Examining the feasibility of the urban mining of hard disk drives

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Abstract

Cities are becoming one of the greatest generators of waste and thus a potential source of secondary materials. One of the most attractive waste streams in cities is waste electrical and electronic equipment (WEEE) as they contain many valuable metals, mainly in the printed circuit board (PCB), with a high risk of a disruption in their supply. Many of the PCBs contained in small WEEE are separated by destructive operations, as the economic feasibility of their separation using non-destructive operations remains unclear. This paper examines the feasibility of separating the PCB and the permanent magnets (PMs) contained in hard disk drives (HDD) using non-destructive operations. The economic cost of separating these parts is evaluated by the disassembly sequences, the disassembly schemes, and using the 'ease of Disassembly Metric' (eDiM). In HDD, the economic cost for the non-destructive separation of the PCB is €0.05 while the cost to harvest the PCB as well as the PMs is €0.39. In both cases, such cost is well below the estimated economic value of the gold, silver, and palladium contained in the PCB (€0.85). As a result, the paper concludes that the separation of the PCB and the PMs of HDDs is economically profitable. Measures for promoting the non-destructive separation of the PCBs and the PM of HDDs should be further promoted, as they could help improve the supply of secondary raw materials.

1. Introduction

Cities are nowadays considered one of the most important sources of secondary materials (Li, 2015). Buildings and infrastructures are made of a large quantity of concrete, bricks and ceramics as well as other materials like gypsum and wood, steel and copper (Müller et al., 2017). Cities are also a great generator of wastes, including waste electrical and electronic equipment (WEEE). In 2016, Barcelona generated 2.3 kg of WEEE per inhabitant while cities like Copenhagen and Berlin generated 1.2 kg and 4 kg per inhabitant, respectively (Petersen, 2018; United Nations, 2016; Vogt and Fehrenbach, 2017). The world generated a total of 44.7 million metric tonnes of WEEE in 2016. By 2021, the total volume of WEEE is due to increase by 17% and reach over 50 million metric tonnes (Balde et al., 2017). The interest in recovering secondary materials from WEEE is increasing, as it has become an economic and environmentally feasible source of materials (Cucchiella, 2015; Shaw et al., 2013). For instance, the recycling of metals requires from 10 to 15% less energy than their production from ore concentrates (Tesfaye et al., 2017). The total treatment costs of obtaining copper and gold from recycled cathode ray tube (CRT) televisions is estimated to be 13 times lower than the cost from virgin mining (Zeng et al., 2018). Additionally, WEEE contains higher concentrations of valuable metals than in the mineral ores extracted from mines. For instance, mobile phones contain 200 times the amount of gold in typical gold ores, and about 14 times the gold contained in the highest known grade deposit (Charles et al., 2017; Takahashi, 2009). In the EU, urban mining can become an alternative source of materials that are generally imported, thus reducing the dependency on external sources and possibly reducing the potential of supply disruptions, and therefore price fluctuation (Blengini et al., 2017).

Printed Circuit boards (PCBs) are one of the key parts of the vast majority of the electrical and electronic equipment (EEE) on the market as they are crucial to provide many of their functionalities. PCBs are made of flat sheets of insulation material, often composed of epoxy resin and glass fibre, and multiple copper layers (Szalatkiewicz, 2014). They provide a stable support for the interconnection of various semiconductors and other components, which together provide the necessary functionality of EEE. Some authors state that PCBs contain more than 20 valuable metals while representing up to 6% of the mass of WEEE (Cucchiella, 2015). They include some of the substances regulated by the EU's Restriction of Hazardous Substances (RoHS) and by the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) (European Commission, 2016a, 2011). Many materials in the PCBs are strategically crucial for the EU economy due to their application in information technology and in low carbon energy technologies (European Commission, 2017) (Blengini et al., 2017). Due to all the previous statements, since 2012, the WEEE directive enforced the separation of those PCBs with a surface area greater than 10 square centimetres (European Commission, 2012). The EU report on Best Environmental Management Practices states that non-destructive separation methods for PCBs are preferred as the recovery rates for gold, silver and palladium are higher (European Commission, 2016b). Some recyclers separate the PCB through manual sorting before the HDDs are shredded (Habib, 2015) however, destructive operations are still the dominant technology used to separate the PCBs from WEEE because the feasibility of disassembly operation remains unclear (Binnemans et al., 2013; Sprecher et al., 2014). Many PCBs are assembled using highly customized designs that limit their accessibility and separation.

The aim of this paper is to present a methodology to analyse the feasibility of separating certain parts of EEE that have a significant content of valuable materials using non-destructive operations. For this purpose, the study first presents the methodology describing the steps to estimate the disassembly operations; the time for disassembly and the resulting economic cost, as well as the economic value of the part separated. Then, it continues with the description of a case study that analysed the feasibility of separating the PCB and the permanent magnets (PMs) of HDDs collected in a recycling company in Barcelona. The results section includes a description of the disassembly schemes and the disassembly sequences for the HDD units disassembled, the estimated cost for disassembly and the economic value of the PCB. The discussion focuses on the economic profitability of disassembly and the significance of HDDs in the Barcelona area. The paper ends with a conclusion section where the results are summarised.

