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Advancing in the analysis of materials in electr(on)ic equipment

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Abstract

Despite there is a great effort to support strategies for a circular economy of electr(on)ics as maintenance, repair, remanufacture and reuse, recycling keeps being the final ultimate stage reached by them. As the supply of materials has become a key issue for the economic and technology development, more information about the content of materials in electr(on)ics is in order. This is especially for printed circuit boards contained in the majority of electr(on)ics which have a great variety of materials with a significant economic value. This paper discusses two methodologies to quantify the material composition of these parts. The first methodology quantifies the material content using two algorithms to identify the typologies of electr(on)ics components, and the average material composition of some typologies of electr(on)ic components given by original manufacturers. The second methodology uses the Database of SEmiconductors (DoSE) which contains the full material composition of about 250 different electr(on)ic components of printed circuit boards. A case study based on the analysis of two models of battery management systems contained in the batteries of electric vehicles is developed to compare the material composition results obtained from the two methodologies. Although the analysis is limited to some electr(on)ic components, mainly the integrated circuit and capacitors, the results of the composition of the battery management system are given for a list of materials including aluminum, copper, iron, gold, lead, nickel and tantalum. For two of the most economically relevant materials, copper and gold, the results obtained by the two methodologies differ 2% for copper and 4% for gold. To advance towards more automatized and systematic methodologies to estimate the material composition of the battery management systems, there are some further developments needed: to increase datasets for other electr(on)ic components as connectors, and better quantification of the number of layers and finishing of the circuit boards as they are made of significant quantities of copper and gold.

Keywords: circular economy, recycling, ewaste, semiconductors, printed circuit board

1. Introduction

In 2019, according to the Global e-waste monitor almost 54 million metric tonnes of electronic waste were generated [1]. In 2030, the amount of e-waste will reach 74 million metric tonnes, which confirms that e-waste continues to be the fastest growing domestic waste stream [2]. From the amount of e-waste generated, only about 17% is properly collected and recycled while the remaining 82% is kept stored, burned or landfilled. As result, the quantities of valuable materials as gold, silver, palladium, copper among others was lost and remains unrecoverable [1].

In the EU, an economy highly dependent on the imports of some of those raw materials from third countries, e-waste can represent a significant source of secondary materials. The increasing concern about their economic importance and potential supply restriction is leading to new actions aiming to favor the collection, the reuse, the repair and the recycling of electr(on)ic products. The latest representing the last opportunity to close the loop of materials [3].

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Since late 2015, there have been published two Circular Economy action plans (CEAP) that include actions aimed to curb the amount of e-waste reaching their end of life [3,4]. The 2020 CEAP has been published as part of the EU green deal [5]. It includes actions as the 'Circular Electronics Initiative' aiming at promoting electr(on)ics with longer lifetimes, measures for establishing the 'right to repair', and also a revision of EU rules on restrictions of hazardous substances in electrical and electronic equipment. For the latter, the EU aims to advance in the harmonization and improvement of recycling infrastructure for e-waste. It is on this line, where having more detailed knowledge about the material composition of e-waste could become relevant.

As electr(on)ic equipment has progressively become more complex in terms of internal architecture as well as in relation to the quantity and diversity of materials, it has become even more urgent to access material composition data thus to improve for the identification of the optimal reuse and recycling processes. This happens especially in the case of the printed circuit boards (PCBs) contained in electr(on)ic products. Although these parts represent a low mass of the PCBs, they hold up a high economic value due to their content of high economic value materials as copper, gold and palladium [6]. Therefore obtaining specific data about their material composition is highly relevant.

This paper presents two methodologies to assess the material composition of two battery management systems (BMS) contained in the batteries of electric vehicles. The first methodology using algorithms to classify the typology of the PCBs and their electr(on)ic components, to later quantify the material composition [7]. The second methodology uses the material composition datasets available in the Database of SEmiconductors (DoSE®) (i-depot: 120008) to quantify the content of materials in the BMS [8]. The results obtained by each method are compared and discussed to draw some conclusions about the use of diverse methodologies to advance on better knowledge of electr(on)ics.

