of repair types (Table 5) after characterising the life span of each small household EEE category, as reported in Table 6.
- Replacement scenarios can be defined after identifying the life span for each small household EEE category (Table 3). The number of replacement scenarios will equal the number of years in the life span of each small household EEE category, as reported in Table 6.

Table 3. Average data on the energy use and consumables needed while each kind of small household EEE is used (Pérez-Belis et al., 2017b).

	Vacuum cleaner	Hand blender	Coffee maker	Heater	Juicer	Iron	Sandwich maker	Hair dryer	Toaster
Life span (years)	7	6	6	9	6	6	7	6	8
Monthly uses (times/month)	1.08Eþ01	8.30Eþ00	1.54Eþ01	2.01Eþ01	8.40Eþ00	8.00Eþ00	7.50Eþ00	8.00Eþ00	1.25Eþ01
Time/use (h)	5.00E-01	5.00E-02	1.60E-01	2.50E-01	5.00E-02	5.00E-01	1.60E-01	8.00E-02	3.00E-02
Power (kW)	1.00Eþ00	6.00E-01	1.00Eþ00	2.00Eþ00	4.00E-02	2.20Eþ00	7.50E-01	2.20Eþ00	9.80E-01
Consumables	filters	–	filters	–	–	–	–	–	–

Table 4. Repair types per small household EEE category (Bovea et al., 2017).

		Vacuum cleaner	**Hand blender**	**Coffee maker**	**Heater**	**Juicer**	**Iron**	**Sandwich maker**	**Hair dryer**	**Toaster**
Repair type	1	MOT	PCB	CAB	VEN	CAB	CAB	CAB	CAB	CAB
	2	FIL	CAB	PLU	PCB	PLU	PLU	PLU	PLU	PLU
	3	CAB	PLU	ACC	CAB		VSP			HEA
	4	PLU	MOT	HEA	PLU		SOL			
	5	DEPd	POC	PIT	MOT		DEPw			
	6	CDR	BLD	COV	TIN		THE			
	7	PCB		SWI	HEA		HEA			
	8	POC		FIL-c			TSW			
	9	SWH		ANT						

3.3. *Life cycle assessment*

3.3.1. Goal and scope definition

The aim of this study is to identify the best end-of-life scenario for different small household EEE categories from an environmental point of view. For each category, two end-of-life options will be analysed: repairing initial small household EEE when it breaks down and continuing to use it until the remaining life span after its breakage (repair & reuse scenarios) *vs.* replacing initial small household EEE when it breaks down with a new appliance that is equivalent to the replaced one during the remaining life span after its breakage (replacement scenarios).

The system boundary for each scenario reported in Table 6 includes all the inputs (raw materials, energy and water) and outputs (airborne, soil and waterborne emissions and solid waste) by characterising each stage of the average life cycle of each small household EEE category, as shown in Fig. 3.

The functional unit selected for the LCA case study corresponds to the use of each of the small household EEE during its entire life span; that is to say, it refers to the use during the average life span that corresponds to the EEE category to which it belongs, from the raw material acquisition and manufacturing stage to its end-of-life treatment. This functional unit has been selected following the recommendations of Bovea et al. (2018a).

3.3.2. Life cycle inventory

The LCI model involves quantifying the input and output flows of each stage considered in the system boundary (Fig. 3) for each small household EEE category. In this way a specific LCI model was drawn up from the primary data that came directly from the characterisation of the appliances (Bovea et al., 2016b) and from surveys carried out to identify consumer habits (Pérez-Belis et al., 2017b) and repair types (Bovea et al., 2017), as reported in Tables 1–5.

The Ecoinvent Database (2017) was applied to complete the LCI model for minor materials, fuel and electricity. Table 1 includes the inventory data needed to model the raw material acquisition and pro- duction stage. By considering these data and those reported in Table 2, Table 7 was obtained to model the inventory data for the distribution stage.

Table 5. Average composition of the repair types reported in Table 4 (Bovea et al., 2018a).

			MOT	FIL	CAB	PLU	DEPd	ACC	PCB	POC	SWH	BLD	ACC	HEA	PIT	COV	SWI	FILc	ANT	FAN	TIN	VSP	SOL	DEPw	THE	TSW
MATERIALS	Plastics	PP									x				x	x	x	x				x		x		
		PVC																				x				
		ABS		x			x	x		x										x						
		PC																			x					x
	Electronic components	Thermostat																							x	
		Plug				x																				
		Cable			x																					
		PCB							x																	
		Engine	x																							
		Heating element												x												
	Ferrous metal											x	x										x			
	Paper & cardboard			x																						
	Rubber																		x							
PROCESSES	Manufacturing	Injection moulding		x			x	x			x				x	x	x	x		x	x	x		x		x
		Shell moulding								x													x			
		Ferro metal extrusion											x													
		Plastic metal extrusion																	x			x				
	Repair	Welding			x				x																	
		Glued																					x			
		Manual assembly	x	x			x			x																

Table 6. Number of scenarios for each small household EEE category.