2. Methodology

The analysis of the feasibility of disassembly mostly focuses on methods to estimate the time and the cost of disassembly (Mohite, 2005; Peeters et al., 2018; Talens Peiró and Ardente, 2015). The methodology presented in this paper systematically combines the information collected from the methods mentioned above with an economic assessment of the value of the harvested part/s. The objective is to provide more complete and comprehensive knowledge to support or oppose the decision to disassemble EEE. Figure 1 shows the four main steps of the method proposed. A description of each of the steps of the methodology follows.

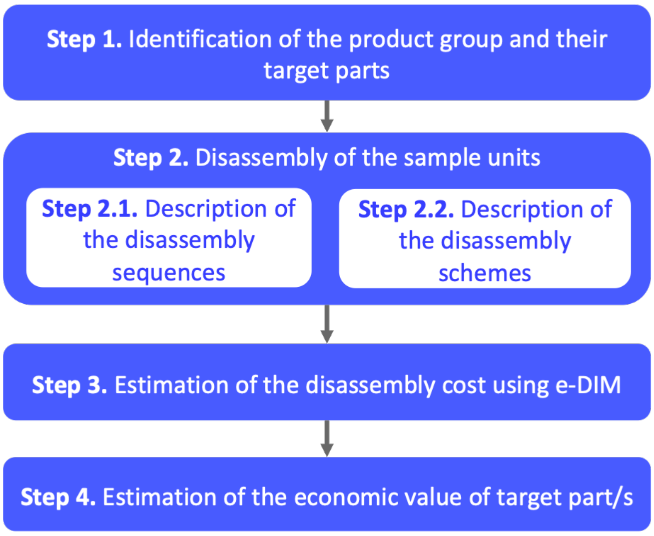

Figure 1. Steps of the method proposed to analyse the HDD sample units

Step 1 of the methodology is to identify a relevant product group. Relevant products are those whose presence in the waste collection sites is increasing or due to increase considerably in the coming years, and have a significant content of materials which are strategically important for the EU (European Commission, 2016c). At this stage, target parts that are relevant due to their material content are also identified. PCBs are generally one of the target parts as they contain the greatest number and quantity of relevant materials.

In step 2, a number of samples of the product due to be analysed is disassembled in order to collect information about the internal design. Each sample is labelled, weighed and measured. Other characteristics such as model name, model number, and manufacturing year are also noted. Information about each of the samples is collected in parallel in the form of a disassembly sequence (step 2.1) and a disassembly scheme (step 2.2). Both of them represent the main source of information to identify design features hindering the accessibility of product parts, and therefore the recovery of materials. The disassembly sequence gives descriptive information about accessibility, the disassembly operations, and the tools required to reach the parts (de Ron and Penev, 1995). The accessibility of a part in a product can be evaluated based on the number and the types of fasteners with other parts of the product. The disassembly operations are described by disassembly tasks such as to unplug a connection, to remove a lid, to unscrew, or to transfer the parts to a different position (Peeters et al., 2018). The tools include equipment such as a screwdriver, a lever, a spudger, suction cups, and a hammer, among others. The use of standardised fasteners, and therefore tools, favours non-destructive operation for disassembly.

Moreover, the disassembly schemes seek to graphically represent the progressive separation of parts by levels. In the schemes, the rectangles represent the parts of the product while the arrows are the linkages between the parts. The parts of the product that are readily accessible are represented at Level 0 while the parts that are highly linked to other parts and more restricted are represented at the higher levels. The parts that are accessible and promptly separated with few operations and few linkages are more likely to undergo non-destructive disassembly and be fully recovered. Both the disassembly sequences and the disassembly schemes can be generally complemented with pictures in order to keep additional information about the links between the parts contained in the product, and the position of fasteners.

In step 3, the time for disassembly using the ‘ease of Disassembly Metric’ (eDiM) method is estimated (Peeters et al., 2018). eDiM has already defined the time to perform six basic disassembly tasks: *tool change, identification of connectors*, m*anipulation*, p*ositioning*, *disconnection* and r*emoving* (Vanegas et al., 2018). The longer the disassembly time, the more difficult and costly the disassembly operations are (Hesselback and Kühn 1998). The disassembly times are also used to judge the design of a product by calculating the effort required for disassembly. Supporting information S1 includes the disassembly time estimated for a list of basic tasks defined by eDiM. The results from eDIM are subsequently used to make an educated guess of the cost of disassembly. The economic cost is calculated based on the annual working hours, and the cost of a specialist mechanical operator to perform the disassembly. It can be expressed per unit of product, as well as for the total units collected during a certain period of time (i.e. one year).

The final step is to do an assessment of the economic value of the target part/s based on a number of materials and their quantities. The amount of the materials contained in a product can be taken from existing studies or be calculated using theoretical estimates of the composition of the EEE. The prices of the materials evaluated are gathered in websites such as the London Metal Exchange (London Metal Exchange, n.d.), Infomine (Informines, n.d.), Focus Economics (Focus Economics, 2019a, 2019b, 2019c) and reports by organisations such as the German Federal Institute for Geoscience and Natural Resources (Bastian, 2018), among others.