Nomenclature

BGA ball grid array integrated circuit
BMS battery management system
EV electric vehicle
IC integrated circuit
PCB printed circuit board
SME small and medium enterprise

2. Methodology

2.1. Development and use of algorithms to analyse electr(on)ics

The most reliable approach to investigate the material content of electr(on)ic components contained in PCBs is to access their material declarations. However, material declarations are not always available and hard to find, as it doesn't exist any regulation imposing the publication and accessibility of this information to original component manufacturers. To obtain full material declarations, a previous intensive task aimed at data mining is needed. To overcome this existing limitation, The Politecnico di Milano (POLIMI) has developed a methodology to automatize the quantification of the material content in PCBs [8]. In order to do so, some assumption and simplification were made in regard to the identification and classification of the typology of the PCBs and their components [9].

The methodology proposed is shown Fig. 1. As illustrated, there are two major steps: the construction of the algorithm (top part) and its application (bottom part).

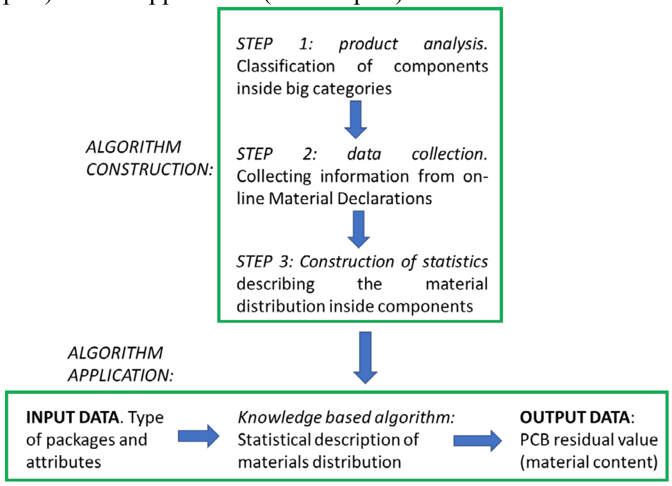
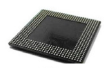


Fig. 1– Method used for the construction of the algorithm for the estimate of the residual value of a PCB.

For the construction of the algorithms three additional steps are defined. The first step referred to as product analysis consist in identifying and classifying the different electr(on)ic components of the PCB in specific categories. This approach is common to all knowledge-based methods aimed to describe a product from a conceptual point of view. The electr(on)ic components contained in a PCBs can be classified in several typologies from a mechanical point of view (i.e, integrated circuits, capacitors). Table 1 contains a list of diverse general typologies of integrated circuits (ICs) with the description of the most common acronym to refer to the type, the complete name and a picture to illustrate their form. Although within each of the general typologies identified there are several subtypes of components. For example, the ball grid array (BGA) integrated circuits can be further classified into plastic, ceramic and flex tape BGAs among others. In this analysis, all BGAs were grouped under the general typology 'BGA' as this *level of classification was proved* sufficient for the use of the algorithms.

Table 1. Eelectr(on)ic component categories used in the algorithm methodology.

Package acronym	Package full name	Picture
BGA	Ball Grid Array	
QFP	Quad Flat Pack	
SOIC/TSSOP	Small Outline ICs/ Thin Shrink Small Outline Package	
SOT	Small Outline Transistors	
DPAK	D Package	
J	J leaded (two leads)	

The second step of the method referred to as 'data collection' consists of simplified data mining process developed to have the material content distribution of the electr(on)ic components classified in the first step. About 60 different material declarations from the common manufacturers of electronic components were collected and used at this stage. At the third step, data collected from the two previous steps are treated statistically (including a regression analysis) to define an algorithm for the assessment of the material content of electr(on)ics. Figure 2 shows an example of the distribution of gold in a quad flat pack (QFP) integrated circuit. As illustrated, the gold distribution increases linearly to the number of pins. This information is used to build up the algorithm used to quantify the content of gold in electr(on)ics.

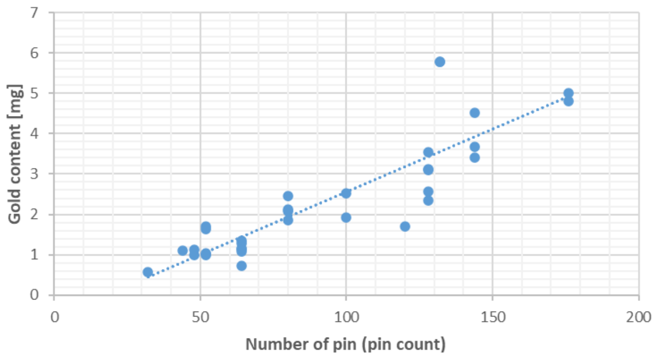


Fig. 2 Gold content in an integrated circuit (QFP) versus pin count.

