Automotive printed circuit boards recycling: an economic analysis

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End of Life Vehicles (ELVs), together with Waste from Electric and Electronic Equipments (WEEEs), are re-known as an important source of secondary raw materials. Since many years, their recovery allowed the restoring of great amounts of metals for new cars' production. However, the management of electronic systems embedded into ELVs is yet rarely considered by the scientific literature. The purpose of the paper is trying to fill in this gap through the proposition of an innovative economic model able to identify the presence of profitability within the recovery process of automotive Waste Printed Circuit Boards (WPCBs). Net Present Value (NPV) and Discounted Payback Time (DPBT) will be used to demonstrate the validity of investments in this type of plants. Furthermore, a sensitivity analysis on a set of critical variables (plant saturation level, gold (Au) content, Au market price, Au final purity level, WPCBs pur-chasing cost and opportunity cost) will be conducted for the evaluation of the impact of significant variations on results. Finally, the matching of predicted European ELVs volumes (during the period 2015 –2030) and NPVs coming from the economic model will quantify the potential advantages coming from the implementation of this new kind of circular economy.

Keywords:
Scrap automotive electronics
Waste printed circuit boards
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Recycling

1. Introduction

In the past twenty years, the booming consumer electronics industry rapidly changed the economic and social landscape (Li et al., 2015; Golembiewski et al., 2015; Sun et al., 2015). Highly innovative products, with even lower lifetimes, generated a so high amount of obsolete electronic devices that they became increasingly a global challenge, nowadays re-known as WEEEs, or electronic wastes (e-wastes) problem (Lu et al., 2015; Hong et al., 2015). Printed circuit boards (PCBs) represent the most complex, haz-ardous, and valuable component of e-wastes. They can contain more than 60 elements (on average), including plenty of heavy metals (such as Lead (Pb), Chromium (Cr), Cadmium (Cd), Mercury (Hg), Arsenic (As)) and toxic organic substances (such as brominated flame retardants, polycyclic aromatic hydrocarbons, dechlorane plus, etc.) (Song and Li, 2014; Huang et al., 2014). From the automotive sector point of view, the use of PCBs inside a car for the management of almost all the functionalities of a vehicle drastically increased in the last decades (Kim et al., 2014). Hence, this trend undoubtedly contributed in increasing volumes of PCBs produced and, so, to the overall amounts of WPCBs dismantled. In fact, the automotive sector, together with the mass electronics sector, is one of the most important sources of waste, both in volumes (Zorpas and Inglezakis, 2012; Cucchiella et al., 2014a; S-iYoshida et al., 2014; Tian and Chen, 2014) and in materials content terms (Berzi et al., 2013; Uan et al., 2007). For this reason, basic guidelines for the reuse, recovery and recycling of ELVs were established all over the world in the last decades. Within the scientific literature, lots of papers analysed and compared different ELV directives and national recovery systems (S-iYoshida et al., 2014; Zhao and Chen, 2011). However, some topics were only superficially studied, for example:

- The recycling of scrap automotive electronics (e.g. Electronic Control Units (ECUs)), together with its environmental impacts, does not appears to have been adequately assessed by the experts (Wang and Chen, 2013a, 2012);
- Some authors identified the potential support in the development of new circular economies given by the recovery of automotive electronic systems, but no practical applications are available in literature (Cucchiella et al., 2015a);
- The existing economic models assessing the profitability of recycling plants are very few, and specialized on a particular phase of the process (Ghosh et al., 2015);
- The limited technological development of scrap automotive electronics processes was assessed by some authors as one of

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the main reason for the lacking of literature focused on this topic. This way, the implementation of new kinds of plants (e.g. mobile recycling plants) was not taken into account since now (Zeng et al., 2015).

Given that, the aim of this paper is threefold. From one side, there is the need to define a mathematical model able to assess the potential profitability characterizing all the phases of a typical WPCBs recovery process (or dismantling, pretreatment and refining). From a second side, this calculation has to be done on different types of plants (for example, field and mobile ones). Finally, the potential profitability has to be linked with the available previsions on future ELVs generated volumes for the quantification of the expected market dimension. The important findings of this investigation could be very helpful to governmental and industrial actors for a direct comparison with results coming from similar types of models available in literature, so to better understand the lost opportunity, by trying to define corrective measures for the management of these new types of e-wastes.

The paper is organized as follows: Section 2 presents a description of the research framework and. Section 3 presents theoretical methods adopted within this study and the economic model at the base of the overall analysis. Economic results are presented in Section 4, under the form of NPV and DPBT indexes. Additionally, a sensitivity analysis on the main critical variables (Section 5) and an overall discussion of results (Section 6) will be conducted. Section 7 presents concluding remarks and future perspectives.

2. Research framework

ECUs are among the most valuable electronic devices embedded in modern vehicles. They are able to perform the reading of signals coming from sensors embedded in a car, and control the behaviour of many sub-systems, as engine, air conditioning system, infotainment system, safety devices, etc. (National Instruments, 2009). The current amount of electronic systems is impressive, both in numbers and in impact on costs. In fact, a modern medium-sized car can embed up to 15 electronic systems on average (Kripli et al., 2010; Freiberger et al., 2012) and luxury cars can reach up to 50 among microcomputers and electronic components (Wang and Chen, 2011). Furthermore, a statistic of the Bayerische Moto-ren Werke Corporation shows that, generally, these systems can account for more than 30% of total vehicle cost, reaching more than 50% in luxury cars (Wang and Chen, 2013b). These last data alone allow to evidence how much important is the recovery of the embedded value in these components. However, current ELV directives (based on weighting principles) seems to do not adequately take into account the management of these types of e-wastes (Cucchiella et al., 2015a). Hence, there are no benefits for the actors involved in the automotive reverse logistic chain to invest in dedicated recovery centres (Cucchiella et al., 2015b).

2.1. Automotive PCBs characterization

Before the treatment of any kind of WPCBs amounts, there is a materials' characterization phase. This means a definition of the set of materials embedded in a certain amount of WPCBs, by chemi-cally analysing a sample of them. This is a relevant phase because it allows to: (i) comprehend the presence (or not) of valuable mate-rials (this way a WPCB is classified as high, medium or low grade waste), and (ii) define the expected revenues coming from their recovery. In literature, the common ways to characterize WPCBs are essentially two: (i) considering already available data coming from other papers or intra-governmental reports (UNEP, 2013), and (ii) implementing dedicated laboratory tests (Wang and Gaustad, 2012). The first one is the most common in papers focused on the economic sustainability of PCBs recycling processes. The second one is common when environmental sustainability is the main focus. Given both the clear focus of this paper on the economic side of sustainability, and the lack of existing data about automotive PCBs composition, the approach selected by the authors was the exploitation of existing data coming from industrial database. This explains the decision to consider IMDS as a relevant source of data from which starting with the economic assessment. IMDS is a materials data management system used in the automotive sector. Designed by Audi, BMW, Daimler, HP, Ford, Opel, Porsche, VW, and Volvo, IMDS was then adopted by other car manufacturers, so becoming a global standard used by almost all the automotive Original Equipment Manufacturers (OEMs) worldwide. Data related to 500 different automotive electronic devices were extracted and, subsequently, categorized into four typologies basing on their weights distribution (divided into quartiles). The four resulting groups are represented by:

- Small WPCBs, going from 0.2 g up to 8.7 g;
- Medium-small WPCBs, going from 8.8 g up to 52.9 g;
- Medium-big WPCBs, going from 53.0 g up to 134.2 g;
- Big WPCBs, going from 134.3 g up to 477.9 g.

