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An in-depth literature review of the waste electrical and electronic equipment context: Trends and evolution

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Abstract

The consumption of electrical and electronic equipment (EEE) is continuously increasing worldwide and, consequently, so is the amount of waste electrical and electronic equipment (WEEE) it generates at its end-of-life. In parallel to this growth, legislation related to this issue has been passed in different countries with the aim of improving the management of WEEE. In order to raise awareness about the situation in which the generation, composition, management or final treatment of this kind of waste currently finds itself, an extensive number of articles have been published around the world. The aim of this paper is to define and analyse the main areas of research on WEEE by offering a broader analysis of the relevant literature in this field published between 1992 and August 2014. The literature researched comprises 307 articles, which are analysed according to the topic they focus on (WEEE management, WEEE generation, WEEE characterisation, social aspects of WEEE, re-use of EEE or economic aspects of WEEE). In addition, a deeper analysis is also presented, which takes into account the temporal evolution (globally and by topic), location of the study, categories and subcategories analysed, etc.

Keywords

Waste electrical and electronic equipment, electrical and electronic equipment, review, e-waste

Introduction

The increasingly rapid growth of production and consumption of electrical and electronic equipment (EEE) has led to a sharp rise in the volume of waste that these products generate at the end of their life, leading as a result to a growing problem of pollution worldwide (Kiddee et al., 2013).

As proposed by Widmer et al. (2005), this kind of waste appears in the literature with different names (e-waste or waste electrical and electronic equipment (WEEE)) and different definitions. According to Directive 2012/19/EU, WEEE means electrical or electronic equipment that is waste, including all components, sub-assemblies and consumables that are part of the product at the time of discarding the waste. According to Puckett and Smith (2002), e-waste encompasses a broad and growing range of electronic devices ranging from large household devices, such as refrigerators, air conditioners, cell phones, personal stereos and consumer electronics, to computers that have been discarded by their users, while Robinson (2009) specifies that e-waste describes waste electronic goods, such as computers, televisions and cell phones, while WEEE also includes traditionally non-electronic goods, such as refrigerators and ovens. One definition that could encompass all of the above is that given by Step Initiative (StEP, 2014), which considers that e-waste is a term used to cover almost all types of EEE that has or could enter the waste stream, including televisions, computers, mobile phones, white goods (e.g. fridges, washing machines, dryers, etc.), home entertainment and stereo systems, toys, toasters, kettles and almost any household or business item with circuitry or electrical components with power or a battery supply.

With the aim of ensuring the proper management and treatment of this kind of waste, some countries have developed a specific framework that seeks to improve the environmental performance of all operators involved in the life cycle of EEE by setting ambitious targets for collection, re-use and recovery. Ongondo et al. (2011a) provide a detailed analysis of WEEE management practices in various countries and regions around the world, concluding that the rate of initiating legislation to deal with WEEE is advancing very slowly around the world, and is indeed inexistent in some cases.

In Europe, the framework applicable to WEEE is provided by Directive 2012/19/EU, the purpose of which is to contribute to sustainable production and consumption through the prevention

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of WEEE and by the re-use, recycling and other forms of recovery of such waste so as to reduce the disposal of waste and to contribute to the efficient use of resources and the retrieval of valuable secondary raw materials. Moreover, it also seeks to improve the environmental performance of all operators involved in the life cycle of EEE, and especially those operators directly involved in the collection and treatment of WEEE. This directive sets out several categories and targets, depending on the date, as shown in Table 1.

To date, several reviews analysing the current situation of WEEE management have been carried out, providing a wide range of information on global trends in the amounts and composition of WEEE, future perspectives on WEEE generation, prevention and regulation, methodologies for processing WEEE, and so on. A good example of this is found in Ongondo et al. (2011a). More recently, Li et al. (2013) examined the current situation in those countries involved in the movement of WEEE and used electrical and electronic equipment (UEEE) by analysing the options available to support a global or regional recycling programme. Other more specific reviews are focused on toxic substances present in e-waste. For example, Kiddee et al. (2013) analysed the environmental potential and human health impacts together with the management strategies currently being used in certain countries, Tsydenova and Bengtsson (2011) summarised the existing knowledge on the chemical hazards associated with recycling and other end-of-life (EOL) options for the treatment of WEEE, Cui and Zhang (2008) analysed the state of the art in the recovery of precious metals from e-waste and Vilaplana and Karlsson (2008) discussed recent developments in the mechanical recycling of their plastics.

These reviews provide information from the literature available on specific issues related to WEEE. However, the aim of this paper is to conduct a comprehensive analysis in order to determine the main areas of research on WEEE issues, the countries, methodologies, aspects and categories of EEE analysed, in order to summarise the information that is available and to create a common framework of knowledge in this field. Results will provide information about the most researched subjects related to WEEE, the most researched WEEE categories and the location of those studies.

Research methodology

The study was conducted by means of a literature review on articles related to the field of WEEE. To achieve a comprehensive multidisciplinary review of the literature on WEEE, we used 1992 as the starting point to cover the different insights developed over the last 20 years. The steps outlined below were followed to review the articles considered in this paper.

Paper selection and delimitations

The review is based on the selection of research articles published in databases, including the major academic publishers. Since there is a wide body of literature on the topic of WEEE, the search was limited to scientific peer-review journals, while papers from conferences, books, chapters, etc., were outside of the boundaries of this work. The considerations adopted to carry out the selection of papers from those databases were as follows:

- search based on the following keywords: “electrical and electronic equipment”, “WEEE”, “waste electrical and electronic equipment”, “e-waste”, “life cycle analysis”, “characterisation”, “material composition”, “re-use”, “recycling process planning”, “WEEE Recycling”, etc.;
- search for articles that were referenced in notable reviews on WEEE, such as Widmer et al. (2005), Robinson (2009), Ongondo et al. (2011a) or Kiddee et al. (2013), which provide an overview of the WEEE topics in various countries and regions of the world.
- search for articles that were referenced in other selected articles, in order to extend the research for specific topics on WEEE.

Over 350 articles underwent a desk review, although some of them were discarded since they analysed specific issues far beyond the scope of the present paper. Finally, 307 were included in the review. The initial aspects analysed were author, journal, year of publication, type of study (review, case study, etc.), WEEE category analysed (based on categories listed in Directive 2012/19/EU), country and continent. Once the first review of articles had been completed, content was analysed more deeply.

Content analysis

A content analysis of the selected articles was performed to identify the main topics addressed in each article, with the aim of developing a qualitative classification. It was a feedback process until defining the final areas, as described in the following section, and the analysis cannot escape the authors’ subjective appreciation.

Seven specific topics were defined, these being identified with a letter: A – WEEE management; B – WEEE generation; C – WEEE characterisation; D – social aspects of WEEE; E – re-use and preparing for re-use, aspects to extend the product life span of EEE; F – design and methodologies to improve recycling; and G – economic aspects of WEEE. These subjects are described in detail in the next section. Finally, the type of article was identified according to three categories: case study, reviews and others.

Review content results

The main characteristics of each topic are discussed in detail in the following sections.

Table 1. Waste electrical and electronic equipment categories and targets based on Directive 2012/19/EU.

Categories until 14 August 2018		*Targets until 14 August 2015*		*Targets from 15 August 2015*		Categories from 15 August 2018		*Targets from 15 August 2018*	
		% recovered	% recycled	% recovered	% prepared for re-use or recycled			% recovered	% prepared for re-use or recycled
1	Large household appliances	80	75	80	80	1	Temperature exchange equipment	85	80
2	Small household appliances	70	50	75	55	2	Screens, monitors, equip. with surface screens >100 cm^2	80	70
3	IT and telecommunications equip.	75	65	80	70	3	Lamps	–	80
4	Electronic and consumer equip.	75	65	80	70	4	Large equipment	85	80
5	Lighting equip.	70	50	75	55	5	Small equipment	75	55
6	Electrical and electronic tools	70	50	75	55	6	Small IT and telecommunication equipment	75	55
7	Toys, leisure and sports equip.	70	50	75	55				
8	Medical devices	70	50	75	55				
9	Monitoring and control instruments	70	50	75	55				
10	Automatic dispensers	80	75	85	80				

WEEE management

Articles dealing with the WEEE management issue contain information on the specific management of WEEE and strategies or tools to manage this waste properly. They also include information on legislation and regulation management systems in each country, current and evolving management practices (re-use, recycling, incineration, landfilling), the role of regulation and policies developed by governments, institutions and product manufacturers, analysis of government data, management schemes/systems, product take-back systems, etc.