As the *level of standardization* of electronic packages is very high, the generated statistical estimates can be applied to the specific type of electr(on)ic component independently from their manufacturer. This is because the variability of the content of material is much smaller than the confidence interval in the statistical regression analysis.

Finally, the bottom part of Figure 1 describes the application of the method once the algorithm based on statistical data has been constructed. At this step, data generated by the algorithm are used to have a material composition estimate for electr(on)ics.

2.2. Use of the Database of Semiconductors - DoSE®

DoSE® [8,10,11] is a specialized digital database on semiconductors and other electronics that aims to support the material and environmental modeling of electr(on)ics. The main motivation to develop DoSE® was to create a reference database to gather material composition datasets of electrical and electronic components in electr(on)ic products. In DoSE®, datasets have been generated using component manufacturer official material declaration data. As it is now, it contains information of the material composition of over 250 components contained in PCBs. Once the components mounted in the PCB are visually identified by the user, component data can be easily selected to model the material composition of the PCB contained in electr(on)ic.

DoSE® includes two principal tabs: the 'Semiconductor and other components', and the 'Printed Circuit and Board'. The 'Semiconductor and other components' contains the material composition data of different typologies of IC, capacitors, inductors, resistors and connectors. A physical description of each component is included as well in terms of mass (mg), dimension (cm), manufacturer, manufacturer description, and fabrication year. The manufacturer's websites, the datasheet and the full material declaration by the original manufacturers are given as supplementary material. The 'Printed Circuit Board' tab includes a section to include the description of the PCB that is the dimensions (cm), mass (g), typology together with pictures of both sides of the PCBs, and information about the product or part where the PCB was contained. It also includes a section to include a short description of the disassembly operations and the disassembly scheme followed to separate the PCBs. An estimate of the lifetime of the product (in months) and the method use for such end can be added as well. The last part of the tab includes a drop-down display list with the components with data available in the 'Semiconductor and other components' of DoSE®. The material composition of the PCB is generated automatically as components are progressively added in the PCB. The resulting material composition can be either exported as an excel file, or either as an activity to LCADB v.2® [11] to create the life cycle inventory to perform the life cycle assessment of an electr(on)ic products.

The tandem DoSE®-LCADB® has been conceived as an on-line platform to work as an individual user, as well as in collaboration within research teams, and as part of a project a network. The ultimate objective is to provide a collaborative environment that facilitates the sharing and the exchange of material composition datasets to develop economic and environmental assessments within interested organizations.

3. Analysis of the battery management systems of batteries of electric vehicles

This paper uses a case study based on a BMS of the battery of an EV to test the two methodologies presented previously: the algorith-based analysis and the digital database DoSE®. Two samples of BMS obtained from e-repair, an Italian SME focused on the repair of electronic products, have been analysed. These two samples were harvested from EV batteries in 2020. The the two BMS were firstly disassembled from the original aluminium/steel case in order to perform the visual analysis at POLIMI. This visual analysis consists in counting and sizing different typologies of electr(on)ic components. All the ICs and the tantalum and electrolytic capacitors identified were considered. Afterwards, the two samples were analysed following the methods described in section 2.

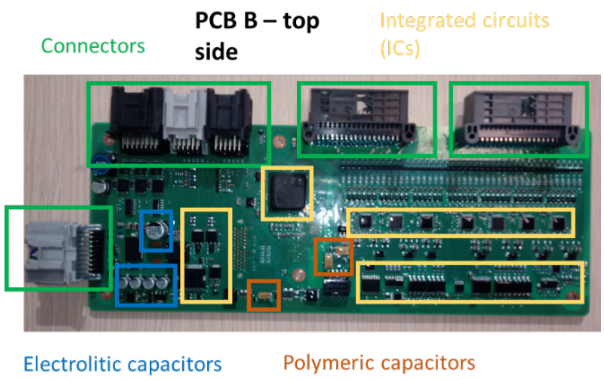


Fig. 3. Electr(on)ic components identified in PCB B.