	Vacuum cleaner	Hand blender	Coffee maker	Heater	Juicer	Iron	Sandwich maker	Hair dryer	Toaster
Repair & reuse scenarios	9	6	9	7	2	8	2	2	3
Replacement scenarios	7	6	6	9	6	6	7	6	8

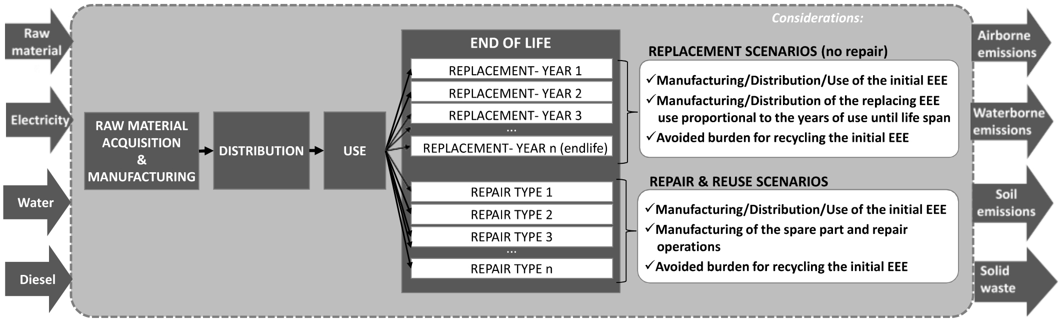


Fig. 3. System boundary for each scenario.

Table 7. LCI data for the distribution stage (tkm per functional unit).

	Vacuum cleaner	Hand blender	Coffee maker	Heater	Juicer	Iron	Sandwich maker	Hair dryer	Toaster
Transport Lorry - 40 t (tkm)	2.81Eþ00	4.03E-01	3.30E-01	7.65E-01	6.02E-01	5.70E-01	1.12Eþ00	1.76E-01	6.58E-01
Transoceanic ship (tkm)	5.62Eþ01	8.05Eþ00	6.60Eþ00	1.53Eþ01	1.20Eþ01	1.14Eþ01	2.25Eþ01	3.52Eþ00	1.32Eþ01

Table 8. LCI data for the use stage (per functional unit).

	Vacuum cleaner	Hand blender	Coffee maker	Heater	Juicer	Iron	Sandwich maker	Hair dryer	Toaster
Electric use (kWh/life span)	4.54Eþ02	1.79Eþ01	1.77Eþ02	4.52Eþ02	1.21Eþ00	6.34Eþ02	7.56Eþ01	1.01Eþ02	3.53Eþ01

Table 9. Substitution ratios of the recycled materials (based on Rigamonti et al (2009)).

	Substitution ratios
Ferrous/Non-ferrous metal	1:1
Paper/cardboard	1:0.833
Plastic	1:0.81
Glass	1:1

Table 8 reports the inventory data for the use stage, which were calculated by taking into account the data reported in Table 3 on the consumer use and average power of the small household EEE categories. According to Table 3, only the vacuum cleaner and coffee maker categories use consumables (filters) during the use stage of their life cycle. The manufacturing process of the respective filters considers not only their production but also their manual assembly inside the equipment, as detailed by Bovea et al. (2018a). The environmental impact of this process has been modelled based on inventory data from Ecoinvent Database (2017).

To model the end-of-life stage, the final destination of initial EEE (for replacement and repair & reuse scenarios) and the spare parts (for the repair & reuse scenarios) was taken into account. The recycling model for the recyclable materials from discarded EEE considered the burdens due to the recycling process itself and the burdens avoided from the saved/replaced raw material by taking into account the substitution ratios reported in Table 9.

3.3.3. Life cycle impact assessment

The LCA methodology was applied to obtain the environmental performance of each alternative scenario and they were modelled using SimaPro Software (2019). As mandatory elements according to ISO 14040 (2006) and ISO 14044 (2006), the CML method (Guineé et al., 2002) was selected as the mid-point LCIA method, which proposes the following impact categories with the following units considered for each one: acidification (kg SO_2 eq), eutrophication (kg PO_4^{3-} eq), global warming (kg CO_2 eq), ozone layer depletion (kg CFC-11 eq), photo- chemical oxidation (kg C_2H_2 eq) and human toxicity (kg 1,4-DB eq). As an optional element according to ISO 14040 (2006), the ReCiPe method (Goedkoop et al., 2009) was selected as the end-point LCIA method.

Applying not only mid-point but also end-point LCIA methods, that is to say, conducting a sensitivity analysis on the LCA study, makes it possible to estimate the effects of the choice made regarding the LCIA methods applied to the environmental indicators. According to ISO 14044 (2006), it is relevant for reaching consistent conclusions and recommendations.

Fig. 4 shows the results obtained for each life cycle stage analysed and for each small household EEE category for the ReCiPe LCIA end- point method. Figures A1-A9 in the Supplementary Material show the analogous results for each small household EEE and for each impact category considered in the CML mid-point LCIA method.

Note that details of the variability of the impact contribution for each small household EEE analysed (120 appliances), instead of the average for each EEE category, can be consulted in Bovea et al. (2018a) for both the CML and the ReCiPe LCIA methods.