3. The case of hard disk drives in Barcelona

In this paper, the product selected for the case study was a hard disk drive (HDD). A HDD is a data storage device used to store and to retrieve digital information. HDDs are considered a relevant product because they are becoming an increasing waste flow in WEEE as the need for data storage continues to increase and the newer solid-state drives (SSDs) are progressively replacing them (Statista - The statistics portal, 2019a). In addition, the average lifespan of a HDD is from three to five years, which means that almost all units shipped in 2016 are likely to have already reached their end of life (Jeremy, 2017). At recycling sites, wasted HDDs are generally treated with other similar products by semi-automated separation with commercial shredding or smashing, and then, the resulting fractions are manually separated into different material streams (Talens Peiró and Ardente, 2015; Yan et al., 2013). The materials contained in the printed circuit boards (PCBs) liberated in such processes are generally diluted and end up dissipated with other WEEE fractions (Binnemans et al., 2013). Commercial shredding and smashing are still the dominant processes used because the volume of wasted HDDs reaching recycling sites is uncertain and the cost of separating valuable parts contained in HDDs such as PCBs has not been estimated to date, however it is considered unfeasible from a recycler's standpoint. Indeed, one of the reasons to select HDDs for the case study was because a recycling company located in the Barcelona area was interested in gaining further knowledge about the feasibility of using non-destructive processes to harvest the PCBs and the permanent magnets (PMs) from HDDs. PCBs were targeted because of the concentration of valuable metals such as gold, silver and palladium, especially in integrated circuits, capacitors and connectors (Cucchiella, 2015; Habib, 2015; Işıldar et al., 2018; Ogunniyi et al., 2009). PMs, located in the actuator and spindle motor, were selected because of the quantities of rare earths (Project REMANENCE, 2012; Ueberschaar and Rotter, 2015) and their potential in-use stock available as secondary supply (Ciacci et al., 2019). The cost of separating them by non-destructive disassembly however remains unclear. The methodology presented in this paper aims to fill this information gap.

Once the product and the target parts were identified, as described in step 2 of the methodology, the samples were disassembled using standardized tools, generally a manual screwdriver (mainly Torx T6-T8 bits), a lever and puncturing tools. In this study, 25 HDDs manufactured between 1996 and 2015 from a local WEEE recycling facility were disassembled. There were 19 3.5'' HDD samples and six 2.5'' HDD samples analysed. The HDDs selected represented the brands with the greatest market share: Western Digital (38.6%), Seagate (20.9 %), Toshiba (17,7%), Hitachi (2.7%), Sony (2.1%), Fujitsu (1%) and others (17%) (Statista - The statistics portal, 2018). Before their disassembly, each HDD was measured using a digital calliper (SH20), weighed using an electronic scale (Kern & Sohn GmBH model KB 6500-1NM) and coded based on its manufacturing brand, and the number of the sample. Supporting information S2 includes the technical and physical description of each of the HDDs analysed.

During the disassembly of the sample units, the number of components liberated was noted alongside the information of the tasks, the operations, the number and the type of tools used, as well as the number of fasteners. Pictures illustrating the position of parts were also taken. For instance, figure 2 shows the position of the PCB (highlighted in green in the picture on the left), and the position of the PMs (highlighted in green in the picture on the right) in the HDD sample S3. The position of the screws due to be extracted to separate the PCB and the PM1 are noted in red in this example. Supporting information S3 includes pictures of all the parts contained in HDDs.

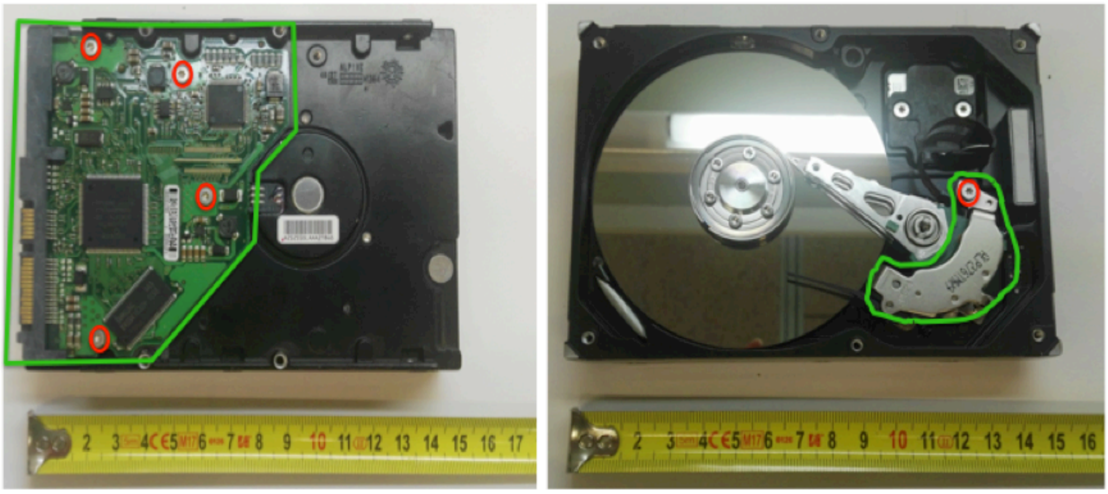

Figure 2. The position of the PCB (left picture) and the PMs (right picture) in the HDD sample S3. The screws due to be extracted are highlighted in red in both pictures.