In addition, articles based on the application of specific analytical tools to manage e-waste are also included: Life Cycle Assessment (LCA) to estimate the effects of material consumption and evaluate the environmental aspects related to the EOL disposal of electronic waste; Material Flow Analysis (MFA) to investigate the generation and streams of e-waste; or Multi Criteria Analysis (MCA) for environmental decision making. On the other hand, articles applying the environmental policy approach of Extended Producer Responsibility (EPR) with the aim of solving e-waste problems at national level have also been considered in this topic.

Table 2 shows the articles reviewed on this topic, stating whether the paper also deals secondarily with other aspects apart from the management issue, the WEEE categories analysed and the geographical distribution (country/continent) of the study.

WEEE generation

Articles related to WEEE generation, estimation of quantities generated, description of how they are generated and classified, including tools and strategies to do so, are grouped in this topic. Table 3 shows the articles reviewed, stating whether other aspects apart from the main issue have been included in the paper, the WEEE categories analysed and the geographical distribution (country/continent) of the study.

In this case, Categories 1–4 have been exploited with more detail, since there are papers focused on all of the subcategories of each category.

WEEE characterisation

This topic includes articles focused on physical and chemical characterisations of WEEE that contain information on material composition, electrical and electronic components, etc. There are also included those focused on environmental impacts associated with their materials and components or resulting from their treatment. Thus, specific studies about the recovery of materials such as plastic and metal are included, but also those based on mechanical separation oriented towards the characterisation of WEEE and the processes for recovery, such as methods for analysing metal additives in recycled thermoplastics, procedures for recycling plastics deriving from WEEE, toxic metals in shredding and separation techniques, and so on.

Articles with extremely detailed information on certain aspects of recovery and treatment processes are outside of the boundaries of this review, as previously stated. The articles about WEEE characterisation that were reviewed are listed in Table 4, including the aim of the characterisation, category of WEEE analysed and location of the study.

As shown in Table 4, WEEE category has not been included in that classification, since most of the articles are focused on a specific WEEE subcategory. Table 5 details the category and subcategory analysed in each article.

Social aspects of WEEE

During the initial review of the content of articles described in the *Content analysis* section, social issues related to WEEE were treated as another research field. Within this group, two trends were clearly defined. On the one hand, there are articles focused on WEEE disposal habits and, on the other, articles focused on human health problems due to informal management of WEEE.

In the first group, the articles provide information on consumer disposal preferences, amounts of WEEE in households, variables for explaining household willingness to recycle e-waste, household preferences for e-waste recycling alternatives, etc. Table 6 lists the articles reviewed, including the aim of the study, WEEE categories, the way the information was obtained from consumers, etc., as well as the respondents that were reached.

In the second group, the articles provide information on human pollution resulting from the primitive recycling of WEEE and the exposure levels of polybrominated diphenylethers (PBDEs) for local residents or WEEE workers at landfills and waste scrapping centres. Some of them summarise the existing knowledge on the chemical hazards associated with recycling and other options for the EOL treatment of WEEE. To do this, these articles analyse human matrices, milk, placenta or hair collected from a group of childbearing-aged women at an electronic waste recycling plant or urine from WEEE recycling workers. Table 7 shows articles related to this trend, their aim, locations and other aspects analysed. Most of the articles related to impacts on the health of WEEE workers refer to the Asian continent, highlighting those from Guiyu (Huo et al., 2007; Xing et al., 2009; Zheng et al., 2008), Zhejiang (Zhao et al., 2008) in China, Bangalore and Chennai in India (Ha et al., 2009) and finally Ghana in Africa (Asante et al., 2012).

Re-use and preparing for re-use

This section contains the articles related to re-use of EEE, especially those focused on characteristics of the product once it has been withdrawn: quality, feasibility of re-use, success factors and barriers, re-use activities of socio-economic enterprises, methods and strategies to improve re-usability, etc. This is the approach used to consider the economic aspect in most of these articles (Babbitt et al., 2011; Geyer and Blass, 2010; Ongondo et al., 2013; Walther et al., 2010; Williams et al., 2008). Table 8 shows

Table 2. Articles focused on waste electrical and electronic equipment (WEEE) management (A).

Reference	Additional aspects	WEEE categories	Location
Andarani and Goto (2014)	D	Cat 1 (refrigerators, washing machine) Cat 3 (personal computers, mobile phones) Cat 4 (television, monitor)	Indonesia/Asia
Estrada-Ayuba and Kahhat (2014)	–	Cat 3(personal computers)	Mexico/America
Hussain and Mumtaz (2014)		General	Global
Laha (2014)	–	General	India/Asia
Needhidasan et al. (2014)	C	General	India/Asia
Niza et al. (2014)	–	General	Portugal/Europe
Popescu (2014)	B	General	Romania/Europe
Premalatha et al. (2014)	–	General	–
Priyadharshini and Meenambal (2014)	–	General	Global
Shumon et al. (2014)	–	General	Malaysia/Asia
Ylä-Mella et al. 2014)	B	General	Finland/Europe
Kiddee et al. (2013)	–	General	Global
Li et al. (2013)	–	General	Global
Qu et al. (2013)	–	General	China/Asia
Sthiannopkao and Wong (2013)	–	General	Asia
Torretta et al. (2013)	–	General	EU
Xue et al. (2013)	–	General	–
Zeng et al. (2013)	–	General	China/Asia
Dwivedy and Mittal (2012)	–	General	India/Asia
Oliveira et al. (2012)	–	General	Brazil/America
Zhou and Xu (2012)	–	General	China/Asia
Akenji et al. (2011)	–	General	Asia
Bernstad et al. (2011)	–	General	Sweden/Europe
Khetriwal et al. (2011)	B	General	Europe
Manomaivibool and Vassanadumrongdee (2011)	–	General	Thailand/Asia
Ongondo et al. (2011a)	B	General	Global
Townsend (2011)	–	General	Global
Wath et al. (2011)	–	General	India/Asia
Wang et al. (2010)	–	General	China/Asia
Wath et al. (2010)	–	General	India/Asia
Yu et al. (2010a)	–	General	China/Asia
Zoeteman et al. (2010)	–	General	Global
Kahhat and Williams (2009)	–	Cat 3 (personal computers)	Peru/America
Khetriwal et al. (2009)	–	General	Switzerland/Europe
Kojima et al. (2009)	–	General	China and Thailand (Asia)
Manomaivibool (2009)	–	General	India/Asia
Shinkuma and Huong (2009)	–	General	Asia
Streicher-Porte et al. (2009)	–	Cat 3 (personal computers)	Colombia/America
Yoshida et al. (2009)	–	Cat 3 (personal computers)	Japan/Asia
Aizawa et al. (2008)	F	Cat 1 (refrigerator, washing machine, air conditioner) Cat 4 (television)	Japan/Asia
Barba-Gutiérrez et al. (2008)	B	Cat 1 (refrigerators, washing machine) Cat 3 (personal computers) Cat 4 (television)	Germany/Europe
Davis and Herat (2008)	–	General	Australia/Oceania
Kahhat et al. (2008)	–	General	USA/America
Nnorom and Osibanjo (2008a)	–	General	Nigeria/Africa
Nnorom and Osibanjo (2008b)	B	General	Nigeria/Africa
Osibanjo and Nnorom (2008)	–	Cat 3 (mobile phones)	Nigeria/Africa
Rousis et al. (2008)	–	General	Cyprus/Europe

(Continued)

Table 2. (Continued)

Reference	Additional aspects	WEEE categories	Location
Lee et al. (2007)	B,C	Cat 1 (refrigerators, washing machines, air conditioners) Cat 3 (personal computers, mobile phones) Cat 4 (television)	Korea/Asia
Ogushi and Kandlikar (2007)	–	General	Japan/Asia
Osibanjo and Nnorom (2007a)	–	Cat 3 (mobile phones)	Nigeria/Africa
Osibanjo and Nnorom (2007b)	–	General	Nigeria/Africa
Gottberg et al. (2006)	–	Cat 3	UK/Europe
He et al. (2006)	B	General	China/Asia
Jain and Sareen (2006)	–	General	India/Asia
Jieqiong et al. (2006)	–	General	China/Asia
Li et al. (2006a)	C	General	China/Asia
McKerlie et al. (2006)	–	General	Canada/America
Schmidt (2006)	–	General	Africa
Selin and VanDeveer (2006)	–	General	EU
Terazono et al. (2006)	–	General	Asia
Kang and Schoenung (2005)	B,C	General	America
Mayers et al. (2005)	–	Cat 3 (printers)	UK/Europe
Scharnhorst et al. (2005)	–	Cat 3 (mobile phones)	Switzerland/Europe
Streicher-Porte et al. (2005)	–	Cat 3 (personal computers)	Delhi/Asia
Hula et al. (2003)	–	Cat 2 (coffee maker)	Germany/Europe
Cooper (2000)	–	General	Delhi/Asia
Zhang et al. (2000)	–	General	Global

A: WEEE management; B: WEEE generation; C: characterisation; D: social; E: re-use; F: methodologies and design; G: economic aspects.

the WEEE categories or products that have been analysed in these studies.