This choice was purely objective and derives from the fact that waste automotive PCBs are very different in terms of size, shape and composition, depending on their functionality (Wang and Chen, 2013a). Hence, a subdivision like the one commonly done for WPCBs coming from WEEEs (or high, medium and low grade waste) was considered as not representative.

2.2. WPCBs recycling processes

Starting from the main assumption that scrap automotive electronic devices are, in effect, WPCBs, consequently it is possible to consider the same technological process followed for the recycling of WPCBs coming from WEEEs (Wang and Chen, 2013a, 2012; Cucchiella et al., 2015a). Hence, the recycling process can be seen as the sum of three main phases that, starting from WPCBs, are able to obtain as final output a set of (almost pure) raw materials. These phases can be distinguished in: dismantling, pretreatment and refining (Sohaili et al., 2012; Yu et al., 2009) – see Fig. 1.

During disassembly, both the casings embedding PCBs and toxic components present on the main board are separated. Toxic components (e.g. condensers or batteries) are disassembled and destined to specific treatments for hazardous materials. Instead, casings (generally, Aluminium (Al)-made elements) can be directly sold to smelters, becoming an additional source of revenues for recyclers. The pretreatment process is implemented through a series of dedicated machines, or shredders, grinders and separators (based on several physical principles). During pretreatment, WPCBs are crushed into micro pieces up to become a uniform powder, through the use of shredders and grinders. After this phase, powders are separated basing on their composition, by distinguishing metal from non-metal powders (Zeng et al., 2015; Li and Xu, 2010). Nowadays, these last ones are destined to landfills, however there are interesting works studying alternative (and valuable) ways to reuse them for different purposes (Li et al., 2012; Hadi et al., 2013). Finally, metal powders are refined, up to obtain almost pure secondary resources (the purity level differs from on material to another (Wang and Gaustad, 2012)) directly reusable for the production of new goods. The refining process can be based on different technologies (e.g. pyrolysis, pyrometallurgy, hydrometallurgy, biometallurgy). In this work, hydrometallurgy is considered

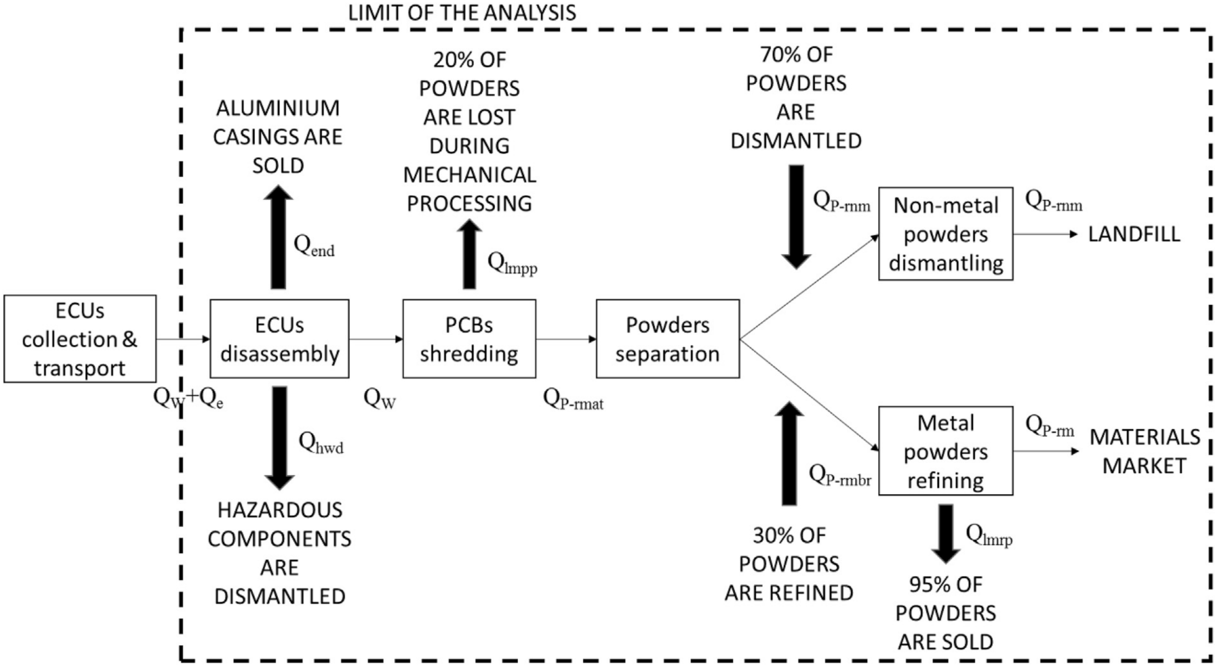

Fig. 1. A traditional WPCBs recycling process – Source: (UNEP, 2013).

as the only refining process because the literature (Behnamfard et al., 2013; Birloaga et al., 2013) commonly agrees on its higher sustainability, if compared to other methods. Although biometallurgy could be even better than hydrometallurgy, currently there are no information about its use at industrial scale (Zhu et al., 2011; Liang et al., 2010).

The economic model that will be proposed in Section 3 has a high level of detail. Hence, it is of utmost importance to take a look on material flows (and related nomenclature) to better comprehend its logic – see Fig. 1. The recycling process starts from the entire ECU (composed by a casing (Q_e) and a PCB (Q_W)). As described before, ECUs are disassembled up to extract PCBs (Q_W) from casings (Q_{end}) and eliminate hazardous components (transferred to dedicated recovery processes – Q_{hwd}). Then, they are reduced into powders and part of them remains trapped into shredder's/grinder's/conveyors mechanisms (Q_{lmpp}). The remaining part ($Q_{p\text{-}rmat}$) is, then, separated into metal ($Q_{p\text{-}rmbr}$) and non-metal ($Q_{p\text{-}rnm}$) powders. The first one is directly refined up to obtain almost pure materials ($Q_{p\text{-}rm}$). For this reason, this part is the one giving an idea of the potentially reachable profitability characterizing input elements. However, during refining a little percentage of materials is lost, because of chemical reactions (Q_{lmrp}). The second one (mainly composed by inert materials, like plastics and ceramics) is currently landfilled ($Q_{p\text{-}rnm}$). In this work, this last part was defined as the difference between the overall WPCB weight and the sum of the metal powders embedded on it.

$$Q_W = p_h * n_h * n_d \tag{1}$$

$$Q_e = Q_W * p_e / (1 - p_e) \tag{2}$$

$$Q_{hwd} = Q_e * p_{ed} \tag{3}$$

$$Q_{end} = Q_e - Q_{hwd} \tag{4}$$

$$Q_{lmpp} = lm_{pp} * Q_W \tag{5}$$

$$Q_{P-rmat} = Q_W - Q_{lmpp} \tag{6}$$

$$Q_{P-rnm} = Q_{P-rmat} * p_{rnm} \tag{7}$$

$$Q_{P-rmbr} = Q_{P-rmat} - Q_{P-rnm} \tag{8}$$

$$Q_{lmrp} = lm_{rp} * Q_{P-rmbr} \tag{9}$$

$$Q_{P-rm} = Q_{P-rmbr} - Q_{lmrp} \tag{10}$$

$$Q_{P-rm,j} = Q_{P-rm} * p_{rm,j} * m_u * \left(1 \Bigg/ \sum_{j=1}^{n_{rm}} p_{rm,j} * m_u \right) \quad \forall j = 1 \ldots n_{rm} \tag{11}$$

$$Q_{P-hrm,j} = \sum\nolimits_{j=1}^{n_{hrm}} Q_{P-hrm,j} \tag{12}$$

$$Q_{P-srm,j} = Q_{P-rm,j} - Q_{P-hrm,j} \tag{13}$$

$$N_W = Q_W / w_W \tag{14}$$

2.3. Recycling plants sizing

After having defined the typical phases constituting a WPCBs recycling process, the next step is the plant's capacity sizing. Given the features of a recycling process (very similar to a productive plant), the sizing activity does not takes into account only the expected level of service (Cucchiella et al., 2015c; Pan et al., 2015), but the required hourly productivity. Hence, by considering the reference values reported in literature (Zeng et al., 2015; Li and Xu, 2010) this parameter was defined to be equal to 0.125 t/h and 0.3 t/h (for mobile and field plants, respectively). These flows are materials (under the form of powders) flowing out from the pretreatment

