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Methodology to prospect electronics compositions and flows, illustrated by material trends in printed circuit boards

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A B S T R A C T

Raw Materials are crucial in the development, production, and improvement of modern-day technology. Reliable access to critical, scarce, and valuable materials used in electronics is becoming a worldwide concern. Therefore, the quantification of material recovery from the urban mine is currently pursued worldwide. Commonly, data on (Waste) Electrical and Electronic Equipment is scattered, not harmonized, and uses different types of classifications and terminology. This provides a big challenge of a structured mapping of secondary raw materials in the urban mine. To address these issues, a state-of-the-art methodology has been developed and is presented by analyzing and tracking printed circuit boards in different key Electrical and Electronic Equipment over time. A total of 4051 composition data records where analyzed to extract the concentration of 19 elements in printed circuit boards between 1990 until 2020. The methodology harmonizes urban mine data, provides structured information that can be used to analyze and monitor the impact of product trends on their components and concentration of the elements in electronics. The resulting database and harmonization protocols are made freely available at the urban mine platform.

1. Introduction

The electronics industry is one of the world's largest and fastest-growing manufacturing sectors in the world (Parajuly and Wenzel, 2017). It is becoming an integral driver for modern lifestyle and plays a crucial role in the improvement of the quality of life in society. Unfortunately, the fast design cycles of products, highly complex components, and blend of materials reduce recycling efficiencies which, as a result, represents a burden on the waste management system. According to the Global E-waste Monitor, the European Union (EU) generated 12 Mt of Waste Electrical and Electronic Equipment (WEEE) in 2019, corresponding to an average of 16.2 kg per inhabitant (Balde et al., 2017), abbreviations can be found in Table 2.

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Table 2
Nomenclature list.

Abbreviation	Description
CN	Combined Nomenclature codes
CRM	Critical Raw Materials
CRT	cathode-ray tube
EC	European Commission
EEE	Electrical and Electronic Equipment
EoL	end-of-life
EU	European Union
Eurostat	European Statistical Office
INSPIRE	Infrastructure for Spatial Information in Europe
IT	Information Technology
LCD	Liquid Crystal Display
MFA	Material Flow Analysis
Mt	Million tons
PCB	printed circuit boards
PM	precious metals
POM	Products placed on the Market
PRO's	producer responsibility organizations
PRODCOM codes	Community Production codes
ProSUM	Prospecting Secondary raw materials in the Urban mine and Mining wastes
REE	Rare earth elements
RMI	Raw Material Initiative
SDI	Spatial Data Infrastructure
SQL	Structured Query Language
SRM	Secondary Raw Materials
STDEV	Standard Derivation
Telecom	Telecommunication
UDM	unified data model
UMKDP	Urban Mine Knowledge Data Platform
UML	Unified Modeling Language
UNU Keys	United Nations University product key
UNU	United Nations University
WEEE	Waste Electrical and Electronic Equipment
WG	Waste being Generated

Collection and recycling of WEEE constitute a significant potential source in the recovery of critical raw materials (CRMs) (Grawunder and Merten, 2012). Only 5.1 Mt out of 12 Mt of WEEE generated in the EU is reported as collected and properly recycled (Forti et al., 2020). The rest forms the so-called complementary flows (Huisman et al., 2015), referring to all waste flows not reported at a national (Wolk-Lewanowicz et al., 2016). Information on flows is essential for the recovery of material, monitoring and prevention of unofficial flows. Reported flows at a product level can be found in national statistics. However, data on product composition is usually unknown, and therefore it is challenging to estimate the flows of CRMs. Generally, product composition information is scattered among various sources. Usually, this data is (1) unstructured, (2) lacks harmonization, (3) product classifications vary among researchers, (4) data sources are not provided and (5) some studies provide information directly at elemental level (Musson et al., 2006), but often only for selected components (e.g. the hard drive in computers) or at the material level (e.g. Nd in hard drive magnets) (Deetman et al., 2018a, 2018b bib_Deetman_et_al_2018a, 2018b). Given the lack of qualitative and collated statistical product composition and flow information it is very challenging to quantify relevant information in the urban mine due to (1) accessibility and availability due to confidentiality issues data is not publicly available and (2) harmonization, information can be found in various formats depending on the data repositories (statistical offices, manufacturers, retailers, etc.). This type of information is vital not only for policymakers and recyclers but also for producers and academia. Producers, e.g., have come under pressure in recent years to provide consumers with environmentally sound and more circular products (Witjes and Lozano, 2016). Attempts on unified databases of Electrical and Electronic Equipment (EEE) composition are available, such as databases for CRMs (Moulton, 1993), input-output (Tukker et al., 2009), and material stocks and flows (Myers et al., 2019; Tanikawa and Hashimoto, 2009). However, none of the found methodologies was adequate to cover data from product to element level for composition as well as flow information placed on the market, stock and waste generated. Therefore, a new methodology was created and used for the urban mine platform.