Design and methodologies to improve end-of-life

This section contains those studies related to design methodologies and actions that aim to minimise the negative consequences of EOL of EEE, mainly focused on the following (Table 9):

- decision support tools for policymakers and regulators to optimise the reverse logistics network of electronic products;
- methods to involve consideration of both environmental and economic aspects at the EOL;
- priorities for recycling and the ecodesign of certain products;
- life cycle environmental benefits achieved by incorporating remanufacturing into a product system; or
- decision-making methods to evaluate the amenability of mechanical separation processes, etc.

Apart from the articles in Table 9, there is a range of studies specifically focused on analysing the environmental performance of EEE and their alternative EOL from a product life cycle perspective. Due to their number, they are reported in Table 10, including the product studied.

Economic aspects

This section includes articles focused on the economic aspects of WEEE, including those that highlight this topic above the others. Among the different papers there are some that analyse the economic benefit of the re-use of WEEE, contain tools to assess the cost of a product over its entire life cycle (Life Cycle Cost, LCC), develop mathematical formulations based on the cost–benefit analysis concept, evaluate the recycling rates or quantify the cost and economic benefits of WEEE management.

Table 11 shows the articles on economic aspects that were reviewed, with details of the aim of the study, categories analysed and location.

Findings from the literature overview

As mentioned earlier, although the classification according to the content analysis cannot elude certain subjective appreciations by the authors, an explanation of certain findings and a deeper analysis is provided below that takes into account the evolution over time, both globally and by topic, the location of the study, the type of publication or categories and the subcategories analysed.

Publications per year and topic

Very little interest was shown in WEEE until 2002, which is when the first specific European legislation related to WEEE was

Table 3. Articles focused on waste electrical and electronic equipment generation (B).

Reference	Additional aspects	Cat 1	Refrigerators	Freezer	Washing machine	Air conditioner	Microwaves	Cat 2	Vacuum	Cat 3	Laptop	Personal computer	Printers	Mobile phones	Cat 4	Televisions	Stereos	Cat 5	Cat 6	Cat 7	Cat 8	Cat 9	Cat 10	Electronic Components	Location
Breivik et al. (2014)	–																								Global
Khan et al. (2014)	A, D																								Global
Lu et al. (2014)	–	•	•		•	•				•		•			•	•									China/Asia
Nakatani and Moriguchi (2014)	A	•													•	•									China/Asia
Orzturk (2014)	A,C	•	•		•	•				•		•		•	•	•									Turkey/Europe
Rahmani et al. (2014)	A									•		•		•											Iran/Asia
Bigum et al. (2013)	–																							•	Denmark/Europe
Kim et al. (2013)	–																								South Korea/Asia
Araújo et al. (2012)	–	•	•	•	•					•		•		•	•	•	•								Brazil/America
Kahhat and Williams (2012)	–											•													US/America
Pólak and Drápalová (2012)	–									•				•											Czech Republic/Europe
Queiruga et al. (2012)	–																								Spain /Europe
Solé et al. (2012)	–																								Spain /Europe
Ongondo et al. (2011b)	–														•	•									England/Europe
Salhofer and Tesar (2011)	C	•					•	•	•	•		•	•		•			•	•	•	•	•	•		Austria/Europe
Wäger et al. (2011)	C																								Switzerland/Europe
Zhang et al. (2011)	–		•			•	•					•				•									Nanjing/Asia
Dwivedy and Mittal (2010a)	–												•												India/Asia
Dwivedy and Mittal, (2010b)	–																								India/Asia
Gaidajis et al. (2010)	–																								Greece, Japan, Switzerland
Yu et al. (2010b)	–									•		•													Global
Steubing et al. (2010)	–																								Chile/America
Robinson (2009)	–																								New Zealand/Oceania
Wagner (2009)	–																								US/America
Yang et al. (2008)	G	•	•		•	•				•		•			•	•									China/Asia
Babu et al. (2007)	–																								India/Asia
Kang and Schoenung (2006a)	–									•		•													California/America
Liu et al. (2006a)	D	•	•		•	•				•		•			•	•									China/Asia
Liu et al. (2006b)	–	•	•		•	•				•		•			•	•									China/Asia
Hicks et al. (2005)	D, G																								China/Asia
Hischier et al. (2005)	–	•						•		•					•										Switzerland/Europe
Khetriwal et al. (2005)	–																								Switzerland – India
Widmer et al. (2005)	C																								Global
Feszty et al. (2003)	–																								Scotland/Europe

A: WEEE management; B: WEEE generation; C: characterisation; D: social; E: re-use; F: methodologies and design; G: economic aspects.

Table 4. Articles focused on waste electrical and electronic equipment characterisation and their environmental impacts (C).

Reference	Aim of the characterisation (material or component)				Location
	Plastics	Metals	Elec. components	Env. impacts	
Alsheyab (2014)		•			Jordan
Bizzo et al. (2014)			•		Brazil
Jayaprakash and Anandan (2014)				•	–
Long et al. (2014)		•			China
Nakamura (2014)		•			Japan
Palmieri et al. (2014)	•		•		Italy
Park et al. (2014)		•			Korea
Peeters et al. (2014)	•				Belgium
Wang and Xu (2014)	•		•		China
Zeng and Li (2014)			•	•	China
Zeng et al. (2014)			•		China
Menad et al. (2013)	•	•			France
Oguchi et al. (2013)		•			Japan
Pérez-Belis et al. (2013)	•		•		Spain
Stenvall et al. (2013)	•				Sweden
Bigum et al. (2012)		•			Denmark
Martinho et al. (2012)	•				Portugal
Oguchi et al. (2012)		•			Japan
Tuncuk et al. (2012)		•			Turkey – Italy
Wäger et al. (2012)	•				Switzerland
Delfini et al. (2011)		•	•		Italy
Moltó et al. (2011)			•		Spain
Oguchi et al. (2011)		•	•		Japan
Wang et al. (2011a)				•	China
Muenhor et al. (2010)				•	Thailand
Omolaoye et al. (2010)	•				Nigeria
Tang et al. (2010)				•	China
Tarantili et al. (2010)	•				Greece
Taurino et al. (2010)	•				Italy
Chancerel and Rotter (2009)	•	•	•		Germany
Chen et al. (2009)				•	China
Dimitrakakis et al. (2009a)	•				Germany
Dimitrakakis et al. (2009b)	•				Germany
Luo et al. (2009)				•	China
Moltó et al. (2009)				•	Spain
Nnorom and Osibanjo (2009)	•				Nigeria
Odusanya et al. (2009)				•	South Africa
Shen et al. (2009)				•	China
Wang et al. (2009a)				•	China
Betts (2008a)					USA
Betts (2008b)					USA
Cui and Zhang (2008)	•	•			Norway
Spalvins et al. (2008)				•	Florida
Vilaplana and Karlsson (2008)	•				Sweden
Cui and Forssberg (2007)	•	•			Sweden
Deng et al. (2007)				•	China
Gullett et al. (2007)				•	USA
Leung et al. (2007)				•	China
Li et al. (2007)				•	China
Lincoln et al. (2007)				•	USA
Morf et al. (2007)	•	•	•		Switzerland
Schlummer et al. (2007)	•				Germany
Wong et al. (2007a)				•	China
Wong et al. (2007b)				•	China
Deng et al. (2006)				•	China

Table 4. (Continued)

Reference	Aim of the characterisation (material or component)				Location
	Plastics	Metals	Elec. components	Env. impacts	
Li et al. (2006b)		•			USA
Wang and Guo (2006)				•	China
Yu et al. (2006)				•	China
Mohabuth and Miles (2005)	•	•	•		UK
Wang et al. (2005)				•	China
Matsuto et al. (2004)		•			Japan
Osako et al. (2004)				•	Japan
Cui and Forssberg (2003)					Sweden
Jang and Townsend (2003)				•	USA
Fink et al. (2000)	•				Germany
Gungor and Gupta (1999)					USA
Gungor and Gupta (1998)					USA
Zhang and Forssberg (1997)	•		•		–
Yang (1993)				•	Asia
Hoffmann (1992)		•			USA

published (Directive 2002/96/EC). Each European Union country had 18 months to bring that Directive into force in their national legislation system. From then on, the number of articles related to WEEE published annually has increased significantly, as Figure 1 shows.