Nomenclature

j:	recycled metal	p_{rnm}:	% of not metals in recycled materials
lm_{pp}:	lost materials in pretreatment process	Q_e:	quantity of envelope
lm_{rp}:	lost materials in refinement process	Q_{end}:	quantity of not dangerous envelope
m_u:	1 kg of WPCB	Q_{hwd}:	quantity of hazardous waste (disassembly)
n_d:	number of days	Q_{lmpp}:	quantity of lost materials (pretreatment)
n_h:	number of hours	$Q_{P\text{-}hrm,j}$:	quantity of hazardous recycled metal
n_{hrm}:	number of hazardous recycled metal	Q_{lmrp}:	quantity of lost materials (refinement)
n_{nrm}:	number of non recycled metals	$Q_{P\text{-}rm}$:	quantity of powders (recycled metals)
n_{rm}:	number of recycled metals	$Q_{P\text{-}rmat}$:	quantity of powders (recycled materials)
N_W:	number of WPCBs	$Q_{P\text{-}rm,j}$:	quantity of powders (recycled metal j)
p_e:	% of envelope	$Q_{P\text{-}rmbr}$:	quantity of powders (before refinement)
p_{ed}:	% of “dangerous” envelope	$Q_{P\text{-}rnm}$:	quantity of powders (recycled non-metals)
p_h:	hourly productivity	$Q_{P\text{-}srm,j}$:	quantity of selling recycled metal
p_{hwd}:	% of hazardous waste (disassembly)	Q_W:	quantity of WPCBs
$p_{rm,j}$:	% of metal j in 1 kg of WPCB	w_W:	weight of WPCB

phase. Furthermore, by considering a working period of 240 days and 8 working hours per day (according to equation (1)), these are the overall resulting values:

- 240 t powders/year (mobile plant);
- 576 t powders/year (field plant).

These two configurations of a plant are proposed together because, within the EU-28, there are very different distributions of e-wastes from one country to another and within the same country. In some cases, a field plant is useful to recover great amounts of wastes from a specific location. In other cases, a mobile plant able to be transferred from one location to another is preferable to guarantee always a correct saturation of the plant (Zeng et al., 2015; Cucchiella et al., 2014b). However, these generic dimensions present a common limit. In fact, they are related to mono-core plants (able to treat only one type of e-wastes), with a very low flexibility level.

3. Research methodology

Given the literature gaps reported in Section 1 and the detailed description of the research framework in Section 2, it is now possible to better comprehend the economic model at the base of this paper. Firstly, an analysis of the current economic models available in literature (and related to e-waste recycling processes) will be presented. Secondly, the basic pillars (Discounted Cash Flow (DCF) method and reference financial indexes — NPV and DPBT) taken into account for the profitability assessment will be assessed. Finally, the economic model will be described into detail, together with economic and technical input.

3.1. Current economic models

The main features (see Section 1) characterizing almost all of the current economic models focused on e-waste recycling processes can be listed in three points: (i) the focus on a particular phase of the process (Ghosh et al., 2015), (ii) the absence of standards in material composition of WPCBs taken into account (Wang and Gaustad, 2012), and (iii) the limited set of application fields (Wang and Xu, 2015). The focus on a particular phase of the process, even if can leave more space to different technological configura-tions of a recycling plant, influences the overall economic result given by the proposed model. So, from a practical point of view this can offer a limited support to industrial actors when they have to decide to invest (or not) in this type of plants. WPCBs materials composition is the most important variable influencing the prof-itability of the entire recycling process, as already underlined in Section 2. Hence, it is important to correctly characterize WPCBs to maintain the reliability of results. Finally, current studies are almost completely focused on PCBs coming from a particular set of WEEEs, or the ones re-known by the experts as the most profitable to be recovered. Hence, because of the lack in data about WPCBs from automotive scraps, this topic was rarely considered (IMDS, 2015). In practice, the previous three lacks generated a particular kind of papers, whose goals can be briefly synthetized here:

- A costs comparison of different PCBs dismantling processes (e.g. manual versus mechanical techniques) (Zeng et al., 2013);
- A costs comparison of different PCBs disassembly processes (e.g. on a specific product) (Fan et al., 2013);
- A cost comparison of different PCBs shredding + separation processes (e.g. different technologies and plants dimensions)(Zeng et al., 2015; Li and Xu, 2010; Xue et al., 2013);
- A cost comparison of different powders refining processes (e.g. through hydrometallurgical technologies) (Kamberovic, 2011);
- An evaluation of theoretical economic models for PCBs recycling (Niu et al., 2007); of entire PCBs (Wang and Gaustad, 2012).
- An assessment of potential revenues coming from the recovery

Table 1 reports a list of economic indexes currently used within these papers.

Given the current state of literature about economic models related to e-waste recycling processes, it is now possible to evidence the main differences between the proposed model and the existing ones.

3.2. Discounted cash flow method

DCF is a well-known economic assessment method estimating the attractiveness of an investment opportunity. The standard practice is to define a vision of future events precise enough to be captured in a DCF analysis (Courtney et al., 1997). The reliability of this approach is guaranteed also by the European Commission, proposing it as reference method for the evaluation and comparison of investments (Regio, 2008). The main points characterizing the DCF method are the following:

- Only cash inflows and outflows are considered within the analysis;
- The determination of investment's cash flows is based on the incremental approach;
- The aggregation of occurring cash flows during different years requires the adoption of an appropriate discount rate.

Table 1
Current economic indexes used in literature.

Plant size	Index	Value	Reference
0.5 kt WPCBs	Total cost	25,000 \$ (manual) 50,000 \$ (mechanical)	(Zeng et al., 2013)
10 kt WPCBs	Total cost	350,000 \$ (mechanical) 400,000 \$ (manual)	(Zeng et al., 2013)
Not specified	Net profit	1.61 € (per notebook)	(Fan et al., 2013)
0.1 t WPCBs/h	Net Profit	600 RMB	(Niu et al., 2007)
0.2 t WPCBs/h	Net Profit	1300 RMB	(Niu et al., 2007)
0.125 t WPCBs/h	Gross Profit	−83 \$/t (field plant) 14 \$/t (mobile plant)	(Zeng et al., 2015)
0.3 t WPCBs/h	Gross Profit	129 \$/t (manual–automatic line) 256 \$/t (automatic line)	(Li and Xu, 2010)
50 kg of WEEE per batch	Total revenues Payback Time	62,000 \$/y (200 ppm Au) 161,000 \$/y (1000 ppm Au) Not feasible (200 ppm Au) 3 y (1000 ppm Au)	(Kamberovic, 2011)
100 kg of WEEE per batch	Total revenues Payback Time	99,000 \$/y (200 ppm Au) 339,000 \$/y (1000 ppm Au) Not feasible (200 ppm Au) 1 y (1000 ppm Au)	(Kamberovic, 2011)
Not specified	Payback Time Internal rate of return	2.5 y 43%	(Xue et al., 2013)
1 t WPCBs	Potential revenues	21,500 \$/t (baseline scenario) 3800–52,700 \$/t (alternative scenario)	(Wang and Gaustad, 2012)

A critical point of this method is that its reliability completely depends by the level of confidence of future cash flows.