Following step 3 of the methodology, the time for the disassembly tasks was estimated using the “ease of Disassembly Metric” (eDiM) methodology. The economic cost of separating the PCB and the PMS was calculated based on the annual working hours (1,780 hours) and the economic cost of a specialist mechanical operator (€19,152) in Barcelona. The economic cost of an operator is estimated to be the gross salary, defined by the Spanish Collective agreement for the recovery and recycling of waste and secondary raw materials (Spanish Ministry of employment and social security, 2016), plus the cost the company assumes to hire the worker (33% of the gross salary). Based on those figures, the estimated cost of an operator in a recycling site to perform disassembly tasks is estimated to be €0.003 per second.

The final step was to estimate the economic value of the target parts of the HDD. The analysis was limited to the quantity of gold, silver and palladium contained in the PCBs for several reasons. The first reason was because these metals are the most valuable in the PCBs. Often the harvesting of the PCBs is not feasible if these metals are not contained in significant quantities. The quantity of gold, silver and palladium in a PCB was estimated to be 3,440 ppm, 1,020 ppm and 210 ppm respectively, based on (Ueberschaar and Rotter, 2015). The second reason was because of the lack of a competitive rare earth industry in the EU, and thus a secondary sector where the recycled materials from the PMs can be supplied (Ciacci et al., 2019). Another reason was because data about the recovery yields of materials from the shredded PCB and the PCBs treated by non-destructive operations are only available for gold, silver and palladium. The recovery rate for gold and palladium is 36%, while the recovery rate for silver is 72% (Chancerel et al., 2009). Thus, to calculate the economic value of the PCB, the prices for the three metals were taken from the (Focus Economics, 2019a, 2019b, 2019c). In short, the economic value of the PCBs was estimated to be €0.85 when disassembled and €0.34 when shredded. See supporting information S4 for further details.

4. Results

This section shows the results in terms of time and economic cost regarding the separation of the printed circuit board (PCB) and the permanent magnets (PMs) of 25 HDDs analysed. One of the most important steps in the methodology was to generate a disassembly sequence and a disassembly diagram for each HDD. Table I shows the disassembly sequence for sample S3. As illustrated, the PCB was removed using two operations, one of them consisting of unscrewing four Torx TT8 screws. The actuator PMs were separated at task 5 and at task 13, respectively. The operations to separate the actuator PMs were to unscrew one Torx TT8 screw and then to lift the magnet. The PM contained in the spindle motor (PM3) of sample S3 was harvested after unscrewing two Torx TT8 screws and pulling the motor apart using the hands. A total of 15 tasks, 25 operations and the removal of 28 Torx TT8 screws were needed to fully disassemble the sample S3. The tools used were a screwdriver, a lever and hands.

Table I. Disassembly sequence of sample S3.

Level #	Task #	Task description	Operation #	Operation description	Tools	Fastener type	# Fastener
0	1	Remove printed circuit board (PCB)	1	unscrew	screwdriver	Torx TT8	4
			2	lift	hands		
0	2	Remove top casing	1	unscrew	screwdriver	Torx TT8	6
			2	tear label	lever		
			3	unscrew	screwdriver	Torx TT8	1
			4	pull	hands		
1	3	Remove PBC pad insulator	1	pull	hands		
1	4	Remove debris filter	1	pull	hands		
1	5	Remove actuator magnet 1	1	unscrew	screwdriver	Torx TT8	1
			2	lift	lever		
1	6	Remove counterweight	1	tear	lever		
1	7	Remove actuator PCB head	1	unscrew	screwdriver	Torx TT8	2
			2	lift	lever		
1	8	Remove spindle ring 1	1	unscrew	screwdriver	Torx TT8	6
			2	lift	lever		
2	9	Remove plastic holder	1	remove	hands		
2	10	Remove spindle ring 2	1	pull	hands		
2	11	Remove read/write head	1	unscrew	screwdriver	Torx TT8	1
			2	pull	hands		
3	12	Remove platter 1	1	pull	hands		
3	13	Remove actuator magnet 2	1	unscrew	screwdriver	Torx TT8	1
			2	lift	lever		
4	14	Remove spindle motor	1	unscrew	screwdriver	Torx TT8	3
			2	pull	hands		
5	15	HDD casing	1	remove	hands		

Disassembly schemes were developed once the disassembly sequences were complete. Figure 3 shows the disassembly scheme for sample S3. For this sample, there were five subsequent levels of operations (represented by discontinuous blue lines) where diverse parts were separated. The light green rectangles denote the target components while the rest of the parts are illustrated by the white rectangles. Each of the rectangles includes an orange heptagon with a number inside representing the number of fasteners due to be unscrewed (in this sample all the fasteners were Torx TT8 screws). The grey circle inside the rectangles with a number inside gives information on the number of operations needed to separate the part. Black arrows graphically represent the links between parts. In sample S3, the PCB could be readily separable without removing any additional part by two operations including the unscrewing of four Torx TT8 screws. Figure 4 also shows the top casing and the PCB needed to be removed in order to separate the actuator PMs. A total of 12 operations and the removal of 15 screws were needed to harvest the actuator PMs from sample S3. The PM3 of the spindle motor was separated in 16 operations by extracting 20 screws. The disassembly sequences and the disassembly schemes of all the HDD samples analysed are included in the supporting information S5 and S6.