The legislation and implementation of good practices related to WEEE has not been developed in the same way in Europe and other continents/countries. Before Directive 2002/96/EC came into force in 2002, some European countries, such as Switzerland or Sweden, had previous experience of implementing voluntary formal collection and management programmes for WEEE (Khetriwal et al., 2009; Streicher-Porte, 2005). Canada has passed WEEE legislation since 2006 (McKerlie et al., 2006) just as has the USA, which has approved WEEE legislation referring to WEEE since 2006 in its different States (Electronic Coalition, 2014). In Asia, and specifically in China, it was not until 2004 when three major national-level legislative documents were drafted in response to the perceived problem of WEEE management: (1) a technical policy providing guidance for the state environmental protection administration's management of WEEE, which came into effect in 1996 (Hicks et al., 2005); (2) administrative measures on the control of pollution caused by electronic information products and focused on restrictions on the use of hazardous substances in EEE enacted in March 2007; and (3) the regulations on the administration of the recovery and disposal of WEEE (Jieqiong et al., 2006). Finally, this draft legislation was adopted and promulgated in 2009, coming into effect from 2011 (Wang et al., 2009c). In Japan, in order to decrease the environmental impact of WEEE, the Home Appliance Recycling Law (HARL) was introduced and came into force in April 2001 (Zhang and Kimura, 2006).

As Figure 2 shows, characterisation (C) and management (A) of WEEE are the issues that have been most active throughout the period analysed, these being top of the ratings in 2006 and 2009 and in 2005 and 2008, respectively. WEEE characterisation provides information about material composition, thus allowing experts to develop methods to recover or modify their composition, thereby improving their EOL. From 2006 onwards, a high interest in the EOL management of plastic and metal components present in WEEE is detected, since legislation sets increasingly restrictive recycling and recovery quotas for each fraction, mainly plastic and metal. Coinciding with the approval of the Directive 2009/125/EC, known as the Ecodesign Directive, the number of research works related to design and methodologies to improve recycling (F) shows an increase as of 2010.

Re-use and issues related to the extension of the working life of EEE (E) are numerous from 2009 onwards, especially in 2012, since the updated Directive 2012/19/EU recognises the importance of re-use, promoting it by stating that priority should be given to preparing for re-use of WEEE and its components, sub-assemblies and consumables. In recent years there have been many studies and reports on the re-use of WEEE and how this re-use could be integrated from different approaches. From the design perspective, materials could be improved in order to facilitate recycling. Other articles highlight the importance of suitable reverse logistics in order to prevent the destruction of value in products that can potentially be re-used. There are also a number of papers that remind us that the improved efficiency of newer products sets limitations on when re-use is a desirable strategy.

Finally, articles focused on the economic aspect emerged slowly from 2003 onwards, reaching a maximum in 2013. They are mainly focused on the economic benefits from disassembly and the incorporation of design considerations, cost of recycling processes or economic performance of the reverse logistics, re-use and recycling operations for end-of-use of WEEE.

Table 5. Categories and subcategories analysed in each article focused on waste electrical and electronic equipment (WEEE) characterisation (C).

Reference	**Cat 1**	Refrigerators	Freezers	Washing machines	Air conditioning	Microwaves	Heaters	**Cat 2**	Irons	Vacuum cleaners	Toasters	Coffee makers	Shavers	Clocks	Blenders	Hair dryers	Electric Toothbrushes	**Cat 3**	Laptops	Computers	Printers	Photocopiers	Calculators	Mobile phones	Computer peripherals	**Cat 4**	Radios	Flat screens	Televisions	Cameras	Loudspeakers	DVD and audio	Monitors	Stereos	**Cat 5**	**Cat 6**	**Cat 7**	Videogames	Toys	Sports equipment	**Cat 8**	**Cat 9**	**Cat 10**	Elect. comp./batteries
Alsheyab (2014)																		•	•																									
Bizzo et al. (2014)																		•		•																								•
Long et al. (2014)																																												
Nakamura (2014)	•	•		•	•																					•			•															
Palmieri et al. (2014)																		•						•																				
Park et al. 2014)	•	•																								•			•															
Peeters et al. (2014)																										•			•															
Wang and Xu (2014)																										•			•															
Zeng and Li (2014)																																												•
Zeng et al. (2014)																																												•
Menad et al. (2013)								•																		•										•								
Oguchi et al. (2013)		•		•	•	•									•				•	•	•			•	•		•		•	•		•		•										
Pérez-Belis et al. (2013)																																					•		•					
Stenvall et al. (2013)																																												
Bigum et al. (2012)																		•								•																		
Marthino et al. (2012)		•	•																		•	•							•				•											
Oguchi et al. (2012)	•						•	•		•	•			•				•			•			•	•	•				•	•				•									
Tuncuk et al. (2012)[a]																																												
Wäger et al. (2012)	•							•										•								•		•	•				•											
Delfini et al. (2011)																		•		•						•			•				•											
Moltó et al. (2011)																								•																				
Oguchi et al. (2011)	•	•		•	•													•		•	•			•	•	•	•		•	•							•	•						
Wang et al. (2011a)[a]																																												
Muenhor et al.(2010)[a]																																												
Omolaoye et al. (2010)																																					•		•					
Tang et al. (2010)[a]																																												
Tarantili et al. (2010)[a]																																												
Taurino et al. (2010)																		•		•						•			•															
Chancerel and Rotter (2009)	•						•	•	•	•		•	•		•			•	•	•				•	•												•	•	•					
Chen et al. (2009)[a]																																												
Dimitrakakis et al. (2009a)								•		•				•		•	•	•					•	•	•	•	•				•					•	•	•		•				
Dimitrakakis et al. (2009b)	•							•										•								•									•	•	•				•	•	•	
Luo et al. (2009)																																												•

Table 5. (Continued)

Reference	**Cat 1**	Refrigerators	Freezers	Washing machines	Air conditioning	Microwaves	Heaters	**Cat 2**	Irons	Vacuum cleaners	Toasters	Coffee makers	Shavers	Clocks	Blenders	Hair dryers	Electric Toothbrushes	**Cat 3**	Laptops	Computers	Printers	Photocopiers	Calculators	Mobile phones	Computer peripherals	**Cat 4**	Radios	Flat screens	Televisions	Cameras	Loudspeakers	DVD and audio	Monitors	Stereos	**Cat 5**	**Cat 6**	**Cat 7**	Videogames	Toys	Sports equipment	**Cat 8**	**Cat 9**	**Cat 10**	Elect. comp./batteries
Moltó et al. (2009)																		•						•																				
Nnorom and Osibanjo (2009)																		•						•																				
Odusanya et al. (2009)[a]																																												
Shen et al. (2009)[a]																																												
Wang et al. (2009a)[a]																																												
Betts (2008a)[a]																																												
Betts (2008b)[a]																																												
Cui and Zhang (2008)																		•		•			•	•		•			•			•												
Spalvins et al. (2008)																																												
Vilaplana and Karlsson (2008)[a]																																												
Cui and Forssberg (2007)																										•			•															
Deng et al. (2007)[a]																																												
Gullett et al. (2007)[a]																																												
Leung et al. (2007)[a]																																												
Li et al. (2007)[a]																																												
Lincoln et al. (2007)																		•						•																				
Morf et al. (2007)								•	•	•	•					•	•	•		•		•		•		•			•				•											
Schlummer et al. (2007)																										•			•				•											
Wong et al. (2007a)[a]																																												
Wong et al. (2007b)[a]																																												
Deng et al. (2006)[a]																																												
Li et al. (2006b)																		•		•																								
Wang and Guo (2006)[a]																																												
Yu et al. (2006)[a]																																												
Mohabuth and Miles (2005)																																												•
Wang et al. (2005)[a]																																												
Matsuto et al. (2004)		•		•	•																								•															
Osako et al. (2004)[a]																																												
Cui and Forssberg (2003)[a]																		•		•						•			•															
Jang and Townsend (2003)																																												
Fink et al. (2000)																										•																		
Gungor and Gupta (1999)[a]																																												
Gungor and Gupta (1998)[a]																																												
Zhang and Forssberg (1997)[a]																																												
Yang (1993)																																												•
Hoffmann (1992)[a]																																												

[a]General WEEE, no specification.