3.3.4. Interpretation of the results

An analysis of the results shown in Fig. 4 and Fig A1-A9 in the Supplementary Material shows that the life stages with the highest environmental impact depend on the small household EEE category. However, a general pattern can be observed taking into account the results for the different impact categories of the mid-point LCIA method or of the end-point LCIA method applied and for the different small household EEE categories analysed. Generally, it can be observed that the use and the raw material acquisition and manufacturing stages are the ones with the highest environmental impact, while the environ- mental impact of the distribution stage is negligible compared to the others. The main differences between the replacement and the repair & reuse scenarios are to found in the end-of-life stage. The environmental impact of this stage is usually lower for repair & reuse scenarios, except for types of repair that involve the substitution of the PCB or motor. In addition, for the global warming and human toxicity impact categories, it is found that the avoided burdens from recycling the equipment at the end of its entire lifetime always offset the environmental impact associated to the end-of-life stage for the repair & reuse scenarios, that is to say, the impact of repairing and reusing operations. So, for these impact categories the repair & reuse of broken equipment always makes a lower contribution to the impact than its replacement with an equivalent appliance.

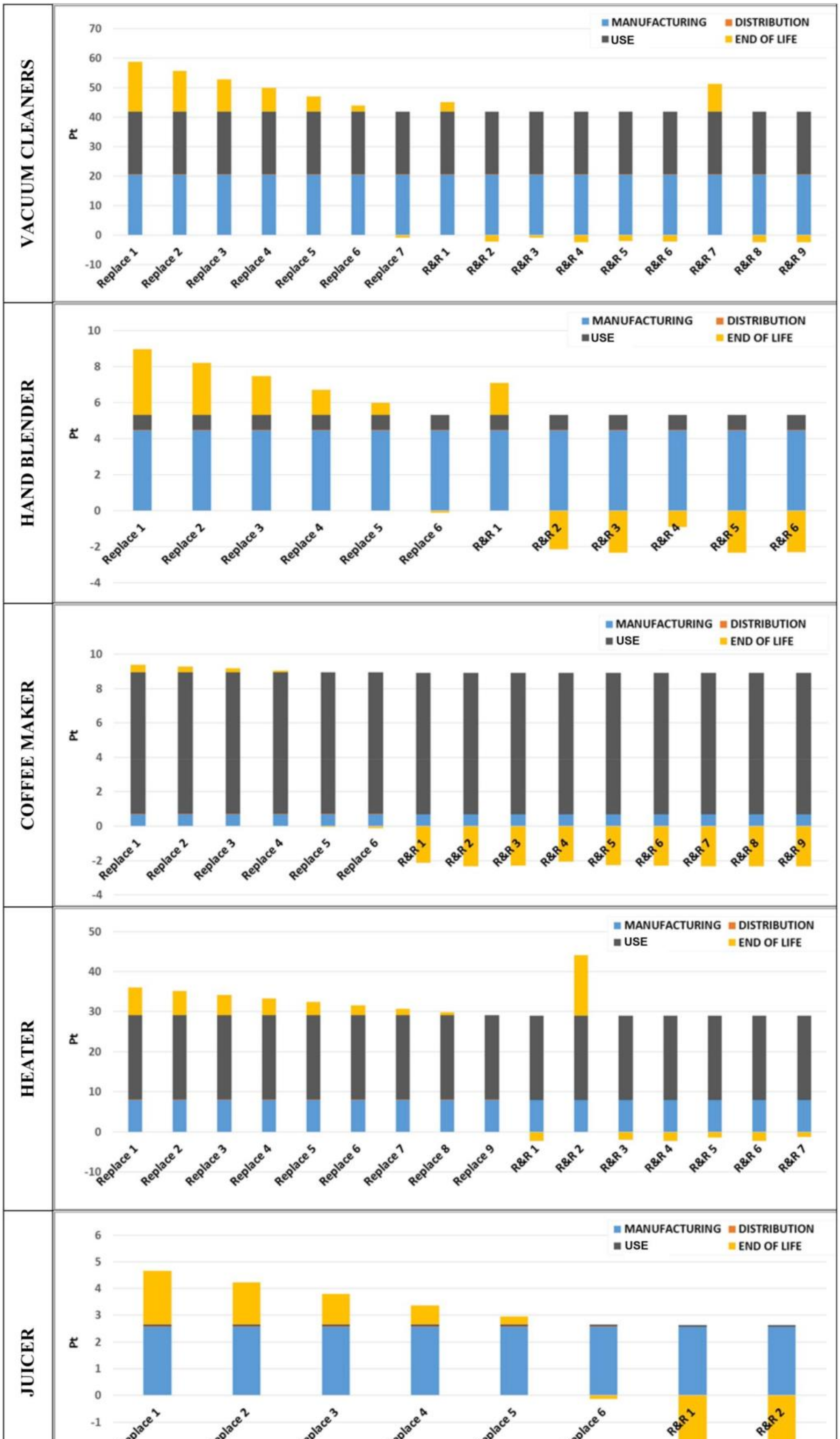


Fig. 4. LCA results for each small household EEE category for the ReCiPe end-point LCIA method (per functional unit).