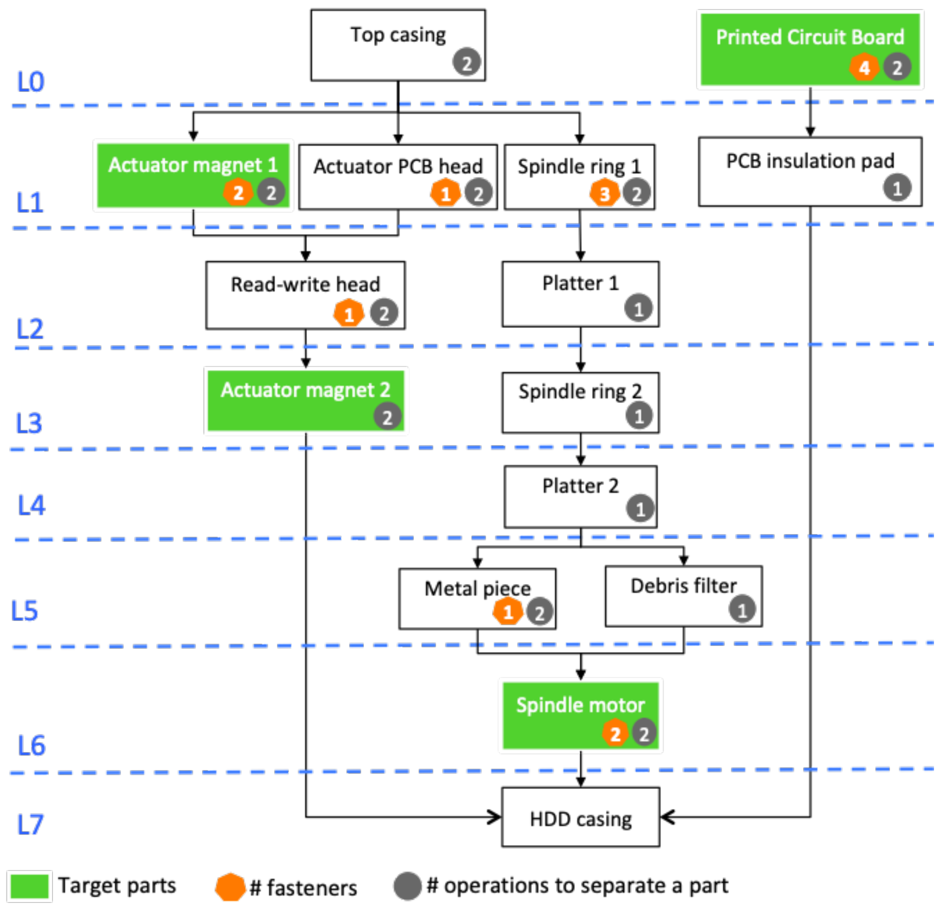

Figure 3. Disassembly scheme of sample S3.

Based on the disassembly sequences and the disassembly schemes, one of the first observations was that only one HDD (sample HP2) out of the 25 HDDs could not be fully disassembled using non-destructive methods because the heads of the screws located in the top casing were worn out. In this sample, the only part that could be successfully separated was the PCB. A second observation was that the internal design of the HDD is identical in the two sizes of the HDD analysed despite being manufactured more than ten years apart. Therefore, HDDs could be considered a highly standardised product (Sprecher et al., 2014). From a technical standpoint, non-destructive operations could be considered a feasible option to separate valuable parts.

4.1. Separation of the Printed Circuit Board (PCB)

The PCB was the only target part readily separable in all of the HDD samples. The position of the PCB and its fixtures has not experienced significant changes through the years, despite the fact that the mass of the PCB has been reduced to half. For instance, the mass of the PCB of S1 (1996) is twice that of WD4 (2015) while equal steps are needed to separate them. In 96% of all the HDDs analysed, the PCB was readily accessible and separated by two operations: the unscrewing of the fasteners and the lifting of the PCB. Regarding the number of fasteners, five out of the six 2.5'' HDD samples used six screws while one HDD used nine screws. Almost 70% of the 3.5” HDDs used four screws, 16% of the HDDs used five screws and the remaining three HDD samples used six, seven and nine screws. The type and the size of the screwdriver bit were the Torx size 8 (TT8) in 73% of the HDDs analysed. In short, the design of the HDD allows for easy accessibility and separation of the PCB.

4.2. Separation of the permanent magnets (PMs)

The assembly design of the PMs did not vary with the size or the year of manufacture. The main difference was the number and the type of fixtures (i.e. screws, plastic fixtures). In all the HDDs analysed, the upper actuator PM1 was accessible at level L1. In the 2.5” HDDs, the number of operations ranged from five to seven while for the 3.5” HDDs, four to seven operations were needed. In most of the HDDs, six operations were required, and the most common number of fixtures was nine for the 2.5” HDDs and eight for the 3.5”HDDs.

The lower actuator PM2 was accessible at level 3 in all of the HDDs (regardless of the size and the storage capacity) except for one 3.5” drive (HP1) that had its PM2 positioned at level 4. In the 2.5” HDDs, the number of operations to harvest the actuator PM2 ranged from ten to 13 operations while for the 3.5” HDDs, it varied from nine to 13 operations. The number of screws ranged from nine to 13 screws in the 2.5” HDDs and from four to 15 screws in the 3.5” HDDs.