The presented work describes this methodology, which is used to create a unified database, where quantification and harmonization of EEE composition and flow information were conducted. It includes more than 800 sources found in various formats and sampling, covering approximately 62% of elements in the periodic table and waste flows over time from 1980 to 2020. It is the biggest collection of its kind in Europe, which can be integrated with other databases from various sectors to analyze product composition and material flows globally (EEE database per collection category see appendix A12).

To illustrate the advantages of this methodology over others on an example, 4051 composition data records from printed circuit boards (PCBs) were harmonized and analyzed. Furthermore, the outcomes and results of the methodology are illustrated and discussed by providing (1) a comparison of the mass of PCBs placed on the market and waste generated per EU-6 collection category of the WEEE Directive 2002/96/EC (Appendix 2) from 2000 to 2020, (2) estimation of the weight contribution of PCBs in WEEE for key selected EEE from 1995 to 2015 and (3) the content of selected precious metals (Ag, Au, Pd, and Pt), Rare Earth Elements (Ce, Dy Eu, Gd, La, Nd, Pr, and Tb), special metals (Co, Ga, Ge, and Ta) and hazardous base metals (Pb, Sb, Sn, and Zn) over time (1990–2020) from PCB in screens are presented and discussed (The European Parliament et al., 2003). This methodology can be applied to other products sectors and used to build up a raw materials knowledge base by creating and providing an inventory of potential sources of secondary raw materials in the urban mine.

2. Materials and methods

It is essential to create a methodology to quantify and provide structured information on the urban mine. Subsequently, it is imperative to have clear and harmonized definitions of each term and compositional level used, supporting the classification system, such as the type of products, components, materials, and elements analyzed. In the proposed methodology, the quantification of compositions and flows of products can be achieved in a harmonized structure, which is not possible with any other methodology found in literature.

2.1. Theoretical methodology

EEE available information placed on the market, composition data, stocks, and waste flows for EEE for all EU 28 Member States plus Switzerland and Norway were compiled and analyzed ("Urban Mine Platform," 2017). All the data can be found in appendix A12 and is freely available online ("Urban Mine Platform," 2017). This work focuses on describing the methodology for calculating and evaluating EEE composition with a focus on PCBs.

To analyze EEE product compositions, different aspects of the study of a product's stocks and flows, namely flow (f), product (p), component (c), material (m), and elements (e) are created as shown in Fig. 1a. Each level got assigned a character to relate them with other levels. An analysis of, for example, elements (e) found in components (c) is designated with "e-c". In other words, e-c provides information on the average total mass of an element in a specific component in a unit of measurement (mg/kg, g/ton, %, etc.). When assigning a character (f, p, c, m, e) to each level, the terms used are chosen first to avoid confusion, such as products instead of goods or substances instead of materials/elements. This facilitates its use when making a material flow analysis. To allow the flexibility of analyzing materials (m) and subcomponents of a component (e.g., capacitors on PCBs, appendix A3) (c-c), the term indicates an assembly or subassembly in a product. This is not used in this methodology as only the components needed in the final assembly of a product are defined and considered.