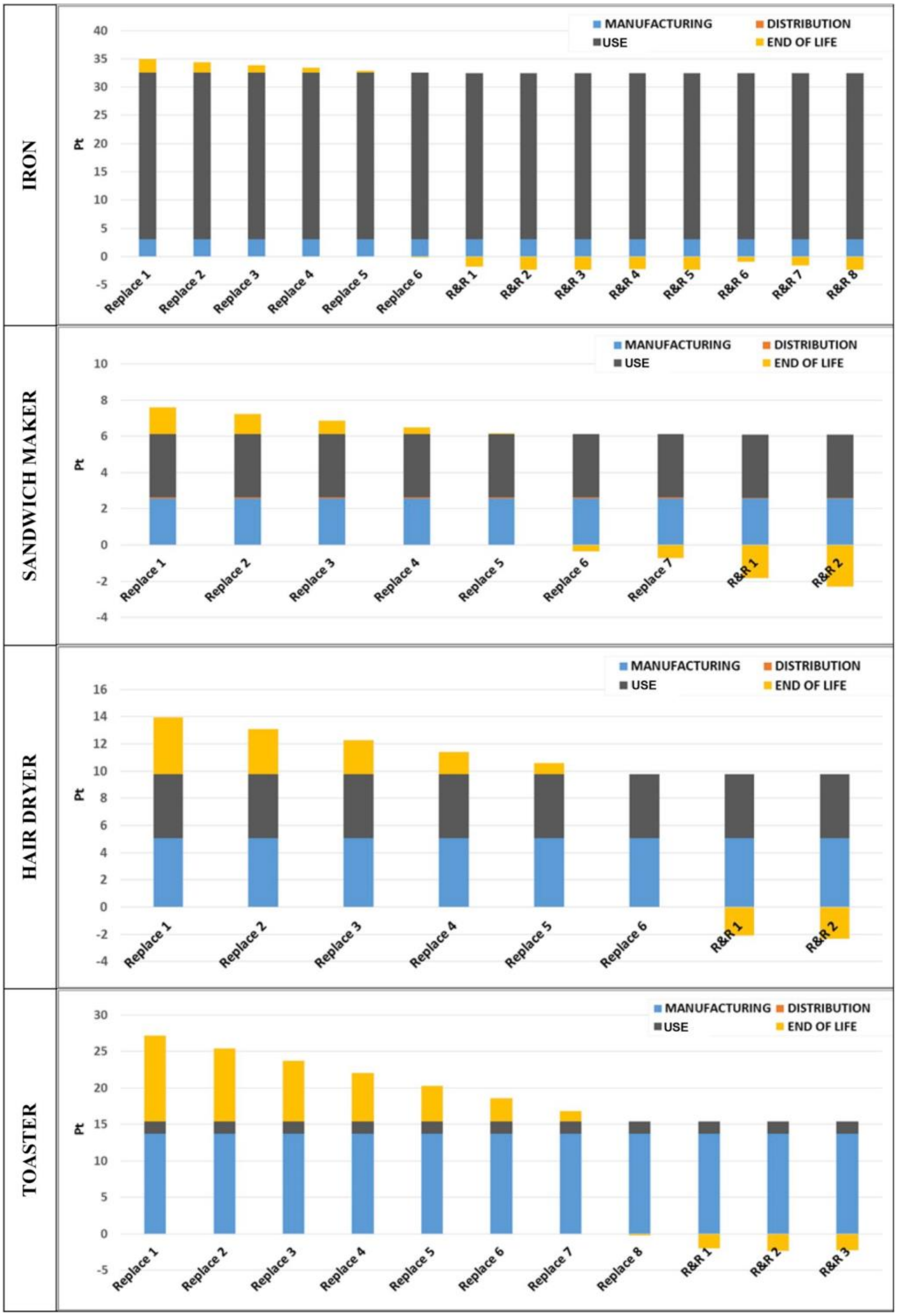


Fig. 4. (*continued*).

Table 10. The best end-of-life scenario for each small household EEE for the ReCiPe end-point LCIA method .

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
VACUUM CLEANERS	**Repair type 1**	R & R	R & R	R & R	R & R	R & R	REPLACE	REPLACE		
	Repair type 2	R & R	R & R	R & R	R & R	R & R	R & R	R & R		
	Repair type 3	R & R	R & R	R & R	R & R	R & R	R & R	R & R		
	Repair type 4	R & R	R & R	R & R	R & R	R & R	R & R	R & R		
	Repair type 5	R & R	R & R	R & R	R & R	R & R	R & R	R & R		
	Repair type 6	R & R	R & R	R & R	R & R	R & R	R & R	R & R		
	Repair type 7	R & R	R & R	R & R	REPLACE	REPLACE	REPLACE	REPLACE		
	Repair type 8	R & R	R & R	R & R	R & R	R & R	R & R	R & R		
	Repair type 9	R & R	R & R	R & R	R & R	R & R	R & R	R & R		