The spindle PM3 was the only target part that could not be separated using non-destructive operations in all the HDDs. In all of the 2.5” HDDs, the spindle PM3 was assembled in the base casing and could not be separated as a unique part in any of the drives. In the 3.5” HDD, in only seven out of the 19 HDDs the spindle PM3 was separated using non-destructive methods.

4.3. The time and cost of disassembly

Table II summarises the time and cost of the disassembly of the PCB and the PMs using e-DIM. The detailed calculation of the time for disassembly estimates is given in the supporting information S7, S8 and S9.

The results show that the minimum time to separate the PCB was 13 seconds for the 2.5” HDDs and 10 seconds for the 3.5” HDDs. The maximum time for both HDD sizes was 16 seconds, which results in an estimated cost of €0.05. The time and the cost of separating the PMs differed among samples as a result of a variable number of operations and fixtures. Depending on the number of the PMs due to extract, the time varied from 15 to 115. The maximum economic cost is estimated to be €0.35. It is worth noting that the time to extract the PCB and all three PMs did not vary much compared to the time to separate all three PMs. The economic cost to separate the three PMs is estimated to be €0.39. In conclusion, the economic value of the separated PCB (€0.85) outweighs the economic cost of the non-destructive disassembly of the PCB and the PMs.

Table II. The time (seconds) and the economic cost (€) to separate the PCB and the PMs contained in HDDs.

Target parts		2.5" HDD units		3.5" HDD units	
		Time (Seconds)	Cost (Euros)	Time (Seconds)	Cost (Euros)
PCB	Min	13	0.04	10	0.03
	Max	16	0.05	16	0.05
PM1	Min	22	0.07	15	0.05
	Max	30	0.09	31	0.09
PM2	Min	37	0.11	28	0.08
	Max	51	0.15	55	0.16
PM3	Min	82	0.25	59	0.18
	Max	103	0.31	115	0.35
PCB + PM1 + PM2	Min	49	0.15	39	0.12
	Max	63	0.19	71	0.21
PCB + PMs	Min	94	0.28	70	0.21
	Max	116	0.35	131	0.39

5. Discussion

As mentioned above, one of the motivations to perform this study was the need to assess the feasibility of the non-destructive separation of the PCB and the PMs contained in HDDs collected from a recycler in Barcelona. Once the results suggested that the separation of the PCB and the PMs was feasible, the next step was to understand the economic cost and value of the disassembly of wasted HDD generated in Barcelona. Based on the latest statistical information, the city of Barcelona generated 483 thousand tonnes of waste, with almost 3% of this classified as WEEE in 2016 (Waste Agency Catalonia, 2018). Data on the quantity of

HDDs generated in Barcelona were generally given with the other WEEE generated (Waste Agency Catalonia, 2018) and in other cases. Data were reported with the quantities of other product groups from year to year (Tersa-Siresa, 2018). The result was that there are no direct data on the quantity of HDDs.

The way to estimate the quantity of HDDs was to identify the diverse actors involved in their end of life management to then calculate the quantity collected. In Barcelona, there are three main actors involved in the end of life management of WEEE: the Waste Agency of Catalonia (WAC), the authorized transport and storage companies (SCRAP) and the recycling companies. The public WAC is responsible for the management of the WEEE. Then, the SCRAP, a non-profit organization created by the manufacturers and importers of EEE, is responsible for transporting and storing the WEEE. Recycling plants treat the WEEE from SCRAP as well as WEEE from private companies ("Personal communication with Ecotic," 2018). In Barcelona, HDDs reach recycling companies as part of servers and other information technology (IT) equipment such as desktop computers, and laptop computers, and also as stand-alone equipment. Recycling operators separate only those HDDs contained in IT equipment when not swappable. Based on estimates given by each of the actors, we estimated that Barcelona generated 51 tonnes of wasted HDDs in 2016 as illustrated in Figure 4 ("Personal communication Electrorecycling," 2018). Only about 25% of the HDDs were collected as stand-alone equipment while the majority was collected as part of other equipment. This figure is aligned with Sabbaghi et al. that assumes that about 25% of used HDD undergo proper recovery processes in the EU (Sabbaghi et al., 2019) .