Table 6. Articles focused on social aspects of waste electrical and electronic equipment (WEEE): consumer behaviour (D).

Reference	**WTP**		**Consumer behaviour**				**WEEE categories**										**Survey**						
	Green electronic products	E-waste recycling/treatment	Habits –disposal reasons	E-Waste Recycling behaviour/preferences	Determining factors for recycling	Generation/collection WEEE	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6	Category 7	Category 8	Category 9	Category 10	Via telephone	Interview	Mail | Internet	Postal	Professionals/literature review	**nº responses**	**Location**
Chi et al. (2014)			•	•		•	•	•	•	•												430	Taizhou, China.
Colesca et al. (2014)				•	•																	253	Romania
Afroz et al. (2013)		•	•				•		•	•								•				350	Kuala Lumpur, Malaysia
Dwivedy and Mittal (2013)				•			•		•	•									•			148	India
Lau et al. (2013)																		•			•	1230	Hong Kong
Milovantseva and Saphores (2013a)						•				•									•			3156	USA
Milovantseva and Saphores (2013b)			•						•	•									•			3156	USA
Achillas et al. (2012a)		•			•																	n/a	Greece
Fraige et al. (2012)		•				•																n/a	Jordanian
Li et al. (2012)		•	•	•			•	•	•	•								•				346	Baoding, China
Manomaivibool and Vassanadumrongdee (2012)			•				•		•	•	•							•				1529	Thailand
Saphores et al. (2012)		•		•															•			2136	USA
Song et al. (2012a)		•	•	•														•				400	Macau, China
Bouvier and Wagner (2011)					•	•			•	•							•					92	Maine (USA)
Chung et al. (2011)							•		•	•												1105	Hong Kong
Gutierrez et al. (2011)							•	•		•							•					1537	Spain

Table 6. (Continued)

Reference	WTP		Consumer behaviour			WEEE categories											Survey						
	Green electronic products	E-waste recycling/treatment	Habits –disposal reasons	E-Waste Recycling behaviour/preferences	Determining factors for recycling	Generation/collection WEEE	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6	Category 7	Category 8	Category 9	Category 10	Via telephone	Interview	Mail | Internet	Postal	Professionals/literature review	**nº responses**	**Location**
Ongondo and Williams (2011a)						•			•											•		102	UK
Ongondo and Williams (2011b)			•		•				•										•			2287	UK
Saphores and Milovantseva (2011)						•				•												3156	USA
Wang et al. (2011b)				•																		957	Beijing
Gutierrez et al. (2010)			•				•	•		•							•					1537	Spain
Jang and Kim (2010)			•	•					•												•	1090	Korea
Nixon et al. (2009)		•		•															•			357	California
Nnorom et al. (2009)	•			•					•													115	Nigeria
Saphores et al. (2009)					•	•	•	•	•	•									•			2136	USA
Gurauskiene (2008)					•																•	–	Global
Queiruga et al. (2008)						•															•	–	Spain
Saphores et al. (2007)	•				•				•										•			357	California
Hansmann et al. (2006)		•			•															•		623	Switzerland
Huang et al. (2006)		•				•	•		•	•								•				2096	Ningbo, China
Melissen (2006)			•																			–	Netherlands
Saphores et al. (2006)				•	•	•													•			357	California
Darby and Obara (2005)			•		•			•	•	•			•					•		•		1477	Cardiff, Wales (UK)
Karagiannidis et al. (2005)			•			•	•	•	•	•								•			•	95	Thessaloniki, Greece

WTP: Willingness to pay

Table 7. Articles focused on social aspects of waste electrical and electronic equipment (WEEE): human health (D).

Reference	Additional aspects	Samples analysed	Location
Lau et al. (2014)	–	Suspended air particulates, surface dust and floor dust collected from the above study areas in five workshops (cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), mercury (Hg) and zinc (Zn))	Asia
Pandey and Govind (2014)	–	Living conditions of workers at some dismantling sites in Delhi	Asia
Song and Li (2014)	–	Exposure routes (dietary intake, inhalation and soil/dust ingestion) and human body burden markers (placenta, umbilical cord blood, breast milk, blood, hair and urine)	Asia
Asante et al. (2012)	C	Urine of e-waste recycling workers	Africa
Eguchi et al. (2012)	C	Serum from e-waste recycling workers and residents near a coastal area in India	Asia
Tsydenova and Bengtsson (2011)	C	Review of scientific data on human exposure to chemicals, workplace and environmental pollution recycling, incineration and landfilling.	Global
Leung et al. (2010)	C	Human matrices, namely milk, placenta and hair, collected from a group of childbearing-aged women at an electronic waste area	Asia
Sepúlveda et al. (2010)	C	Air, bottom ash, dust, soil, water and sediments in WEEE recycling areas	Asia
Ha et al. (2009)	B, C	Human hair collected from e-waste recycling sites	Asia
Li et al. (2009)	C	Landfill simulation in columns	America
Wang et al. (2009b)	–	Scalp hair samples	Asia
Xing et al. (2009)	–	Human milk samples	Asia
Leung et al. (2008)		Surface dust samples were collected from recycling workshops, adjacent roads, a schoolyard and an outdoor food market	Asia
Zhao et al. (2008)	C	Hair samples collected from the disassembly sites and from the control site	Asia
Zheng et al. (2008)	C	Blood lead levels (BLLs) of children	Asia
Huo et al. (2007)	C	BLLs of children	Asia
Qu et al. (2007)	C	Polybrominated diphenylethers (PBDE) serum levels in residents from an electronic waste dismantling region, residents living within 50 km of the dismantling region and a referent group with no occupational PBDE exposure	Asia
Leung et al. (2006)	C	The pollution levels generated from electronic waste (e-waste) activities	Asia

A: WEEE management; B: WEEE generation; C: characterisation; D: social; E: re-use; F: methodologies and design; G: economic aspects.

Topic and location of publications

Figure 3 shows the relationship between the location and the topic. Regarding the social aspects of WEEE (E), countries from Europe and Asia report the highest number of publications, although most of the articles focused on the impacts of WEEE on human health refer to Asia and most of those focused on consumer behaviour refer to Europe. Concerning the first group, areas such as Guiyu, Zhejiang, Bangalore and Chennai are specifically analysed. The topic related to re-use of WEEE (F) is a subject that is analysed globally with special attention to Europe, while other topics, such as WEEE management (A) and WEEE generation (B), are studied mainly in Europe and Asia.

WEEE categories and subcategories analysed

Focusing on WEEE categories, it can be observed that 37% of the reviewed studies refer to general WEEE while the others are focused on a specific category. With the aim of analysing which categories and subcategories are analysed most often, Figures 4 and 5 provide the distribution of the remaining 63%. Figure 4 shows the distribution of articles by WEEE category and topic, while Figure 5 shows the distribution of articles by subcategory (specific electrical and electronic product) and topic.

Categories 1–4 are the most commonly researched ones throughout the literature, while the remaining categories had not received much interest from researchers. Regarding subcategories, personal computers (16.1%) along with mobile phones (11.8%) and televisions (13.6%) are the products that are most often researched in the field of WEEE, followed by products belonging to Category 1 (refrigerators, freezers, dishwashers, washing machines and air conditioners). Monitors also receive special interest (4.3%).

The interest in products such as personal computers, mobile phones and televisions is due to the fact that they are products with a high level of consumption and short period of substitution.

Table 8. Articles focused on re-use and preparing for re-use issues (E).

Reference	**Cat 1**	Refrigerators	Dishwashers	Washing machines	Microwaves	**Cat 2**	**Cat 3**	Laptops	Personal computer	Mobile phones	**Cat 4**	Televisions	DVD and audio	Monitors
Kissling et al. (2013)	•						•							
Ongondo et al. (2013)							•							
Agamuthu et al. (2012)[a]														
Dindarian et al. (2012)	•				•									
Kissling et al. (2012)	•						•							
Ravi (2012)									•					
Babbitt et al. (2011)[a]														
Achillas et al. (2010a)[a]														
Geyer and Blass (2010)							•			•				
Walther et al. (2010)[a]														
Babbitt et al. (2009)							•		•					
Devoldere et al. (2009)	•			•										
Ramzy and Williams (2009)							•		•					
Williams et al. (2008)							•		•					
Truttmann and Rechberger (2006)	•	•	•	•	•	•	•		•		•	•	•	•

[a]General WEEE, no specification.