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
HAND BLENDER	**Repair type 1**	R & R	R & R	R & R	REPLACE	REPLACE	REPLACE			
	Repair type 2	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 3	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 4	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 5	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 6	R & R	R & R	R & R	R & R	R & R	R & R			

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
COFFEE MAKER	**Repair type 1**	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 2	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 3	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 4	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 5	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 6	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 7	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 8	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 9	R & R	R & R	R & R	R & R	R & R	R & R			

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
HEATER	**Repair type 1**	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R
	Repair type 2	REPLACE	REPLACE	REPLACE	REPLACE	REPLACE	REPLACE	REPLACE	REPLACE	REPLACE
	Repair type 3	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R
	Repair type 4	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R
	Repair type 5	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R
	Repair type 6	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R
	Repair type 7	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
JUICER	**Repair type 1**	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 2	R & R	R & R	R & R	R & R	R & R	R & R			

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
IRON	**Repair type 1**	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 2	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 3	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 4	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 5	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 6	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 7	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 8	R & R	R & R	R & R	R & R	R & R	R & R			

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SANDWICH MAKER	**Repair type 1**	R & R	R & R	R & R	R & R	R & R	R & R	R & R		
	Repair type 2	R & R	R & R	R & R	R & R	R & R	R & R	R & R		

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
HAIR DRYER	**Repair type 1**	R & R	R & R	R & R	R & R	R & R	R & R			
	Repair type 2	R & R	R & R	R & R	R & R	R & R	R & R			

		YEAR OF LIFE SPAN								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
TOASTER	**Repair type 1**	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	
	Repair type 2	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	
	Repair type 3	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	

3.3.5. Identification of best end-of-life scenario

Once the environmental indicator had been obtained for the replacement scenarios ($EI_{REPLACEMENTx}$) according to Eq. (1) and the repair & reuse scenarios ($EI_{R\&Ry}$) according to Eq. (2), they were compared depending on the life span years of the EEE that had already elapsed (age of EEE when it breaks down) and the repair type. So in order to identify the best end-of-life scenario for each EEE, the following comparison needs to be made:

- If $EI_{REPLACEMENTx}$ (replacing the broken EEE in year "x" with equivalent equipment) is higher than $EI_{R\&Ry}$ (repairing EEE with repair type "y" and continuing to use it until the end of its life span), the preferable scenario is repair & reuse (R&R in Table 10 and Tables A1- A9 in the Supplementary Material).
- If $EI_{REPLACEMENTx}$ (replacing the broken EEE in year "x" with equivalent equipment) is lower than $EI_{R\&Ry}$ (repairing EEE with repair type "y" and continuing to use it until the end of its life span), the preferable scenario is replacement (REPLACE in Table 10 and Tables A1-A9 in the Supplementary Material).

Although the results depend on the small household EEE category and the LCIA method applied, a general pattern was observed when analysing the results reported in Table 10 and Tables A1-A9 in the Supplementary Material:

- For any failure in the first 3 years of the life span of EEE, the Repair & Reuse scenario has a lower environmental impact than the Replacement scenario, so repair is clearly preferred.
- When analysing the influence of failure type on the results, we observe that failures related with Printed Circuit Boards (PCB), which are present in the categories vacuum cleaner, hand blender and heater, offer better environmental performance in the replace- ment scenarios for all the impact categories, no matter what its age is when the EEE fails. This is because the impact that results from repairing PCB or motors is higher than when new EEE is obtained. For the same small household EEE categories, when a motor fails in the last 2 years of the life span of EEE, the replacement scenarios are still preferable to the repair ones.

4. Conclusions

This paper proposes a methodology based on LCA, the aim of which is to identify the best end-of-life scenario (repair & reuse vs. replace- ment) for different EEE categories depending on the repair type and the age of the equipment when it fails. This is one of the main contributions of the methodology, since it makes it possible to consider the environ- mental impact of the need for spare parts/components or maintenance/ repair operations for each specific failure and for each specific EEE category.

Although the proposed methodology can be applied to any category of energy-using products, the case study presented here considered 120 appliances belonging to nine different small household EEE categories. This has allowed representative results to be obtained for such categories. Except for Pini et al. (2019), who consider five EEE categories, the current literature usually only compares end-of-life scenarios for one EEE category and only one appliance in each of them.

The results indicate that for all the analysed categories, the repair & reuse option generally proves environmentally better than replacement, as Directive 2012/19/EU promotes and in line with some previous LCA results on reuse (Cheung et al., 2018; González et al., 2017; Schischke et al., 2003). However, for some failures, e.g. those related to the motor or printed circuit boards, if they occur in a later product life cycle stage, it is better to replace the equipment, as the environmental impact from their repair operations is so high than it does not offset the increase in the number of years of useful life obtained. These results are also in line with Pini et al. (2019), whose results showed that reuse is a preferable option depending on which set of components are replaced, and with Lu et al. (2017), who found that reuse could be a reasonable option for part of a product, but not necessarily suitable for the whole product.