3.3. Profitability indexes

Several economic indexes can be chosen to represent profitability, as evidenced in Section 1. However, net and gross profit seems to be the most common among the experts. The problem is that they do not analyse all the lifetime of an investment, but only a predefined period. Hence, the authors decided to consider other kind of indexes, as Net Present Value (NPV), Discounted Payback Time (DPBT) and Internal Rate of Return (IRR) (Cucchiella et al., 2015c; Chiaroni et al., 2014; Larsson et al., 2015; Weigel et al., 2015; Cucchiella et al., 2015d):

- NPV is defined as the sum of present values of individual cash flows;
- DPBT represents the number of years needed to balance cumulative discounted cash flows and initial investment;
- IRR identifies the discount rate at which the present value of all future cash flows will balance the initial investment.

However, among these three indexes only NPV and DPBT were selected, because of the poor relevance of criticisms related to them. In fact, NPV does not consider the size of the plant and DPBT ignores both instant and value of cash flows. However, these indexes provide a single result. Instead, IRR can cause conflicting answers (multiple IRR can occur) when compared to NPV in mutually exclusive investments (Brealey et al., 2011).

3.4. The economic model

The profitability of a recycling plant is influenced by two main variables, or materials embedded into WPCBs and plant capacity. For this reason the set of selected scenarios evaluated in this paper are eight. They are obtained by a combination between the four WPCBs groups (Small WPCBs, Medium-small WPCBs; Medium-big WPCBs and Big WPCBs) and the two sizes of the plants (240 t/y and 576 t/y) – please see Section 2 for details. The economic model considered within the paper can be described with the following equations:

$$\mathrm{NPV} = \sum_{t=0}^{n} C_t \Big/ (1+r)^t = \sum_{t=0}^{n} (I_t - O_t) \Big/ (1+r)^t \tag{15}$$

$$\sum_{t=0}^{\mathrm{DPBT}} C_t \Big/ (1+r)^t = 0 \tag{16}$$

$$I_t = \sum_{j=1}^{n_{rm}} Q_{P-srm,j} * pl_{rm} * pr_{rm,j,t} \quad \forall t = 1 \ldots n \tag{17}$$

$$0_t = C_{lcs,t}^{2^\circ s} + C_{lis,t}^{2^\circ s} + C_{lcs,t}^{3^\circ s} + C_{lcs,t}^{3^\circ s} + C_{o,t}^{1^\circ s} + C_{o,t}^{2^\circ s} + C_{o,t}^{3^\circ s} + C_{tr,t} + C_{tax,t} \quad \forall t = 1 \ldots n \tag{18}$$

$$C_{inv}^{2^\circ s} = C_{inv}^{u,2^\circ s} * Q_W \tag{19}$$

$$C_{lcs,t}^{2^\circ s} = C_{inv}^{2^\circ s} \Big/ n_{debt} \quad \forall t = 0 \ldots n_{debt} - 1 \tag{20}$$

$$C_{lis,t}^{2^\circ s} = \left(C_{inv}^{2^\circ s} - C_{lcs,t}^{2^\circ s} \right) * r_d \quad \forall t = 0 \ldots n_{debt} - 1 \tag{21}$$

$$C_{inv}^{3^\circ s} = C_{inv}^{u,3^\circ s} * Q_{P-rmbr} \tag{22}$$

$$C_{lcs,t}^{3^\circ s} = C_{inv}^{3^\circ s} \Big/ n_{debt} \quad \forall t = 0 \ldots n_{debt} - 1 \tag{23}$$

$$C_{lis,t}^{3^\circ s} = \left(C_{inv}^{3^\circ s} - C_{lcs,t}^{3s} \right) * r_d \quad \forall t = 0 \ldots n_{debt} - 1 \tag{24}$$

$$C_{o,t}^{1^\circ s} = C_{a,t}^{1^\circ s} + C_{d,t}^{2^\circ s} + C_{l,t}^{1^\circ s} \tag{25}$$

$$C_{a,t}^{1^\circ s} = C_a^u * Q_W \tag{26}$$

$$C_{a,t+1}^{1^\circ s} = C_{a,t}^{1^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{27}$$

$$C_{d,t}^{1^\circ s} = C_d^u * Q_{hwd} \tag{28}$$

$$C_{d,t+1}^{1^\circ s} = C_{d,t}^{1^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{29}$$

$$C_{l,t}^{1^\circ s} = C_l^u * n_d * n_{op}^{1^\circ s} \tag{30}$$

$$C_{l,t+1}^{1^\circ s} = C_{l,t}^{1^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{31}$$

$$C_{o,t}^{2^\circ s} = C_{cm,t}^{2^\circ s} + C_{e,t}^{2^\circ s} + C_{i,t}^{2^\circ s} + C_{l,t}^{2^\circ s} + C_{m,t}^{2^\circ s} \tag{32}$$

$$C_{cm,t}^{2^\circ s} = C_{cm}^u * Q_{P-rnm} \tag{33}$$

$$C_{cm,t+1}^{2^\circ s} = C_{cm,t}^{2^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{34}$$

$$C_{e,t}^{2^\circ s} = C_e^u * \left(e_u^{2^\circ s} \big/ p_h \right) * Q_W \tag{35}$$

$$C_{e,t+1}^{2^\circ s} = C_{e,t}^{2^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{36}$$

$$C_{i,t}^{2^\circ s} = p_i * C_{inv}^{2^\circ s} \tag{37}$$

$$C_{i,t+1}^{2^\circ s} = C_{i,t}^{2^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{38}$$

$$C_{l,t}^{2^\circ s} = C_l^u * n_d * n_{op}^{2^\circ s} \tag{39}$$

$$C_{l,t+1}^{2^\circ s} = C_{l,t}^{2^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{40}$$

$$C_{m,t}^{2^\circ s} = p_m^{2^\circ s} * C_{inv}^{2^\circ s} \tag{41}$$

$$C_{m,t+1}^{2^\circ s} = C_{m,t}^{2^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{42}$$

$$C_{o,t}^{3^\circ s} = C_{d,t}^{3^\circ s} + C_{e,t}^{3^\circ s} + C_{i,t}^{3^\circ s} + C_{l,t}^{3^\circ s} + C_{m,t}^{3^\circ s} + C_{rem,t}^{3^\circ s} \tag{43}$$

$$C_{d,t}^{3^\circ s} = C_{cm,t}^{3^\circ s} * Q_{P\text{-}hrm} \tag{44}$$

$$C_{d,t+1}^{3^\circ s} = C_{d,t}^{3^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{45}$$

$$C_{e,t}^{3^\circ s} = C_e^u * e_u^{3^\circ s} * Q_{P-rmbr} \tag{46}$$

$$C_{e,t+1}^{3^\circ s} = C_{e,t}^{3^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{47}$$

$$C_{i,t}^{3^\circ s} = p_i * C_{inv}^{3^\circ s} \tag{48}$$

$$C_{i,t+1}^{3^\circ s} = C_{i,t}^{3^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{49}$$

$$C_{l,t}^{3^\circ s} = C_l^u * n_d * n_{op}^{3^\circ s} \tag{50}$$

$$C_{l,t+1}^{3^\circ s} = C_{l,t}^{3^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{51}$$

$$C_{m,t}^{3^\circ s} = p_m^{3^\circ s} * C_{inv}^{3^\circ s} \tag{52}$$

$$C_{m,t+1}^{3^\circ s} = C_{m,t}^{3^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{53}$$