As regards mobile phones, according to Pólak and Drápalová (2012), they are one of the most frequently sold EEE on the market and, at the same time, one of the equipment with the lowest collection rate. This is due to the second-hand market around them, since the number of re-used mobile phones is higher than the number of those that are recycled. Thus they are also an attractive WEEE subcategory that could be interesting to analyse for its consumption and disposal habits.

Subcategories belonging to Category 1 are also of interest, since household electronic appliances, such as refrigerators, washing machines, televisions and air conditioning units, are considered the four largest sources of consumer WEEE in Japan, and their management is determined by the HARL (Zhang and Kimura, 2006). Thus, results are higher than in other categories since most of the articles from Japan are focused on that category.

In line with the topic of study and the categories and subcategories analysed, Figure 5 shows that most of the subcategories have been analysed from the point of view of their characterisation, while subcategories such as refrigerators, washing machines, air conditioners, mobile phones and televisions have been analysed in all the topics.

Conclusions

The aim of this paper is to define and analyse the main areas of research on electrical and electronic waste, while offering a broader analysis of the relevant literature in order to summarise the information available and to create common knowledge. The broad review of the relevant literature in this field consists of 307 articles published in scientific journals between 1992 and August 2014.

Several research topics have been identified, including WEEE management, WEEE generation, WEEE characterisation, social aspects on WEEE, re-use or aspects considered to extend the product life span of WEEE, methodologies and design, and economic aspects of WEEE. The analysis of these topics has made it possible to determine the main issues or concerns mentioned quite often in the literatures, being the focus of several discussions.

The key concerns observed from the literature are related to the following.

- The alarming growth of WEEE, since the accelerated technological progress, the high obsolescence and the rapid consumption rates of EEE have increased the amount of generated WEEE. This e-waste generation and the estimation of quantities are one of the main issues analysed in the literature, concluding that there is a lack of standardised methods for their estimation in several countries.
- The composition of WEEE is a complex assembly of different toxic materials with impacts both on health and the environment. Articles on WEEE characterisation provide useful information about material composition, which is essential to determine the potential percentage of recovery and recycling of materials, to set design recommendations aimed at

Table 9. Articles focused on ecodesign and design methodologies (F).

Reference	Ecodesign and methodologies	Products
Banar et al. (2014)	Methods of Multi Criteria Decision Making (MCDM) to select the site of the plants used for planning and recycling of electrical and electronic equipment wastes	WEEE
Fujita et al. (2014)	Evaluation of a recycling process for printed circuit board	Printed circuit board from discarded personal computer (PC)
Li et al. (2014)	Creating sustainable development strategies from a local solution to global opportunities that will elevate ecodesign or design for environment to a new level in new materials selecting, CE industry development, integrated e-waste management and legislation	Consumer electronics
Menikpura et al. (2014)	In-depth investigation of the effectiveness of WEEE recycling on GHG mitigation.	Washing machines, refrigerators, air conditioners and televisions
Nelen et al. (2014)	Development of an indicator set that allows to quantitatively demonstrate the recycling benefits of WEEE	LCD televisions
Tan et al. (2014)	Methods or tools for EOL	Cartridge, copier and information technology (IT) servers
Yao et al. (2013)	Comprehensive solution approach to address a complete WEEE collection and transportation network	WEEE
Katsamaki and Bilalis (2012)	Actions that aim to minimise negative environmental consequences of EOL treatment	WEEE
Zhang et al. (2012)	Environmental, economic, and social implications of e-waste recycling	WEEE
Renteria et al. (2011)	New methodology for the selection and design of operations of a recycling system	Television sets and monitors
Achillas et al. (2010b)	Decision support tool for policy makers and regulators to optimise products' reverse logistics network	WEEE
Gamberini et al. (2010)	Technical and economic analysis for recovering specific materials for specific WEEE streams	WEEE
Ijomah and Chiodo (2010)	Active disassembly (AD) to extend profitable remanufacturing	Small electrical and electronic products
Kou (2010)	A collaborative-design platform to provide component information to enable the manufacturer's design for disassembly and recycling analysis	WEEE
Zhou and Qiu (2010)	A new technology for recycling materials from waste printed circuit boards	Waste printed circuit boards
Gamberini et al. (2009)	Innovative container for WEEE collection and transport	WEEE
Giudice and Kassem (2009)	Structured method for the analysis and reconfiguration of the disassembly depth distribution of components making up a constructional system	Video-entry phone
Iakovou et al. (2009)	Multicriteria Matrix methodology methodological framework for management of electronic products	WEEE
Johansson and Luttropp (2009)	Theoretical concept of disassembly structures to introduce the concept of "material hygiene"	Dishwasher
Abu Bakar and Rahimifard (2008)	Integrated framework for the planning of the processes involved in the recycling of WEEE	Refrigerator
Gurauskiene and Varzinskas (2006)	Ecodesign methodology	WEEE
Ravi et al. (2005)	Analytic network process (ANP)-based decision model	Computers
Schmidt (2005)	Material flow system	WEEE
White et al. (2003)	Frame an environmental research agenda for recovery management	Computers
Kerr and Ryan (2001)	Quantify the life cycle environmental benefits achieved by incorporating remanufacturing into a product system, based on a study of Xerox photocopiers in Australia	Photocopier
Lee et al. (2001)	Multi-objective methodology to alternatives that can both maximise profit and minimise environmental impact and use a coffee maker as an example	Coffee maker
Yu et al. (2000)	Decision-making model. Methodology for assessing various recycling alternatives to provide environmentally friendly solutions.	WEEE

WEEE: waste electrical and electronic equipment; GHG: greenhouse gas; LCD: liquid crystal display; EOL: end-of-life.

Table 10. Articles focused on Life Cycle Assessment (LCA) studies of electrical and electronic equipment (F).

Reference	Aim	Products
Arushanyan et al. (2014)	LCA (review)	ICT products and services
Bull and Kozak (2014)	LCA (comparison)	Paper and digital media
Soares et al. (2014)	LCA (comparison)	Printed circuit board
Song et al. (2012b)	LCA (case study)	TV (CRT monitors)
Moberg et al. (2011)	LCA (comparison)	e-books as an alternative to paper books
Andrae and Anderson (2010)	LCA (case study)	Desktop computers, laptop computers, mobile phones and TVs
Hischier and Baudin (2010)	LCA (case study)	Plasma TV device
Johansson and Bjorklund (2010)	LCA (case study)	Dishwasher
Yung et al. (2011)	LCA (case study)	Remote sensor that is designed such that it can measure outdoor temperature and humidity
Moberg et al. (2010)	LCA (comparison)	Printed and tablet e-paper newspaper
Silveira and Chang (2010)	LCA (case study)	Cell phone
Duan et al. (2009)	LCA (case study)	Desktop personal computer
Muñoz et al. (2009)	LCA (case study)	Toys
Apisitpuvakul et al. (2008)	LCA (case study)	Fluorescent lamps
Ahluwalia and Nema (2007)	LCA (case study)	Computer waste
Choi et al. (2006)	LCA (case study)	Personal computers
Emmenegger et al. (2006)	LCA (case study)	Mobile phones
Park et al. (2006)	LCA (comparison)	Washing machine
Andræ et al. (2005)	LCA	Telephones
Socolof et al. (2005)	LCA (case study)	CRT and LCD desktop computer displays
Kondo and Nakamura (2004)	LCA	Electric home appliances (TV sets, refrigerators, washing machines, and air conditioners)
Prek (2004)	LCA (case study)	Heating and air conditioning equipment
Gard and Keoleian (2003)	LCA (comparison)	Digital vs. print journals
Hischier and Reichart (2003)	LCA (comparison)	Printed newspaper, an internet newspaper and a TV broadcast
Kim et al. (2001)	LCA (case study)	Desktop personal computer
Yanagitani and Kawahara (2000)	LCA (case study)	Air conditioners
Ueno et al. (1999)	LCA (case study)	Electronic components industry (semiconductor devices, passive components, transducers, CRTs, connecting components, printed circuit boards, LCD devices)

CRT: cathode ray tube; LCD: liquid crystal display.

improving their EOL or to develop effective disassembly or recycling systems. Most of these studies analyse representative samples from WEEE recycling plants and analyse a particular product or a specific WEEE category. The most commonly analysed products are mobile phones, televisions and personal computers, since they are replaced more often than other EEE.