The results of this study are presented using a comprehensible easy- to-use colour code that can serve as a basis for the future preparation of a decision-making tool for selecting the best end-of-life strategy depending on two variables (type of failure and year of breakage) for each EEE category. The interpretation of the resulting matrix does not require any scientific background. This study has also contributed to obtaining better knowledge of the environmental behaviour of the entire life cycle of small household EEE in Spain, comparing two different end-of-life alternatives. It can also be used to target suitable audiences for future awareness campaigns aimed at promoting the extension of the life span of EEE through repairs and the purchase of second-hand appliances.

However, differences in the environmental performance from one end-of-life scenario to another are affected by several factors such as the energy class of the equipment, the new life span of the repaired equip- ment or the equipment that replaces it (Lu et al., 2017), or even the decreased efficiency of worn-out products and the technological progress embodied in new ones (Devoldere et al., 2006). Our case study can therefore be extended by changing some assumptions made in the scenario definition process (i.e. replacement with more energy efficient EEE, extending the life span after repairing, etc.) or certain assumptions made in the LCA study (i.e. changing the functional unit so as to intro- duce changes in the life span or sensitivity analysis for the LCI model). Since, to date, few LCA studies have investigated reuse, this study is thus of value and future research could focus on including economic and social conditions when comparing scenarios in order to choose the best end-of-life option according to sustainability principles.

Acknowledgments

The authors are grateful to the Spanish Ministerio de Economía y Competitividad, Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad for funding for this study (Project DPI2013-40815-R).

References

Ardente, F., Mathieux, F., 2014. Environmental assessment of the durability of energy- using products: method and application. J. Clean. Prod. 74, 62–73. https://doi.org/ 10.1016/j.jclepro.2014.03.049.

Baxter, J., 2019. Systematic environmental assessment of end-of-life pathways for domestic refrigerators. J. Clean. Prod. 208, 612–620. https://doi.org/10.1016/j. jclepro.2018.10.173.

Bobba, S., Ardente, F., Mathieux, F., 2016. Environmental and economic assessment of durability of energy-using products: method and application to a case-study vacuum cleaner. J. Clean. Prod. 137, 762–776. https://doi.org/10.1016/j. jclepro.2016.07.093.

Bocken, N.M.P., de Pauw, I., Bakker, C., Van Der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Bovea, M.D., Pérez-Belis, V., Quemades-Beltrán, P., 2017. Attitude of the stakeholders involved in the repair and second-hand sale of small household electrical and electronic equipment: case study in Spain. J. Environ. Manag. 196, 91–99. https:// doi.org/10.1016/j.jenvman.2017.02.069.

Bovea, M.D., Ibáñez-Forés V., Gallardo, A., Colomer-Mendoza, F.J., 2010.

Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study. Waste Manag. 30, 2383–2395. https://doi.org/ 10.1016/j.wasman.2010.03.001.

Bovea, M.D., Ibáñez-Forés V., Juan, P., Pérez-Belis, V. Braulio-Gonzalo, M., 2018.

Variables that affect the environmental performance of small electrical and electronic equipment. Methodology and case study. J. Clean. Prod. 203, 1067–1084. https://doi.org/10.1016/j.jclepro.2018.08.240.

Bovea, M.D., Ibáñez-Forés V, V., Pérez-Belis, V., Juan, P., 2018. A survey on consumers'

attitude towards storing and end of life strategies of small information and communication technology devices in Spain. Waste Manag. 71, 589–602. https:// doi.org/10.1016/j.wasman.2017.10.040.

Bovea, M.D., Ibáñez-Forés V, Pérez-Belis, V., Quemades-Beltrán, P., 2016. Potential

reuse of small household waste electrical and electronic equipment: methodology and case study. Waste Manag. 53, 204–2017. https://doi.org/10.1016/j. wasman.2016.03.038.

Bovea, M.D., Pérez-Belis, V., Ibáñez-Forés V., Quemades-Beltrán P., 2016. Disassembly properties and material characterisation of household small waste electric and electronic equipment. Waste Manag. 53, 225–236. https://doi.org/10.1016/j. wasman.2016.04.011.

Bracquené, E., Dewulf, W., Duflou, J., 2019. Sustainability assessment of product lifetime extension through increased repair and reuse. In: Proceedings of the Product Lifetimes and the Environment (PLATE) Conference.

Brusselaers, J., Bracquené, E., Peeters, J., Dams, Y., 2019. Economic consequences of

consumer repair strategies for electrical household devices. In: Proceedings of the Product Lifetimes and the Environment (PLATE) Conference.

Cheung, C.W., Berger, M., Finkbeiner, M., 2018. Comparative life cycle assessment of re- use and replacement for video projectors. Int. J. Life Cycle Assess. 23, 82–94. https://doi.org/10.1007/s11367-017-1301-3.

Ciantar, C., Hadfield, M., 2004. A study of tribological durability with associated environmental impacts of a domestic refrigerator. Mater. Des. 25, 331–341. https:// doi.org/10.1016/j.matdes.2003.10.016.

Cole, C., Gnanapragasam, A., Cooper, T., 2017. Towards a circular economy: exploring routes to reuse for discarded electrical and electronic equipment. Procedia CIRP 61, 155–160. https://doi.org/10.1016/j.procir.2016.11.234.