3.1. Analysis of BMS using material composition algorithms

Following the methodology illustrated in Fig 1, electr(on)ic components of the two BMS under analysis were described as the package typology based on their mechanical configuration. Table 2 shows the list of components mounted on the topside of the first BMS analysed referred to as PCB A as an example. The bottom side of PCB A, and the second BMS sample, referred to as PCB B were analysed analogously.

Table 2. List of components in the top side of PCB A.

Type of package	Multiplicity	Length [mm]	Width [mm]	Number of contacts (pin count)
J leaded	30	7	2	2
J leaded	3	6	3	2
J leaded	1	9	3	2
J leaded	6	7	5	2
SOIC/TSSOP	6	5	8	14
SOIC/TSSOP	1	4	8	8
SOIC/TSSOP	1	3	8	8
DPK	4	10	6	3
Electrolytic capacitors	4	10*	10**	

* Diameter; ** height

As described in section 2.1, the algorithm developed using the statistical analysis allowed to estimate the material content of seven materials: aluminium (Al), silver (Ag), gold (Au), copper (Cu), iron (Fe), nickel (Ni) and Tantalum (Ta). The results of table 2 were used to estimate the content of these materials in both BMS given in Table 3.

Table 3. Material content of PCB A and PCB B obtained using algorithm-based analysis developed by POLIMI. All in mg.

Content of Materials (in mg)		PCB A	PCB B
Cu		5,986	7,143
Au	**Max**	15.97	29.44
	Mean	12.34	25.35
	Min	8.701	21.27
Ag		38.78	116,63
Al		3,11	1,728
Fe		155.43	120.49
Ni		-	25.86
Ta		-	308.84

A more detailed analysis of the material composition of each electr(on)ic components shows that the content of Cu, Au and Ag is mainly concentrated in integrated circuits. Most Al and Fe are contained in electrolytic capacitors while Ni and Ta are contained in polymeric capacitors (only identified in PCB B).

3.2. Analysis of BMS using the database DoSE ®

Prior to using DoSE, the electr(on)ic components contained in the two BMS need to be identified by manual or automatic visual inspection. Once all these components were identified, their respective material composition datasets were searched in the DoSE®. Some additional considerations were made for the analysis:

- The electr(on)ic components assessed were identified within the categories used in the statistical analysis (see Table 1). The functionality of the component was only 'estimated' but it was not used for the selection for the material analysis.
- For the classification, only the in-plane dimensions (length and width) were considered. The out-of-plane dimension (thickness) was omitted. The total number of contacts ('pin count') was used as well as an input descriptor to identify and classify electr(on)ics.
- Datasets of components were selected independently of the component manufacturer.
- The finishing for all the IC was assumed to be gold bonding wire, as the identification of the type of finishing was impossible from visual inspection. This means that the results for gold might be overestimated.

Human visual inspection only allowed verifying the type of package, the dimension, and the number of pins while other features as the functionality, the manufacturer and the bonding wire material in finishing cannot be directly verified due to data availability. For example, the dimension and the pin count of an integrated circuit QFP could be easily verified in DoSE® (i.e. *50x50 mm and 140 pin count)* while some assumptions regarding the specific functionality (i.e. counter, voltage controller, inverter), the manufacturer (ie. Microchip, Xilinx) and the bonding wire material (i.e. gold, aluminium, magnesium) have to be selected from the data sets available. This issue is further discussed in section 4.

Once the dataset for each of the components identified in PCB A and PCB B were selected, the material composition of each of the PCBs was generated, as partially showed in Figure 4.