- The need to implement EPR policies for proper WEEE management in developing countries, in order to solve environmental pollution due to informal recycling practices. EPR is considered to be one of the most powerful policy mechanisms in dealing with this issue in developed countries and, therefore, developing countries are encouraged to develop EPR policy mechanisms considering their own limitations.
- The role of consumer behaviour in e-waste management is crucial to fulfil the objectives set by the legislation. The knowledge about amounts of WEEE in households, consumer disposal preferences, variables for explaining household willingness to recycle e-waste, etc., is a powerful tool to develop an e-waste management system. Some studies concluded that the lack of incentive is one of the main reasons that discourage consumers to manage this waste fraction correctly.
- E-waste is an emerging challenge for developing countries, being that their improper management one of the main concerns in the literature. Dealing with the informal recycling sector is a complex issue and one of the major challenges to overcome. Some of these developing countries are experiencing an increase of the amount of WEEE received, being unable to manage them in a sustainable way, mainly due to the lack of appropriate infrastructures and policies. The need for developing a legal framework for the management of this waste fraction is one of the challenges for the policy makers in developing countries.
- Transboundary movement of e-waste is a major issue throughout developing countries. The illegal movement of WEEE has resulted in significant environmental pollution in both developing and developed countries. With the aim of protecting human health and the environment from adverse impacts, the Basel Convention on the control of transboundary movements of hazardous wastes was developed, but its correct

Table 11. Articles focused on economic aspects (G).

Reference	Aim	Categories	Location
Achillas et al. (2013)	Decision support tool for manufacturers and recyclers towards end-of-life strategies for WEEE based on the cost–benefit analysis concept	Cat. 3 (ICT products)	–
Ejiogu (2013)	Overview on the e-waste topic, highlight the economic arguments for dumping e-waste in developing countries	General WEEE	Nigeria/ Africa
Fan et al. (2013)	To evaluate the recycling rates, costs as well as the disassembly time of a notebook at its end-of-life stage	Cat. 3 (personal computer)	Taiwan/Asia
Kuo (2013)	Petri Net (PN)-based analysis approach is proposed to deal with the disassembly and recycling problems in end-of-life WEEE. By using the PN analysis, the optimal trade-off between the cost and environmental effectiveness of the disassembly processes is determined	Cat. 3 (router)	Taiwan/ Asia
Mayers et al. (2013)	To calculate charges for products sold by producers by classifying them according to their eventual end-of-life treatment requirements and cost providing both effective and efficient frameworks for financing WEEE	General WEEE	–
Achillas et al. (2012b)	Multicriteria optimisation model for multi-type carriers of WEEE, based on multiple objective linear programming (MOLP) to minimise total logistics costs, consumption of fossil fuel and production of emissions	General WEEE	Greece/ Europe
Achillas et al. (2011)	An analysis for the quantification of WEEE management cost for Greece, taking into consideration scenarios for reverse logistics network development and WEEE volume scenarios	General WEEE	–
Liu et al. (2009)	To identify the formal management framework with economic feasibility for the e-waste generated in large municipalities of China	Cat.1 (refrigerators, washing machines, air conditioners) Cat. 3 (personal computer) Cat. 4 (televisions)	China/Asia
Gregory and Kirchain (2008)	Framework for evaluating the economic performance of a recycling system. Data from four electronics recycling systems.	General WEEE	America
Masanet and Horvath (2007)	An analytical framework for quantifying the environmental and economic benefits of Design For Recycling for plastic computer enclosures during the design process, using straightforward metrics that can be aligned with corporate environmental and financial performance goals	Cat. 3 (personal computer)	USA/ America
Kang and Schoenung (2006b)	Identify the various techniques used for treating electronic waste at material recovery facilities (MRFs) to investigate the costs and revenue drivers for these techniques	General WEEE	California/ America
Lu et al. (2006)	Analyse the economic incentive structure as well as the environmental implications of the current national policy for recycling notebook computers (NBs) in the nation of Taiwan, using cost–benefit analysis and formal life cycle assessment (LCA)	Cat. 3 (notebook computers)	Taiwan/Asia
Nakamura and Kondo (2006)	Development of a new methodology of Life Cycle Cost. The applicability of the methodology is illustrated by a case study of electric.	Cat. 1 (refrigerators, washing machines, air conditioners) Cat. 4 (televisions)	Japan/Asia
Macauley et al. (2003)	To model the costs and benefits of policies to manage "e-waste" by focusing on a large component of the electronic waste stream – computer monitors – and the environmental concerns associated with disposal of the lead embodied in cathode ray tubes (CRTs) used in most monitors	Cat. 4 (monitors)	USA/ America

WEEE: waste electrical and electronic equipment.

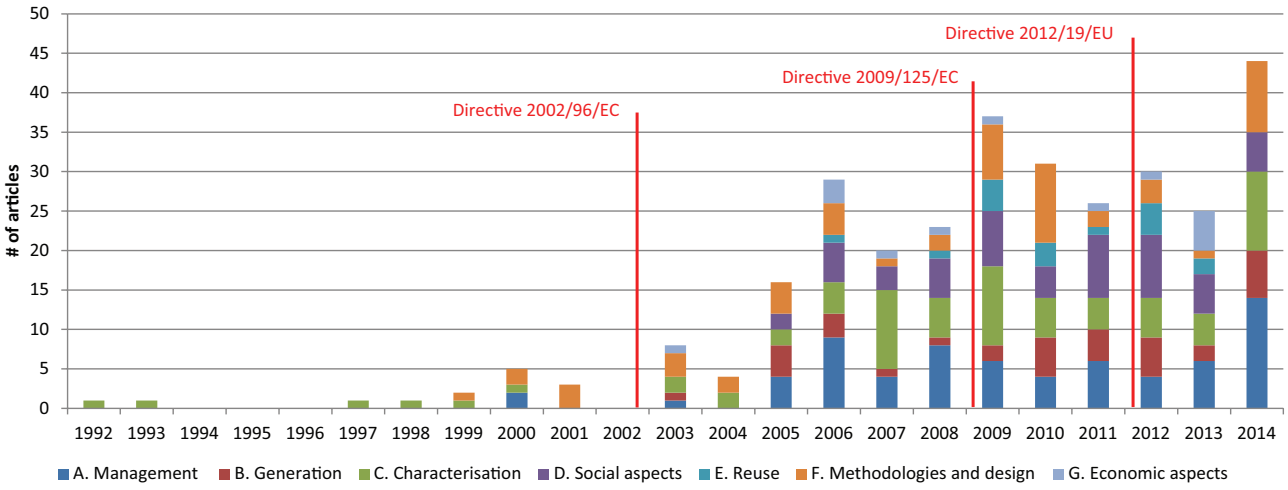

Figure 1. Number of articles by year of publication and topic (until August 2014).

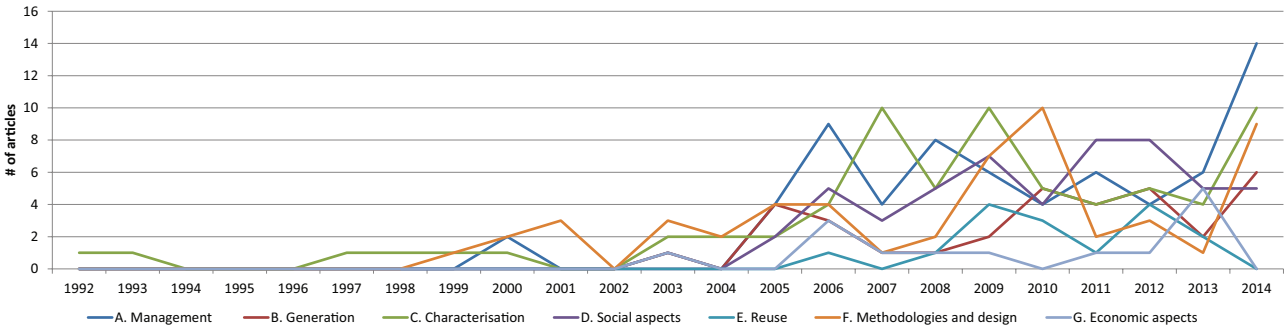

Figure 2. Chronological evolution of articles by topic (until August 2014).