$$C_{rem,t}^{3^\circ s} = C_{rem}^u * Q_{P-rmbr} \tag{54}$$

$$C_{rem,t+1}^{3^\circ s} = C_{rem,t}^{3^\circ s} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{55}$$

$$C_{tr} = C_{tr}^u * (Q_W + Q_e) * d_{tf} \tag{56}$$

$$C_{tr,t+1} = C_{tr,t} * (1 + \mathrm{inf}) \quad \forall t = 1 \ldots n \tag{57}$$

$$C_{tax,t} = ebt_t * C_{tax}^u \quad \forall t = 1 \ldots n \tag{58}$$

3.5. Economic and technical input

Economic and technical inputs are proposed in Table 2. The mobile plant investment cost is evaluated almost 639 k€, while the fixed plant assumed to be almost 1533 k€ (Zeng et al., 2015; Li and Xu, 2010; Kamberovic, 2011; Cucchiella et al., 2014c). This difference evidences the presence of an economy of scale of about 29% and the investment cost is covered by third party funds. The recovered materials evaluation occurs in function of market prices historical trend per a defined period of time. By taking as reference the March 2014–March 2015 period, monthly observations were gathered from the most relevant websites dedicated on raw materials exchanges. Initial assumptions were taken from scientific literature. However, with the aim to better explain the effects of changes in values of relevant variables, a sensitivity analysis will be proposed in the next Section 5.

After having defined the economic model structure (and related input values), all the financial indexes useful for the assessment of the investment will be estimated in Section 4.

4. Results

The economic evaluation of a project allows the easing of its application in a real context, where profitability is verified. In fact, as in waste recycling processes, this could represent not only an environmental protection action, but also an economic opportunity. As already presented in Section 3, eight scenarios are analysed in this work, and is clear that the financial feasibility is always verified (Table 4). Furthermore, it is also important to underline the relevance of results. In fact, DPBT is equal to one year. This means that cash flows allow the re-entering from the investment already at the end of the first year of activity. This result is confirmed also by the work of Kamberovic (2011), even if the author analysed the only metals refining phase and 1000 ppm of Au in WPCBs on average. Instead, NPV varies basing on both plant capacity and WPCBs types. From one side, NPVs reach their maximum value (495,726 €/t) with a field plant and Small WPCBs (presenting 4200 ppm of Au). From the other side, NPVs reach their minimum value (52,495 €/t) with a mobile plant and Big WPCBs (presenting 900 ppm of Au). A direct comparison with existing literature is not possible due to absence of data related to economic performances on WPCBs recycling. However, it is possible to highlight that these values are higher than the ones obtained by Zeng et al. (2015) who considered a field and a

Nomenclature			
C_a:	acquisition cost of WPCBs	C_{tr}^u :	unitary transportation cost of the plant
C_a^u:	unitary acquisition cost of WPCB	d_{tf}:	distances of transportation of the plant
C_{cm}:	conferred material cost	DPBT:	discounted payback time
C_{cm}^u:	unitary conferred material cost	$e_u^{2^\circ s}$:	energy power (pretreatment)
C_d:	disposal cost	$e_u^{3^\circ s}$:	energy power (refinement)
C_d^u:	unitary disposal cost	ebt:	earnings before taxes
C_e:	electric power cost	I_t:	discounted cash inflows
C_e^u:	unitary electric power cost	inf:	rate of inflation
C_i:	insurance cost	n:	lifetime of investment
C_{inv}:	total investment cost	n_{debt}:	period of loan
$C_{inv}^{u,2^\circ s}$:	unitary investment cost (pretreatment)	$n_{op}^{1^\circ s}$	number of operators (disassembly)
$C_{inv}^{u,3^\circ s}$:	unitary investment cost (refinement)	$n_{op}^{2^\circ s}$	number of operators (pretreatment)
C_l:	labour cost	$n_{op}^{3^\circ s}$	number of operators (refinement)
C_l^u:	unitary labour cost	NPV:	net present value
C_{lcs}:	loan capital share cost	O_t:	discounted cash outflows
C_{lis}:	loan interest share cost	p_i:	% of insurance cost
C_m:	maintenance cost	$p_m^{2^\circ s}$:	% of maintenance cost (pretreatment)
C_o:	operational cost	$p_m^{3^\circ s}$:	% of maintenance cost (refinement)
C_{rem}:	reactant materials cost	pl_{rm}:	purity level of recycled metal
C_{rem}^u :	unitary reactant materials cost	pr_{rm}:	price of recycled metal (average value)
C_t:	discounted cash flow	p_{rm}^{sd}:	price of recycled metal (standard deviation)
C_{tax}:	taxes	r:	opportunity cost
C_{tax}^u :	unitary taxes	r_d:	interest rate on loan
C_{tr}:	transportation cost of the plant	t:	time of the cash flow

1°s: "disassembly" step; 2°s: "pretreatment" step; 3°s: "refinement" step.

mobile plant with a capacity of 0.125 t/h. in this case gross profits where equal to −83 \$/t and 14 \$/t (see section 3.1). Furthermore, these values are also different from the ones presented by Li and Xu (2010) who considered a field plant with a capacity of 0.3 t/h and a gross profit equal to 256 \$/t (see section 3.1). However, both the authors considered only the pretreatment phase and only one type of WPCBs presenting an Au content of about 5 ppm. Consequently, their revenues come mainly from the recovery of Cu.

Field plants present a longer lifecycle than mobile plants (10 years out of 5 years). This aspect, starting from equal gross profits, explains the reaching of greater NPVs. Furthermore, from one side economies of scale are exploited. Instead, from the other side, the

Table 2
Economic and technical input.

Variable	Value	Reference	Variable	Value	Reference
C_a^u :	1195 €/t	(Zeng et al., 2015)	$n_{op}^{1^\circ s}$:	1^i; 2^{ii}	(Zeng et al., 2013)
C_{cm}^u:	90 €/t	(Cucchiella et al., 2015d)	$n_{op}^{2^\circ s}$:	2^i; 3^{ii}	(Zeng et al., 2015)
C_d^u:	325 €/t	(Zeng et al., 2015)	$n_{op}^{3^\circ s}$:	2^i; 3^{ii}	(Zeng et al., 2015)
C_e^u:	0.11 €/kWh	(Zeng et al., 2015)	n_{rm}:	Table 3	(IMDS, 2015)
$C_{inv}^{u,2^\circ s}$:	913 €/t^i; 646 €/t^{ii}	(Zeng et al., 2015; Li and Xu, 2010)	n_{rnm}:	Table 3	(IMDS, 2015)
$C_{inv}^{u,3^\circ s}$:	3860 €/t^i; 2740 €/t^{ii}	(Kamberovic, 2011; Cucchiella et al., 2014c)	p_e:	70%	(IMDS, 2015)
C_l^u:	150 €/d	(Ardente et al., 2014)	p_{ed}:	5%	(IMDS, 2015)
C_{rem}^u :	830 €/t	(Cucchiella et al., 2014c)	p_h:	0.125 t/h^i; 0.3 t/h^{ii}	(Zeng et al., 2015; Li and Xu, 2010)
C_{tax}^u :	36%	(Cucchiella et al., 2014c)	p_i:	2%	(Cucchiella et al., 2015d)
C_{tr}^u :	0.34 €/(km*t)	(Zhao et al., 2011)	$p_m^{2^\circ s}$:	25%	(Copani and Rosa, 2014)
$e_u^{2^\circ s}$:	50 kW^i; 141 kW^{ii}	(Zeng et al., 2015)	$p_m^{3^\circ s}$:	5%	(Kamberovic, 2011)
$e_u^{3^\circ s}$:	3900 kWh/t^i; 9500 kWh/t^{ii}	(Cucchiella et al., 2014c)	p_{rnm}:	Table 3	(IMDS, 2015)
d_{tf}:	200 km^i; 0 km^{ii}	(Cucchiella et al., 2014c)	p_{rm}:	Table 3	(IMDS, 2015)
inf:	2%	(Cucchiella et al., 2015d)	pl_{rm}:	95%	(UNEP, 2013)
lm_{pp}:	20%	(UNEP, 2013)	pr_{rm}:	Table 3	(London exchange, 2014; Metces, 2014; Infe, 2014)
lm_{rp}:	5%	(UNEP, 2013)			
n:	$5y^i$; 10 y^{ii}	(Li and Xu, 2010)	r:	5%	Cucchiella et al., 2015d)
n_d:	240 d	(Li and Xu, 2010)	r_d:	4%	(Cucchiella et al., 2015d)
n_{debt}:	5 y	(Cucchiella et al., 2015d)	w_W:	3.73 g^a; 26.66 g^b; 94.99 g^c; 209.09 g^d	(UNEP, 2013)
n_h:	8 h	(Li and Xu, 2010)			
n_{hrm}:	Table 3	(IMDS, 2015)			