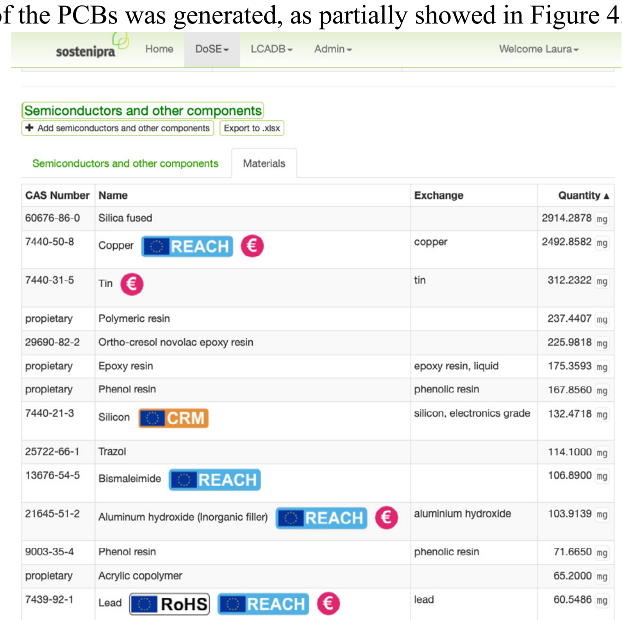


Fig. 4. Material composition (partial) of the PCB A as shown in DoSE®.

DoSE® allows exporting the material composition data as an excel file. For this paper, we include the material composition estimated for both PCBs in Table 4.

Table. 4 Material content of PCB A and PCB B using DoSE®. All in mg.

Material content (in mg)	PCB A	PCB B
Cu	6,799	6,989
Au	17.90	26.43
Ag	35.31	45.16
Al	112.20	63.24
Fe	73.58	30.74
Ni	32.73	58.62
Ta	-	171

**DoSE® provided figures as Al hydroxide, and sintered iron, and some additional calculations were performed.*

4. Results

Once the analyses of the two BMS were performed by each methodology, a comparison of the results proved to be useful for several reasons. First, it was necessary to verify the goodness of both methods, and second to identify the potential discrepancies between them. Table 5 summarises the results calculated for copper and gold for the two samples of the BMS using the algorithm based methodology and DoSE®. Results are only included for these two metals as they are those that justify form the economic standpoint the recycling of e-waste [12].

The estimated quantity of gold is displayed together with a maximum, and minimum estimated when using the algorithm-based methodology. For DoSE, values do not include either minimum or maximum estimates. The most common way to display the gold content is in mg per PCB or g per tonne, the latter being obtained by dividing the amount of gold in mg by the mass of the PCB.

Table 5. Material content for copper (Cu) and gold (Au) in PCBA and PCB B estimated by the algorithm based methodology and DoSE® database.

		Algorithm based analysis				**DoSE®**	
	Materials	**mg**	**g/tonne**			**mg**	**g/tonne**
			max	**mean**	**Min**		
PCB A	Cu	5,964	-	-	-	6,799	-
	Au	12.33	82	63	44	17.90	91
PCB B	Cu	7,143	-	-	-	6,989	-
	Au	25.35	117	101	85	26.43	105

It is also usual to classify PCBs in three categories according to the gold content in low, middle, and low grade [12]. Following this classification, the two PCBs analysed will be classed as ‘middle grade (50-120ppm)’ by both methods. For PCB A, although both methods classify the PCB equally, the results for copper and gold vary respectively 31% for gold and 12% for copper. For PCB B, the amount of copper and gold obtained using the algorithm methodology are very similar to those estimated by DoSE®. For PCB B, the quantities vary nearly 4% for copper and 2% for gold (considering absolute value in mg).

5. Discussion

This section discusses the assumptions made for the analysis due to the lack of data, and compares the results obtained from the two methodologies used in the analysis of the PCBs. As shortly explained earlier, one prior step to the use both methodologies is the visual inspection of the electr(on)ic components in the PCB. Some of the information parameters used (i.e. type of electronic package, thickness and width) for the modeling are readily available through visual inspection while others need to be approximated (i.e. thickness, functionality).