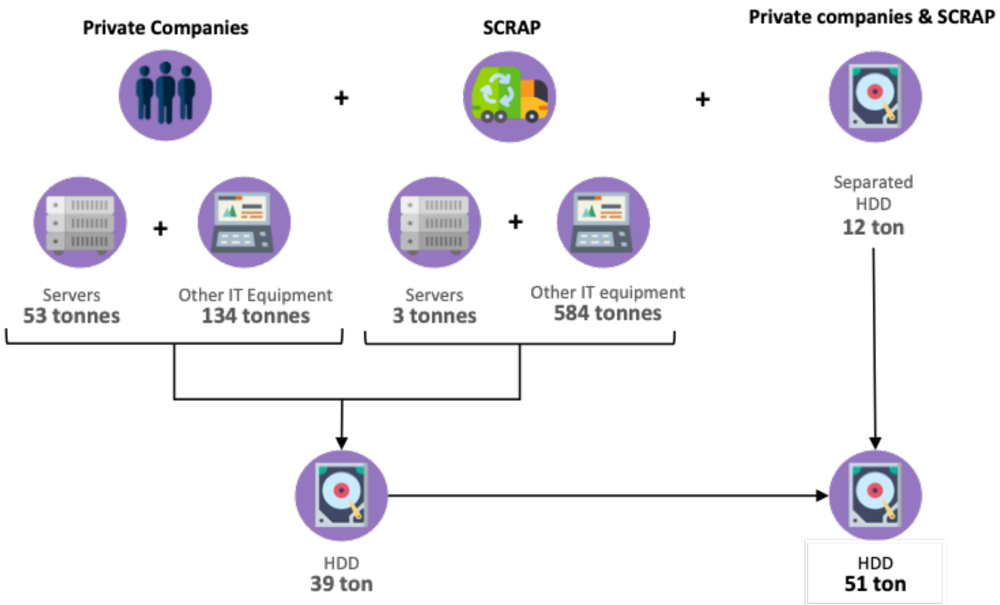

Figure 4. Generation of wasted HDDs in Barcelona for 2016.

To calculate the economic cost of the disassembly of 51 tonnes of wasted HDDs in Barcelona, we needed to first estimate the amount of 2.5" HDDs and 3.5" HDDs and then estimate the average mass of each size of HDD. In 2016, desktop computers represented 40% of the total market share while laptop computers were 60% of computers (Statista -

The statistics portal, 2019b). The average mass of one 2.5” HDD was 98.2 ± 1.2 g while the mass of one 3.5” HDD was estimated to be 525.7 ± 76.6 g. These figures, in addition to the time for disassembly, served to obtain the total economic cost for the disassembly of the wasted HDDs collected in Barcelona. Table III shows the time for disassembly, the number of units estimated for the 2.5” HDDs and the 3.5” HDDs, and the resulting economic cost of separating the PCB and the PMs from the HDDs. The cost of separating only the PCB varies from €9,640 to €12,640. When the PCB and the three PMs are separated, the economic cost increases to €70,750 and €94,600. Table III also includes the number of workers needed to perform the disassembly operations. As illustrated, the compulsory disassembly of the PCB and the PMs would generate up to five new jobs per year.

Table III. The economic cost of the disassembly of the PCB and the PMs of HDDs in Barcelona (2016).

		PCB		PMs						Total			
				PM1		PM2		PM3		PCB + PM1+ PM2		PCB + PMs	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
2.5" HDD	Time for disassembly (seconds)	13	16	22	30	37	51	82	103	49	63	94	116
	Units	207,845											
3.5" HDD	Time for disassembly (seconds)	10	16	15	31	28	55	59	115	39	71	70	131
	Units	58,212											
Total time for disassembly (days)		112	147	188	279	320	476	710	976	432	600	822	1,099
Number of workers		0.5	0.7	0.8	1.3	1.4	2.1	3.2	4.4	1.9	2.7	3.7	4.9
Total labour cost (€ per year)		9,637	12,643	16,214	24,005	27,580	41,012	61,114	84,009	37,217	51,605	70,751	94,603
Total labour cost (€ per unit of HDD)		0.04	0.05	0.06	0.09	0.10	0.15	0.23	0.32	0.14	0.19	0.27	0.36

The economic value of the PCB contained in HDDs was calculated for four different computer market shares given in diverse years and for two end of life scenarios. The market share figures show that laptop computers are progressively gaining ground in the market and their sales are increasing year after year (The Statistics Portal, 2018). By 2022, laptops are expected to dominate the computer market and consequently a greater amount of 2.5" HDDs is anticipated in future WEEE flows. The two end of life scenarios are assessed: the non-destructive separation of the PCB and the PMs, and the shredding of the target parts. As illustrated in table IV, the maximum economic cost of separating the PCB and the PMs is less than half of the economic value of disassembled PCBs. In addition, the economic value of the disassembled PCB is 2.5 times the value of the shredded PCBs (see supporting information 8 for the details of the calculation).

Table IV. Estimation of the economic value of the PCBs of HDDs for scenario A (non-destructive disassembly) and Scenario B (Shredding) in Barcelona.

Market share	2011/2013		2016		2017		2022*	
Desktop	43%		40%		38%		34%	
Laptop	57%		60%		62%		66%	
Materials	Mass (kg)	Value (€)	Mass (kg)	Value (€)	Mass (kg)	Value (€)	Mass (kg)	Value (€)
Silver (Ag)	17.68	8,496	18.00	8,650	18.25	8,770	18.75	9,009
Gold (Au)	5.24	183,389	5.34	186,726	5.41	189,310	5.56	194,479
Palladium (Pd)	1.08	18,569	1.10	18,907	1.11	19,168	1.14	19,692
Other materials	*2,487*	*10,599*	*2,533*	*10,792*	*2,568*	*10,942*	*2,638*	*11,240*
Total Manual disassembly		221,053		225,075		228,190		234,420
Materials	Mass (kg)	Value (€)	Mass (kg)	Value (€)	Mass (kg)	Value (€)	Mass (kg)	Value (€)
Silver (Ag)	12.71	6,108	12.94	6,219	13.12	6,305	13.48	6,478
Gold (Au)	1.86	65,205	1.90	66,392	1.92	67,310	1.98	69,148
Palladium (Pd)	0.39	6,685	0.40	6,806	0.40	6,901	0.41	7,089
Other materials	*2,487*	*10,599*	*2,533*	*10,792*	*2,568*	*10,942*	*2,638*	*11,240*
Total Pre-shredding		88,597		90,209		91,458		93,955

This study excluded the time for the extraction of the HDDs from laptop computers. However, according to Peeters et al., the separation of HDDs from laptops requires from eight to 85 seconds (Peeters et al., 2018). This makes the time for disassembly increase to a maximum of 216 seconds. Even in those cases, the estimated economic cost is half of the economic value of the disassembled PCBs in 2016, and thus the separation of the PCB and the PMs is still feasible. A more realistic estimate of the economic value of the PCBs could be calculated by considering the recovery yield of each material from the metallurgical processes required for the production of secondary materials. As this information becomes available more accurate calculations could be done.