i = mobile plant; ii = field plant.
a = Small WPCBs; b = Medium-small WPCBs; c = Medium-big WPCBs; d = Big WPCBs (average value).
Potential revenues derived by Q_{end} are not considered.
Conversion factor: 1 \$ = 0.93 €

Table 3
Characterization of materials embedded into ECUs.

Materials	Small WPCBs	Medium-small WPCBs	Medium-big WPCBs	Big WPCBs	Generic WPCBs	Generic WPCBs
n_{rm}	p_{rm} (%)	p_{rm} (%)	p_{rm} (%)	p_{rm} (%)	pr_{rm} (€/kg)	p^{sd}_{rm} (€/kg)
Revenues						
Silver (Ag)	0.09	0	0	0	480	45
Gold (Au) (*)	0.42	0.20	0.24	0.09	32,500	4500
Copper (Cu)	18.84	24.19	14.52	16.30	5.13	1.2
Iron (Fe)	0.18	0.17	0.19	0.10	0.064	0.02
Nickel (Ni)	0.69	0.43	1.13	0.89	12	1.2
Tin (Sn)	1.81	1.46	1.23	1.56	16	2.1
Tantalum (Ta)	0.08	0	0	0	148	25
Lead (Pb)	0.71	1.13	0.40	0.27	2.1	0.4
Costs						
n_{rnm}	p_{nrm} (%)	p_{nrm} (%)	p_{nrm} (%)	p_{nrm} (%)		
Epoxy Resin	15.81	3.73	12.73	13.60		
Glass fibre	19.34	35.56	35.53	36.72		
Others(**)	2.63	2.63	1.23	1.47		
Delta mat(***)	39.40	30.50	32.80	29.00		

(*) 0.42% of Au is equal to 4200 ppm, or 4200 g of Au in 1 ton of WPCBs.
(**) Others are all the materials (metals and non metals) cited by the IMDS database, but not considered in this work.
(***) Delta mat (metals and non metals) is the difference between the overall mass of a WPCB and the sum of all the considered materials embedded in a WPCB. It represents the amount of materials not considered by the IMDS database.

Table 4
Economic indexes — baseline scenario.

Index	Small WPCBs	Medium-small WPCBs	Medium-big WPCBs	Big WPCBs
Mobile plant (240 tons of powders/year)				
DPBT (y)	1	1	1	1
NPV (k€)	66,304	30,966	36,639	12,599
NPV/Q_W (€/t)	276,267	129,026	152,662	152,495
Field plant (576 tons of powders/year)				
DPBT (y)	1	1	1	1
NPV (k€)	285,538	134,271	158,562	55,656
NPV/Q_W (€/t)	495,726	233,110	275,280	96,626

higher number of recycled WPCBs allows to recover a higher amount of Au (Table 5). However, as explained in other papers (Zeng et al., 2015; Kamberovic, 2011) mobile facilities applications represent an ideal solution for small countries or cities and, at the same time, they play an important role in collecting wastes.

A scenario with a mobile plant treating Small WPCBs presents a higher NPV (66,304 k€) than a scenario with a field plant treating Big WPCBs (55,656 k€). This means that the percentage of Au embedded into WPCBs has greater effect than dimensions. However, it is of utmost importance to consider that these results were obtained by hypothesizing a full saturation of plants.

To this aim, in the next section of the paper, a sensitivity analysis will be implemented on both non-saturated plants. Instead, there are no market data related to WPCBs original applications and this pushed the authors to consider mono-core plants. However, future research objectives are the evaluation of multi-cores plants, able to treat all types of WPCBs independently from their dimensions and primary industrial application. To this aim, being the Au content a critical variable, during the sensitivity analysis also this aspect will be considered. Furthermore, scientific literature and past pilot plants experiences evidenced as recycling plants flexibility plays a relevant role (Rocchetti et al., 2013). To this aim, potential revenues coming from single waste streams can be used as a benchmarking factor (Cucchiella et al., 2015b). Finally, for what concerns the Au relevance among revenues items, data showed in Fig. 2 are significant: by considering the four types of WPCBs these are equal to 97.7% on average both in mobile and field plants. Another paper fixed the incidence of Au on potential revenues in 71%, by considering a value of about 15,200 $/t, but with a range going from a minimum level of 2500 $/t up to a maximum level of 40,000 $/t. Clearly, the type of WPCBs considered influenced these results. This is why the authors of this paper decided to take into account data coming from the IMDS database, allowing the management of a more significant sample.

Instead, the costs distribution analysis shows as the operational costs are equal to 95.1% for a field plant and 89.1% for a mobile plant. These results are coherent with respect of what proposed by other works (Zeng et al., 2015; Li and Xu, 2010; Kamberovic, 2011; Cucchiella et al., 2015d). The most relevant item is represented by WPCBs purchasing both for field and mobile plants (47,5% and

Table 5
Number of WPCBs treated and quantities of recycled gold.

Index	Small WPCBs	Medium-small WPCBs	Medium-big WPCBs	Big WPCBs
Mobile plant (240 tons of powders/year)				
N_W (1000*unit)	64,343	9002	2527	1148
$Q_{P\text{-}rm,\ Au}$ (kg)	791	380	448	167
Field plant (576 tons of powders/year)				
N_W (1000*unit)	154,424	21,605	6064	2755
$Q_{P\text{-}rm,\ Au}$ (kg)	1898	913	1075	400

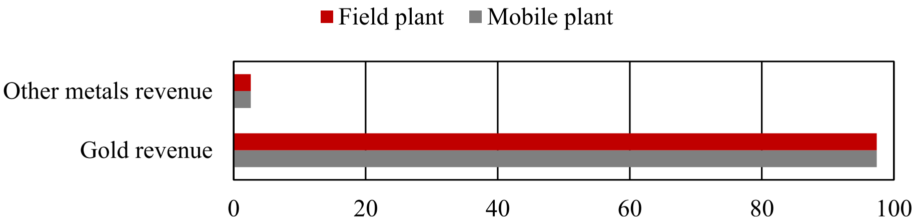

Fig. 2. Plant's revenues distribution – average values.

37.5%, respectively). This value is followed by labour costs (19.9% and 23.6%, respectively). Finally, transport costs are equal to 7.1% in the mobile plant (Fig. 3).

In order to strengthen the obtained results, a sensitivity analysis oriented to alternative scenarios (if compared to what presented before) is implemented in the next section.