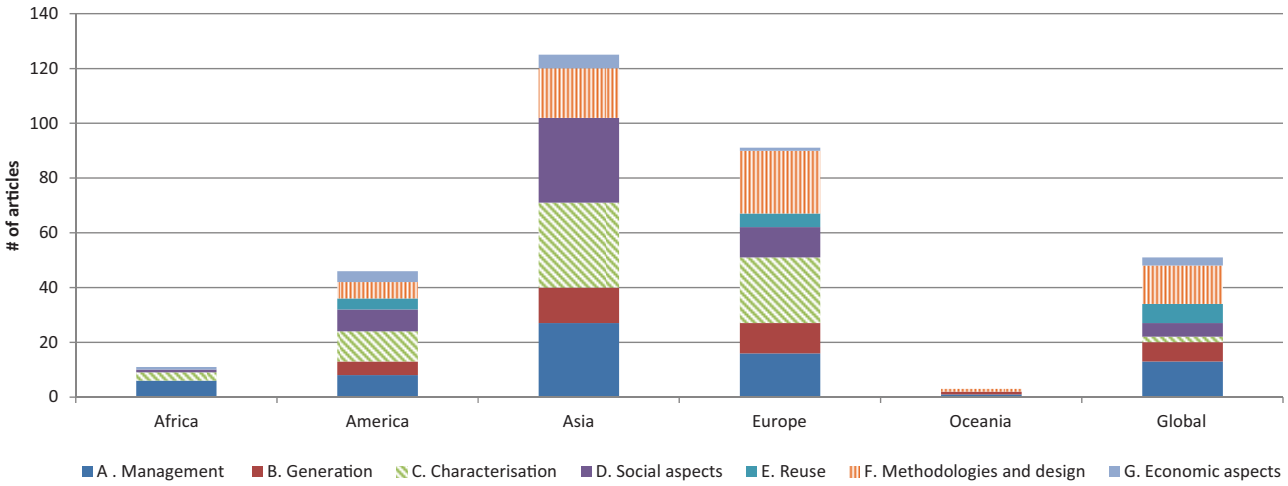

Figure 3. Number of articles by topic and location (until August 2014).

application is still a challenge and concern for many countries.

- Re-using EEE to optimise the use phase of a product, increasing its resource efficiency and as a part of the solution of e-waste management. In recent years, many studies on material substitution, recycling and re-use of WEEE and the way to integrate this into the design of EEE have appeared. The interest in re-use of WEEE comes from the fact that most household appliances that are in perfect working condition are often replaced by others, specifically mobile phones,

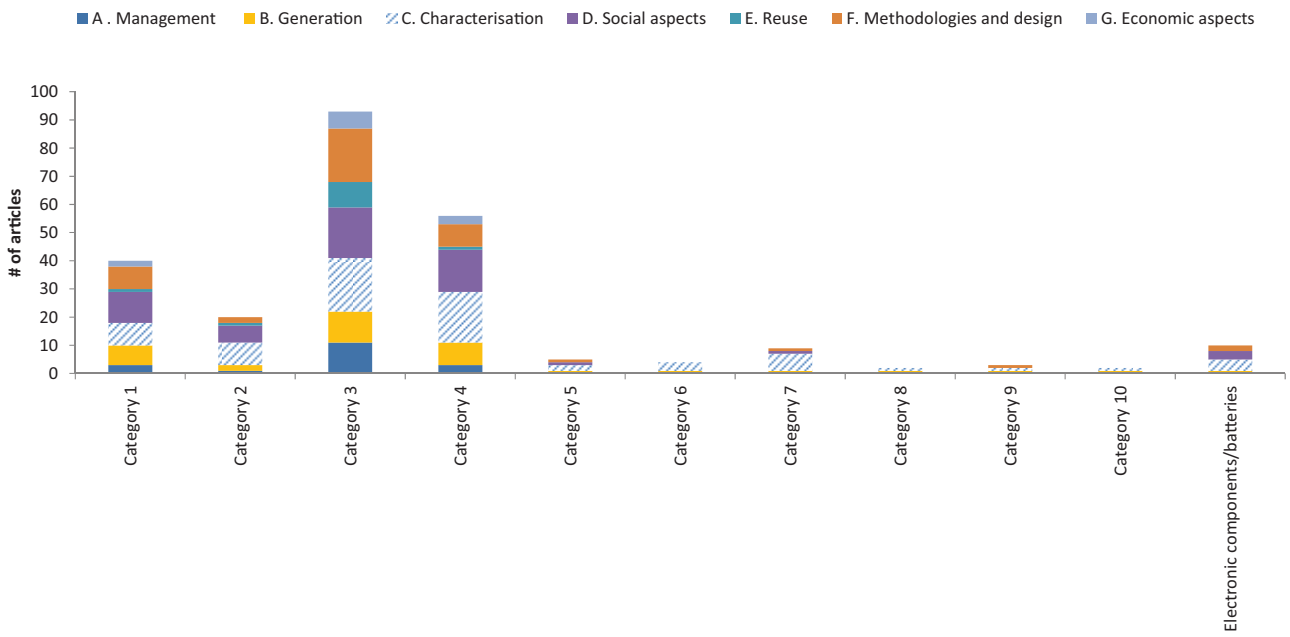

Figure 4. Distribution of articles by waste electrical and electronic equipment category and topic (until August 2014).

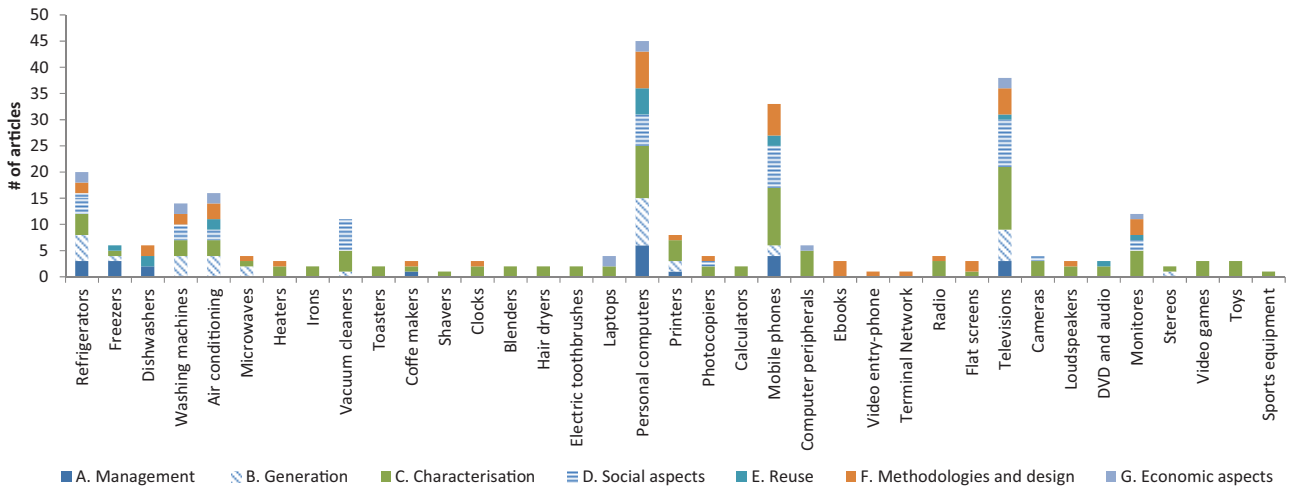

Figure 5. Distribution of articles by waste electrical and electronic equipment subcategory and topic (until August 2014).

televisions and personal computers. To date, the lifetime of second-hand products has not been investigated empirically and there is no authorised testing and certification organisation for such products (Yang et al., 2008). Thus, from now on these certifications, re-use protocols and WEEE disposal conditions will be investigated more often. On this topic, special mention is due to mobile phones, since they are nowadays one of the few electronic products that have a large second-hand market, even more of them being re-used than recycled.

The interest in WEEE research will grow further still, since both consumption of EEE and technology are continually increasing in industrialised countries. Hence, disposal habits of WEEE, material composition and initiatives to facilitate their re-use, recycling and recovery will be further explored.

Although it has to be considered that reviews do not claim to provide exhaustive coverage of all relevant literature, the authors agree that content of this study shows the representative work published on WEEE to date. Our findings make significant contributions to the current literature. Firstly, they provide a detailed review of selected articles in the field of WEEE, and define the main topics and the most researched WEEE categories and products. In addition, they provide a global view of the representative publications in the WEEE field, detailing its location, the main topic of analysis and WEEE categories or products researched. This information is a synthesis of the knowledge currently available about the field of WEEE and its evolution.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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