From a resource perspective in the EU, gold, silver and palladium are all imported from third countries, thus any alternative source of these materials will benefit the EU economy. The quantities of the materials recovered from the HDDs collected in Barcelona represent a low amount when compared to global mine production figures. However, when the worldwide HDD unit shipment is considered, the quantities become considerably more relevant. For instance, based on an average lifespan for a HDD of five years (Jeremy, 2017), we can assume that the 564 million units shipped worldwide in 2014 would have reached their end of life (The Statistics Portal, 2018). The amount of gold from such end of life HDD units (32 tonnes) is greater than the annual gold mine production in the EU in 2018 (23 tonnes) (The Gold World Council, 2019a, 2019b). Likewise, the recovery of palladium from HDDs is estimated to be 1.95 tonnes, which doubles the EU annual mine palladium production in 2016 which was estimated to be 0.95 tonnes (Federal Ministry for Sustainability and Tourism (BMNT), 2018). Silver is the only material whose mine production in the EU will be considerably greater (1,919 tonnes) than the potential quantity recovered from HDDs (9.5 tonnes) (O'Connell et al., 2018). Further analyses to understand the feasibility of recovering these materials from other WEEE and their economic value would be beneficial.

Another way to further promote the recovery of these materials from WEEE will be by introducing changes in current regulations. For instance, the WEEE directive states that those PCBs greater than 10 cm^2 shall be recycled. However, it does not explicitly say which technology or process does so; and nor does it provide a methodology to evaluate the economic feasibility of disassembly. The methodology presented in this paper could be used to analyse the feasibility of recovering PCBs contained in other EEE such as those in tablets. Providing figures of the economic cost will help to gain a better understanding of the feasibility of separating these parts as well as their contribution to resource conservation. The case study on HDDs proves that the separation of the PCB is highly advantageous. The actuator PMs could also be harvested by non-destructive operations while the spindle motor magnet (PM3) was in most cases assembled in the housing and not separated using non-destructive operations. Design features to facilitate the harvesting of these parts could be defined in EU product policies such as the Ecodesign regulations, especially as data storage devices are becoming a more common part in other electronic products besides laptop and desktop computers. Mechanical tools to explore the disassembly for recycling should also be simple, and if possible standardized, to facilitate the disassembly of components (Güngör, 2006). The use of proprietary screws, non-removable batteries and other similar techniques can impede recycling (Svensson et al., 2018).

Some material recovery companies will however be more supportive of the product-centric approach (Reuter and Van Schaik, 2012). This approach suggests that the recycling of products shall be designed to target many materials in order to make the process economically feasible. In the case study of the present paper, we have demonstrated that in the case of HDDs, the disassembly of the PCB and the PMs is economically feasible even though only few materials are targeted. Their preventive separation allows for more homogeneous waste fractions that fit better in the metallurgical processes involved in the recycling of materials.

6. Conclusion

Cities are already seen as a secondary source of materials with a high importance for low carbon technologies and with a high risk of supply disruption. This paper proposes first a methodology to analyse the feasibility of recovering these materials from WEEE generated in cities. Then, the methodology is used to assess the feasibility of using non-destructive operations to separate the PCB and the PMs contained in wasted HDDs. The results show that the economic value of the PCB is much greater than the economic cost of separating the PCB and the PMs, and thus their harvesting is economically feasible. There are two other conclusions regarding the design of HDDs. The first is that the PCB is readily extractable at a very low cost (€0.05) in all the HDDs analysed, thus the requirement to separate this part using a non-destructive method could be further promoted in EU regulations. It is worth noting that while the PCB and the actuator PMs were designed to facilitate their non-destructive disassembly, the spindle motor magnet (PM3) could not be extracted using non-destructive methods. Indeed, the PM was separated using non-destructive methods in four out of the 25 HDDs analysed. The second conclusion is that the internal design of HDDs is largely standardized regardless of the size and manufacturing year. As a result, semi-automatic operations to reduce the time for disassembly would be possible.

In conclusion, the non-destructive separation of valuable parts of WEEE shall be further promoted, especially in cases where the purity of the recovered material needs to be high in order to be reused in new products and other applications. Similar studies such as that presented here, but analysing other EEE, are necessary to understand the feasibility of establishing new processes and new technologies that allow for higher recovery rates from WEEE in the recycling sector. The methodology presented in this paper could be made available using cloud-based information system (Wang et al., 2014) to help also reshape the remanufacturing industry and avoid the leakage of valuable products that could enhance circular economy business models (Sabbaghi et al., 2019).

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