5. Sensitivity analysis

NPV results are based on assumptions of a set of input variables. However, compared to the baseline scenario, the critical variables can record changes with respect to initial estimations (Cucchiella et al., 2015d). Basing on what obtained in Section 4, critical vari-ables are the ones that, more than others, have an influence on revenues and costs. From the revenues point of view, it has been demonstrated that they mainly depend on the recovery of Au. Hence, three are the variables determining results: (i) the Au content, as percentage of the WPCB total weight (it was already analysed, in fact four categories of WPCBs were evaluated in this paper); (ii) the Au market price, varying from an optimistic and pessimistic scenario where the assumed value is equal to 37,000 €/kg and 28,000 €/kg (this range is equal to its standard deviation) – see Table 2; (iii) the final purity level, varying from 60% up to 90%, under the common hypothesis of 95% of the literature. From the costs point of view, the most relevant item is represented by WPCBs purchasing cost. As done for revenues, also in this case an optimistic and pessimistic scenarios are assessed, where costs vary from 1000 €/t up to 1400 €/t (or an offset of about 200 €/t from the base value). Furthermore, in accord to what previously presented, is important to evaluate what happens when plants are not fully saturated. In this case, investment costs are unchanged, but operational incomes will vary. In particular, a lower amount of WPCBs in input represents a lower hourly productivity. To this aim, five pessimistic scenarios are assessed, with saturation levels going from 50% up to 90%. For example, considering the mobile plant, 90% of 240 t/h is equal to 216 t/h (Table 6). Instead, by considering the field plant, 90% of 576 t/h is equal to 518 t/h (Table 7). Finally, the last variable considered is the opportunity cost, able to evaluate the money value in different periods. This is a key parameter of the DCF method. Even in this case, an optimistic and pessimistic scenarios are assessed, with values varying from 4% up to 6%.

The financial profitability is verified in all the one hundred twenty alternative scenarios. WPCBs purchasing and opportunity costs variations are not so relevant. Instead, the most significant offsets comes from a possible low level of wastes in input. In fact, whereas both mobile and field plants have to work with a saturation of 50% (or treating 120 kt and 288 kt, respectively), NPVs are reduced of about 50%. Plants flexibility could allow the treatment of other types of wastes, but this could reduce expected profits. Basing on what evidenced by the literature, WPCBs are valuable compo-nents embedded into WEEEs. The IMDS demonstrated as auto-motive WPCBs are even valuable items, and their Au content could be higher than in WEEEs. Furthermore, the wide Au market price variation could determine critical offsets. However, results – even in less advantageous situations – offer relevant economic oppor-tunities. Hence, further additional costs needed to obtain a higher Au purity level are easily compensated. Results proposed by this paper clearly define the sustainability of these recycling plants from an economic perspective. A global overview on the economic impact related to the recovery of these wastes within the European market is described in the next section.

6. Discussion

The aim of this section is to support the quantification of potential revenues coming from the correct management of e-wastes coming from automotive scraps and try to analyse their expected

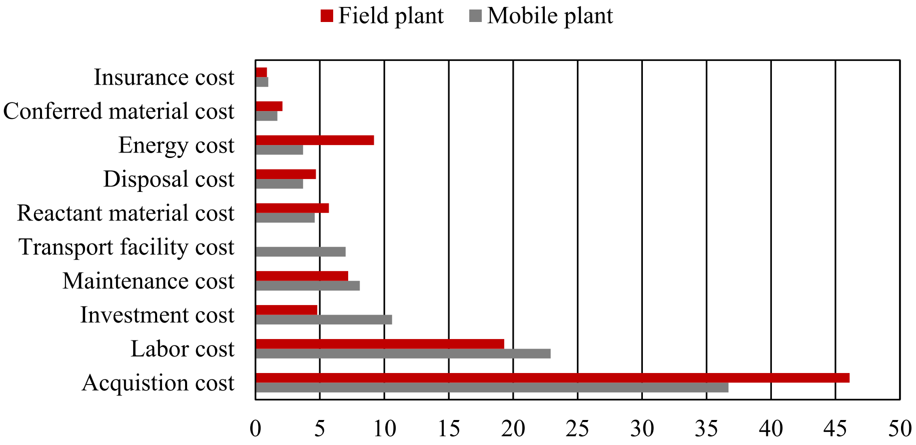

Fig. 3. Plant's costs distribution – average values.

Table 6
Sensitivity analysis — mobile plant.

Variable	Value	Small WPCBs		Medium-small WPCBs		Medium-big WPCBs		Big WPCBs	
		NPV (k€)	Δ%	*NPV (k€)*	Δ%	*NPV (k€)*	Δ%	*NPV (k€)*	Δ%
pr_{Au} (€/kg)	37,000	75,670	14.1	35,472	14.6	41,944	14.5	14,571	15.7
	28,000	56,938	−14.1	26,460	−14.5	31,334	−14.5	10,627	−15.7
pl_{Au} (%)	90	62,744	−5.4	29,254	−5.5	34,622	−5.5	11,253	−10.7
	80	55,624	−16.1	25,828	−16.6	30,589	−16.5	9907	−21.4
	70	48,503	−26.8	22,403	−27.7	26,556	−27.5	8562	−32.0
	60	41,383	−37.6	18,977	−38.7	22,523	−38.5	7216	−42.7
C_a^u (€/t)	1400	66,160	−0.2	30,822	−0.5	36,495	−0.4	5870	−53.4
	1000	66,441	0.2	31,104	0.4	36,776	0.4	12,736	1.1
Q_W (t)	216	59,588	−10.1	27,784	−10.3	32,889	−10.2	12,376	−1.8
	192	52,872	−20.3	24,601	−20.6	29,140	−20.5	10,888	−13.6
	168	52,872	−30.4	21,419	−30.8	25,390	−30.7	9399	−25.4
	144	39,439	−40.5	18,237	−41.1	21,640	−40.9	7911	−37.2
	120	32,723	−50.6	15,054	−51.4	17,891	−51.2	6422	−49.0
r (%)	4	68,180	2.8	31,844	2.8	37,677	2.8	12,957	2.8
	6	64,508	−2.7	30,126	−2.7	35,646	−2.7	12,256	−2.7

Table 7
Sensitivity analysis — field plant.

Variable	Value	Small WPCBs		Medium-small WPCBs		Medium-big WPCBs		Big WPCBs	
		NPV (k€)	Δ%	*NPV (k€)*	Δ%	*NPV (k€)*	Δ%	*NPV (k€)*	Δ%
pr_{Au} (€/kg)	37,000	325,629	14.0	153,558	14.4	181,271	14.3	64,099	15.2
	28,000	245,447	−14.0	114,984	−14.4	135,852	−14.3	47,214	−15.2
pl_{Au} (%)	90	270,299	−5.3	126,940	−5.5	149,929	−5.4	52,447	−5.8
	80	239,821	−16.0	112,277	−16.4	132,665	−16.3	46,029	−17.3
	70	209,342	−26.7	97,615	−27.3	115,401	−27.2	39,611	−28.8
	60	178,864	−37.4	82,952	−38.2	98,137	−38.1	33,193	−40.4
C_a^u (€/t)	1400	284,892	−0.2	133,625	−0.5	157,915	−0.4	55,010	−1.2
	1000	286,153	0.2	134,886	0.5	159,177	0.4	56,271	1.1
Q_W (t)	518	256,545	−10.2	120,510	−10.2	142,330	−10.2	49,812	−10.5
	461	228,053	−20.1	106,987	−20.3	126,378	−20.3	44,068	−20.8
	403	199,060	−30.3	93,226	−30.6	110,147	−30.5	38,223	−31.3
	346	170,567	−40.3	79,702	−40.6	94,195	−40.6	32,479	−41.6
	288	141,575	−50.4	65,941	−50.9	77,964	−50.8	26,634	−52.1
r (%)	4	299,933	5.0	141,044	5.0	166,556	5.0	58,465	5.0
	6	272,161	−4.7	127,978	−4.7	151,132	−4.7	53,047	−4.7