Table 6 summarizes the typology of information and the assumption made to assess the two BMS models. Regarding the type of electr(on)ic component, DoSE contains a drop-down menu where different typologies can be found. Pictures are included to support component identification. Even though data in DoSE are disaggregated per subtypology of electr(on)ic, for this analysis there was not added value to include data in such level of detail. As result, the approximation used in the algorithm statistical analysis was preferred as this was the level under which a comparison of both methodologies was feasible. Data for the ‘in plane dimension’, also referred to as length and width, were used as given in the full material declarations published by the manufacturer. Data about the thickness is considered as an input information for the algorithm-based analysis but could be also measured directly in the PCB without removing the component: when the thickness is directly measurable an included as new data in the algorithm. In DoSE, the thickness values are taken from the full material declarations of the manufacturers. However, this information is not always possible to verify during the visual inspections and in some cases, assumptions are made. In both methods, the pin count of electr(on)ic components is measured directly by visual inspection except that for the case of BGAs, since BGA balls are soldered and are not possible to visualize. In the present analysis, when a BGA was encountered, typical values for balls pitch were used as an approximation by both methodologies. The information regarding the component manufacturer is not always explicitly used in the analysis as in some cases the codes and label are not printed on the top of component or unreadable. DoSE includes information of the codes however this information is not always possible to verify in real life samples. Regarding functionality, this information is hardly captured by both methodologies. However, a more specific study about the field of application and the function of the specific PCB could help in improving the level of detail about both the manufacturer and the functionality of some components. For some components, it would be more probable to find some specific functionalities than others, but this issue is out of the scope of this paper which focuses on the material analysis of the PCBs. The identification of bonding wire material is difficult if not impossible to do. In this study, we assumed that all the bounding material was made of gold, and thus, the estimate for gold represents an upper content.

Table 6. Summary of the typology of information and assumptions made in the analysis of the two BMS samples.

Information	**Assumptions made for the analysis of the BMS**	**Accessible through visual inspection?**
Type of electr(on)ic component	Approximated	Yes
In plane dimensions (Length and width)	Exact	Yes
Thickness	Exact/Approximated	Yes (but other vision tools could be needed)
Pin count	Exact / Approximated	Yes / Not (BGA)
Manufacturer	Neglected	Sometimes (for example through labelling, if present and readable)
Functionality	Approximated	No
Bonding wire material	Gold considered as bonding wire material	No

All in all, the assumptions made by both methodologies lead to some uncertainty in the results. Such uncertainty is needs to be further addressed in future studies. For example, when analyzing the content of gold in SOIC ICs using the algorithm developed, it is observed that the content of gold can follow an upper and lower trend from 18 pins count (see Figure 5). This is because estimates have been taken from two different material component declarations. Using a *mean value as proposed by the algorithm* was proved as useful for obtaining our classification result for both PCB A and PCB B. Certainly, increasing the level of detail will help reduce the uncertainty of this analysis.

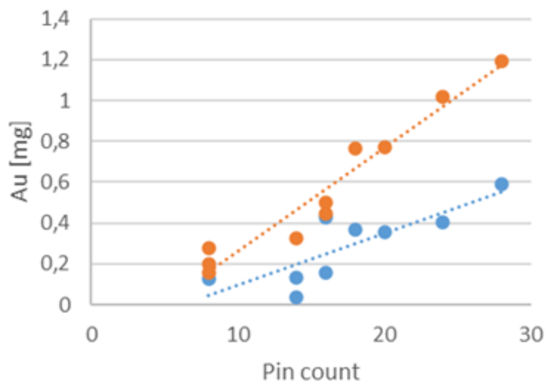


Fig. 5. Gold content (in mg) versus pin count. In blue gold content data from manufacturer 1, in orange gold content given by manufacturer 2.

The results obtained using the algorithm and DoSE, especially regarding the distribution of gold (Au) and copper (Cu) in integrated circuits are highly accurate. However, in line with Arshadia et al. further comprehensive studies on Au as well as other precious metals contained in different e-waste shall be developed [13].

6. Conclusions

At present, it still exist the need to optimize the recycling of e-waste to further advance in technologies and processed that help increase the supply of secondary raw material and minimize EU's dependency on resources from third countries. Advancing in the knowledge about the material composition of electr(on)ics is key to identify the most optimal processes that can lead to greater recovery of materials in terms of quantity as well as in terms of diversity. This paper presented two diverse methodologies that can facilitate the access to more robust and transparent data. Using a set of approximated information directly extracted from the PCB through a visual inspection method first, and second by using the methodologies proposed it is possible to estimate their material composition. The paper also discussed the existing possibilities to further improve the analysis, as for example by describing more in-depth level of detail of the information needed to reduce the uncertainty of the results. Despite some existing limitations when comparing the results obtained from both methodologies, the initial outcome represents a promising pathway to progress towards more efficient recycling processes. Advancing towards a greater availability of data about the material composition of PCBs is crucial to improve inventory data of electronics and thus, provide more accurate results about the potential environmental impacts of electr(on)ics as well.

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