COM 33, 2017. The Implementation of the Circular Economy Action Plan. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

COM 614, 2015. Closing the Loop: an EU Action Plan for the Circular Economy.

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

COM 68, 2001. Green Paper on Integrated Product Policy. Commission of the European Communities.

COM 773, 2016. Ecodesign Working Plan 2016-2019. Communication from the European Commission.

Cooper, D.R., Gutowski, T.G., 2017. The environmental impacts of reuse: a review. J. Ind. Ecol. 21, 38–56. https://doi.org/10.1111/jiec.12388.

de Oliveira Neto, G.C., de Jesus Cardoso Correia, A., Schroeder, A.M., 2017. Economic and environmental assessment of recycling and reuse of electronic waste: multiple case studies in Brazil and Switzerland. Resour. Conserv. Recycl. 127, 42–55. https:// doi.org/10.1016/j.resconrec.2017.08.011.

den Hollander, M.C., Bakker, C. a, 2012. A business model framework for product life extension. In: Proceedings of Sustainable Innovation. Resource Efficiency, Innovation and Lifestyles, pp. 110–118.

Devoldere, T., Dewulf, W., Willems, B., Duflou, J.R., 2006. The eco-efficiency of reuse centres critically explored - the washing machine case. In: Proceedings of the 13th Edition of the CIRP International Conference on Life Cycle Engineering, pp. 265–285.

Dindarian, A., Gibson, A.A.P., Quariguasi-Frota-Neto, J., 2012. Electronic product returns and potential reuse opportunities: a microwave case study in the United Kingdom. J. Clean. Prod. 32, 22–31. https://doi.org/10.1016/j.jclepro.2012.03.015.

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives.

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE).

Ecoinvent Database, 2017. http://www.ecoinvent.org/. ELCD, 2017. http://eplca.jrc.ec.europa.eu/ELCD3/.

Frischknecht, R., Steiner, R., Jungbluth, N., 2009. The Ecological Scarcity Method – Eco- Factors 2006. A Method for Impact Assessment in LCA. Environmental Studies No. 0906. Federal Office for the Environmental. Berne, Switzerland.

GaBi Software, 2019. http://www.gabi-software.com.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2009. ReCiPe 2008 First Edition Report I: Characterisation. Ministerie van VROM. Den Haag, Netherlands.

Goedkoop, M., Spriensma, R., 2000. The Eco-Indicator 99-A Damage Oriented Method for Life Cycle Impact Assessment-Methodology Annex. PRée Consultants, Amersfoort: Netherlands.González, X.M., Rodríguez, M., Pena-boquete, Y., 2017. The social benefits of WEEE re- use schemes. A cost benefit analysis for PCs in Spain 64, 202–213. https://doi.org/ 10.1016/j.wasman.2017.03.009.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. de, Oers, L. van,

Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., Bruijn, H. de, Duin, R. van, Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. I: LCA in Perspective. IIa: Guide. IIb: Operational Annex. III: Scientific Background (Dordrecht: Netherlands).

Ibáñez-Forés, V., Bovea, M.-D., Simó, A., 2011. Life cycle assessment of ceramic tiles.

Environmental and statistical analysis. Int. J. Life Cycle Assess. 16, 916–928. https:// doi.org/10.1007/s11367-011-0322-6.

Iraldo, F., Facheris, C., Nucci, B., 2017. Is product durability better for environment and for economic efficiency? A comparative assessment applying LCA and LCC to two energy-intensive products. J. Clean. Prod. 140, 1353–1364. https://doi.org/ 10.1016/j.jclepro.2016.10.017.

ISO/TS 14048, 2002. Environmental Management. Life Cycle Assessment. Data Documentation Format.

ISO 14040, 2006. Environmental Management. Life Cycle Assessment. Principles and Framework.

ISO 14044, 2006. Environmental Management. Life Cycle Assessment. Requirements and Guidelines.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003. IMPACT 2002 : a new life cycle impact assessment methodology. Int. J. Life Cycle Assess. 8, 324–330. https://doi.org/10.1007/BF02978505.

Kemna, R., van Elburg, M., Li, W., van Holsteijn, R., 2005. Methodology Study Eco- Design of Energy-Using Products: Product Cases Report. VHK-European Commission.

Kim, H.C., Keoleian, G.A., Horie, Y.A., 2006. Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. Energy Policy 34, 2310–2323. https://doi.org/10.1016/j.enpol.2005.04.004.

Li, J., Barwood, M., Rahimifard, S., 2019. A multi-criteria assessment of robotic disassembly to support recycling and recovery. Resour. Conserv. Recycl. 140, 158–165. https://doi.org/10.1016/j.resconrec.2018.09.019.

Lu, B., Li, B., Wang, L., Yang, J., Liu, J., Wang, X.V., 2014. Reusability based on life cycle sustainability assessment: case study on WEEE. Procedia CIRP 15, 473–478. https:// doi.org/10.1016/j.procir.2014.06.046.