trends in the next 15 years. To do that, the first data required was the overall amount of expected ELVs generated from 2015 up to 2030. These data, together with related trends, were gathered directly from the literature (Eurostat, 2014; Møller Andersen et al., 2008). The selection of this source, instead of others, was given by the fact that this is the official estimation of ELVs volumes also considered by the EU commission during the implementation of the current ELV Directive. The second step was the distinction between two ELV categories, or premature and natural ELVs. Premature ELVs, from one side, are almost new cars reaching their end of life prematurely, generally because of a serious accident. Representing almost 20% of total ELVs volumes generated annually (Ferrão and Amaral, 2006; Hiratsuka et al., 2014; Zhou and Dai, 2012), these cars are almost destroyed and there are very few chances to recover some components. Hence, the hypothesis done by the authors within this paper was the recycling of the total amount of volumes. Natural ELVs, from the opposite side, are cars reaching their end of life naturally, generally for ageing reasons, and represent the 80% of the total amount of annual ELVs volumes (Ferrão and Amaral, 2006; Hiratsuka et al., 2014; Morselli et al., 2010; Kanari et al., 2003). This way, they represent a good source of second-hand spare parts or for remanufacturing scopes (remanufactured volumes are estimated in almost 20%–30% of the overall volume of ELVs). However, for the purpose of this paper, expected remanufactured volumes are not considered in calculations. So, the initial amount of ELVs in terms of number of vehicles was translated in terms of million tons to be potentially treated and, then, divided between premature and natural ELVs amounts. The average ELV mass was defined in about 1.16 tons (Zorpas and Inglezakis, 2012; Møller Andersen et al., 2008; Vermeulen et al., 2011). Third step was the definition of the average PCBs mass (in percentage) out of the total ELV mass. This index was defined through a series of phases. A direct observation of about 500 automotive PCBs mass coming from the IMDS database shown that, basing on their function, weights can vary from 0.2 g (e.g. in door controls or cooling fans) up to almost 500 g (e.g. in ECUs, instrument panels or navigation and entertainment systems). The mean weight was defined in 85 g per WPCB. Given that, in a medium car, there are 15 mechatronic components on average (Kripli et al., 2010) and that each of them embeds at least one PCB (Freiberger et al., 2012), this indicates a total weight, in terms of electronic components, of about 1.275 kg per car. Given an average ELV mass of about 1.16 tons (Zorpas and Inglezakis, 2012; Møller Andersen et al., 2008; Vermeulen et al., 2011), the ratio was established in 0.11%, on average. This ratio was used to quantify the annual generation of WPCBs coming from both premature and natural ELVs. Finally, it was possible to predict (with logical approximations) the expected revenues (in a min–max range) coming from the correct management of these amounts of automotive WPCBs. The following Table 8 reports all these data. For example, the calculation of the results reported in Table 8 and related to 2015 was obtained as follows:

Table 8
Estimates of generated ECUs volumes in EU25 from natural and premature ELVs.

	2015	2020	2030
EU ELV projected number (Mvehicles)	13.3	14.6	16.8
EU ELV expected mean weight (tons)	1.16	1.16	1.16
EU premature ELVs annual generation (Mtons)	3.09	3.39	3.90
EU natural ELVs annual generation (Mtons)	12.34	13.55	15.59
EU total ELVs annual generation (Mtons)	15.43	16.94	19.49
EU WPCBs expected mean weight (Kg)	1.275	1.275	1.275
EU premature WPCBs annual generation (Ktons)	3.39	3.73	4.29
EU natural WPCBs annual generation (Ktons)	13.58	14.90	17.15
EU total WPCBs annual generation (Ktons)	16.97	18.63	21.44
EU total WPCBs expected NPVs − min values (M€)	891	978	1125
EU total WPCBs expected NPVs − max values (M€)	8412	9235	10628

Source (Eurostat, 2014; Ferrão and Amaral, 2006; Hiratsuka et al., 2014; Vermeulen et al., 2011); self-made analysis.

$$13.3\text{ Mvehicles}*1.16\text{ t/vehicle} = 15.43\text{ Mtons} \tag{59}$$

$$15.43\text{ Mtons}*20\% = 3.09\text{ Mtons from premature ELVs} \tag{60}$$

$$15.43\text{ Mtons}*80\% = 12.34\text{ Mtons from natural ELVs} \tag{61}$$

$$\begin{aligned}&(3.09\text{ Mtons}*0.11\%) + (12.34\text{ Mtons}*0.11\%)\\&\quad = 3.39\text{ Ktons} + 13.58\text{ Ktons} = 16.97\text{ Ktons}\end{aligned} \tag{62}$$

$$16.97\text{ Ktons}*52,495\text{ €/tons} = 891\ M\text{€} \tag{63}$$

$$16.97\text{ Ktons}*495,726\text{ €/tons} = 8412\ M\text{€} \tag{64}$$

Table 8, in the last two rows, reports the potential dimension of the automotive WPCBs recycling market. Values are impressive, going from 891 million € up to 1125 billion € as minimum values, and refer to the base scenario presented in Section 4. Maximum levels are even more interesting, going from 8412 billion € up to 10628 billion €. These numbers, even if theoretical, demonstrate the utmost importance of automotive WPCBs management and the amount of profits that could be potentially achieved. Trying to strengthen the reliability of these estimates, the application of more accurate prediction models (e.g. Artificial Neural Networks (ANN)) (Chau and Muttil, 2007; Muttil and Chau, 2007) could be an option when complex issues on sustainable topics has to be solved (Zhao et al., 2006; Wu and Chau, 2006; Xie et al., 2006; Muttil and Chau, 2006). Without any doubt, this market could become an interesting business for many companies involved in closed-loop supply chains.

7. Conclusions

End of Life Vehicles are one of the most important sources of secondary raw materials. However, studies demonstrating the embedded value in their electronic systems are quite rare. Even if, from one side, this issue gives space to a potentially new research stream, from another side it represent a big limitation in terms of available data. Hence, this paper suffers of a lack of proved information and the entire economic and sensitivity analysis are done starting from both expected values and data coming from similar sectors. Interesting improvements of this work could be the assessment of environmental impacts of the recycling process, analysis of different configurations of closed-loop supply chains, and definition of corrective policies to current ELV directives. Future directions in this research stream are expected to be the assessment of recycling issues coming from the treatment of hybrid and full-electric cars or auto-guided vehicles. The intention of the paper was not only to partially fill in this literature gap, but also propose something of interesting from a practical point of view. Hence an economic model evaluating potential revenues and costs coming from the recycling of scrap automotive electronics was implemented and described into detail. The obtained indexes (e.g. NPV and DPBT) demonstrated the validity of investments in two different types of plants (mobile and field ones) and for all the four types of WPCBs considered. Economic values obtained from the model are so high, and different from common values available in literature, because of the relevant presence of Au in automotive WPCBs. A sensitivity analysis done on critical variables (e.g. plant saturation level, Au content, Au market price, Au final purity level, WPCBs purchasing cost and opportunity cost) allowed to test the robustness of theoretical evaluations. Finally, the matching of predicted ELVs volumes in the next fifteen years and expected NPV allowed to define the potential dimension of a market dedicated to the treatment of these wastes. These results could be useful for all the actors involved, with different roles, in closed-loop supply chains, as governments, recyclers, OEMs, consumers and other stakeholders, constituting the starting point for the definition of a new kind of circular economy.

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