Lu, B., Song, X., Yang, J., Yang, D., 2017. Comparison on end-of-life strategies of WEEE in China based on LCA. Front. Environ. Sci. Eng. 11, 7. https://doi.org/10.1007/ s11783-017-0994-7.

Lu, B., Yang, J., Ijomah, W., Wu, W., Zlamparet, G., 2018. Perspectives on reuse of WEEE in China: lessons from the EU. Resour. Conserv. Recycl. 135, 83–92. https://doi.org/ 10.1016/j.resconrec.2017.07.012.

Milios, L., 2017. Advancing to a circular economy: three essential ingredients for a comprehensive policy mix. Sustain. Sci.

13, 861–878. https://doi.org/10.1007/ S11625-017-0502-9.

Monier, V., Tinetti, B., Mitsios, A., de Prado Trigo, A., Ax, C., Medhurst, J., 2016. Study on Socioeconomic Impacts of Increased Reparability. Directorate-General for Environment, European Commission.

Morris, A., Metternicht, G., 2016. Assessing effectiveness of WEEE management policy in Australia. J. Environ. Manag. 181, 218–230. https://doi.org/10.1016/j. jenvman.2016.06.013.

Nußholz, J.L.K., 2017. Circular business models: defining a concept and framing an emerging research field. Sustain. Times 9, 1810–1825. https://doi.org/10.3390/ su9101810.

Pérez-Belis, V., Bakker, C., Juan, P., Bovea, M.D., 2017. Environmental performance of alternative end-of-life scenarios for electrical and electronic equipment: a case study for vacuum cleaners. J. Clean. Prod. 159, 158–170. https://doi.org/10.1016/j. jclepro.2017.05.032.

Pérez-Belis, V., Bovea, M.D., Simó, A., 2015. Consumer behaviour and environmental education in the field of waste electrical and electronic toys: a Spanish case study. Waste Manag. 36, 277–288. https://doi.org/10.1016/j.wasman.2014.10.022.

Pérez-Belis, V., Braulio-Gonzalo, M., Juan, P., Bovea, M.D., 2017. Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment. A Spanish case study. J. Clean. Prod. 158, 261–275. https:// doi.org/10.1016/j.jclepro.2017.04.143.

Pini, M., Lolli, F., Balugani, E., Gamberini, R., Neri, P., Rimini, B., Ferrari, A.M., 2019. Preparation for reuse activity of waste electrical and electronic equipment: environmental performance, cost externality and job creation. J. Clean. Prod. 222, 77–89. https://doi.org/10.1016/j.jclepro.2019.03.004.

Popoff, A., Millet, D., Pialot, O., 2016. Development of usage models for the ecodesign of products: the concept of usage ecodrift. Int. J. Interact. Des. Manuf. 10, 235–240. https://doi.org/10.1007/s12008-016-0326-3.

Potting, J., Hauschild, M., 2004. Background for Spatial Differentiation in Life Cycle Impact Assessment – the EDIP2003 Methodology (Copenhagen).

Schischke, K., Kohlmeyer, R., Griese, H., Reichl, H., 2003. Life cycle energy analysis of PCs – environmental consequences of lifetime extension through reuse. Proc. 11th SETAC LCA Case Stud. Symp. 1–4.

SimaPro Software, 2019. https://www.pre-sustainability.com/.

Socolof, M.L., Overly, J.G., Geibig, J.R., 2005. Environmental life-cycle impacts of CRT and LCD desktop computer displays. J. Clean. Prod. 13, 13–14. https://doi.org/ 10.1016/j.jclepro.2005.05.014.

van Nes, N., Cramer, J., 2006. Product lifetime optimization: a challenging strategy towards more sustainable consumption patterns. J. Clean. Prod. 14, 1307–1318. https://doi.org/10.1016/j.jclepro.2005.04.006.

Vanegas, P., Peeters, J.R., Cattrysse, D., Duflou, J.R., Tecchio, P., Mathieux, F., Ardente, F., 2016. Study for a Method to Assess the Ease of Disassembly of Electrical and Electronic Equipment. Method Development and Application in a Flat Panel Display Case Study. Joint Research Center Technical Reports. European Commission. https://doi.org/10.2788/489828.

Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., Duflou, J.R., 2018. Ease of disassembly of products to support circulareconomy strategies. Resour. Conserv. Recycl. 135, 323–334. https://doi.org/ 10.1016/j.resconrec.2017.06.022.

Wenzel, H., Hauschild, M.Z., 1998. Environmental Assessment of Products: Volume 2: Scientific Background, Environmental Assessment of Products. Chapman & Hall, London: United Kingdom.

Zacho, K.O., Bundgaard, A.M., Mosgaard, M.A., 2018. Constraints and opportunities for integrating preparation for reuse in the Danish WEEE management system. Resour. Conserv. Recycl. 138, 13–23. https://doi.org/10.1016/j.resconrec.2018.06.006.

Zink, T., Maker, F., Geyer, R., Amirtharajah, R., Akella, V., 2014. Comparative life cycle assessment of smartphone reuse: repurposing vs. refurbishment. Int. J. Life Cycle Assess. 19, 1099–1109. https://doi.org/10.1007/s11367-014-0720-7.