In doing so, the composition of EEE can be analyzed not only by the components of the products (c-p), such as PCBs in computers, but also by the elements in the different components (e-c), such as gold, silver, or tin in PCBs. Additionally, elements found in the materials of a product (e-m), such as the Fe (e) content in stainless steel (e-m) or the Cu (e) content in Cu-alloys (m) in computers (m-p) can be examined and compared on each composition level with other sources. Furthermore, it allows a comparison with data directly provided as e-p. For instance, when analyzing PCBs in W/EEE, different datasets were recorded for each level as illustrated in Fig. 1b. Information on products and their different flows (e.g., waste generated, market trend, etc.) are dependent on their functionality.

Fig. 1b illustrates that the number of data records is greater than the number of sources, mainly as a result of researchers referencing or citing the same composition mass fraction value from the same study this can be misleading and affects the composition data if not properly handled. It is important to quantify the number of original measurements and data sources to evaluate their quality. To conduct a thorough analysis of the mass fraction of elements in components (e-c) and materials (e-m), a review of the compositions of the products is necessary. Since the United Nations University (UNU) Keys classification was used (description of the UNU Keys classification in appendix A5), analysis within the 54 UNU Keys (p-p) was performed by aggregating information of the aforementioned levels with the products contained within the UNU Keys (e.g., 0303 includes laptops, notebooks, netbooks, and tablets). Each product has different types of components and materials as they are product dependent and, in rare cases, time-dependent. A more structured overview of product composition in all different levels is achieved using this type of classification. Further, the mapping of material in products from different flows can be conducted. Flows in this context are the course a product has within the Urban Mine since when it is placed on the market, stock, officially collected and recycled, becomes waste, disposed of in the waste bin, etc. The type of flow may vary from country to country due to reporting practices and statistics within the country, and therefore composition is affected when quantifying and aggregating this type of information.

A detailed list of components can be found in Appendix A6. All batteries as components in EEE were not considered in the quantification to avoid double counting. This information is found separately in the urban mine platform ("Urban Mine Platform," 2017) using the same methodology as for EEE (Huisman et al., 2020; Mählitz et al., 2020).

In the case of materials, a thorough review and analysis from life cycle assessment databases, national and international standards (European standards or International Organization of Standardization) resulted in a list of the most relevant materials found in EEE and WEEE (appendix A7). Once the different levels in a product and a list of elements, material, and components are defined, a compilation of research data from different sources (reports, journal papers, and statistical bureaus) are extracted and analyzed. The data is extracted, properly documented, and compiled with the minimum requirements previously described.

For the quantification of flows, the data quality assessment implemented is illustrated in Table 1. This assessment is applied to cases where no statistical information is available. When multiple

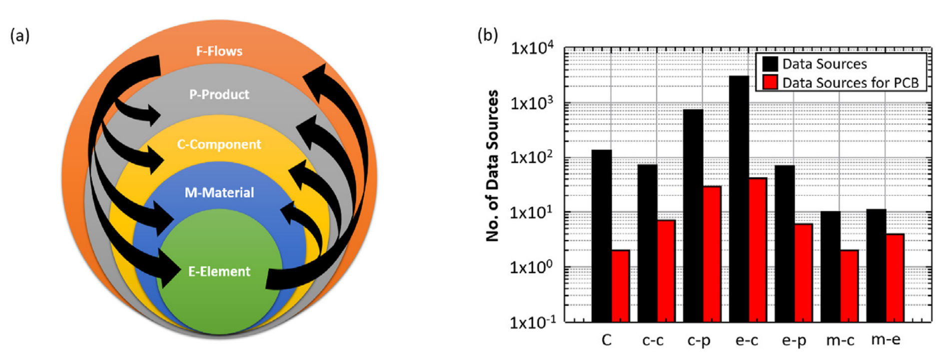

Fig. 1. (a) Simplified calculation sequence (Løvik et al., 2017); (b) Total and PCB mass fraction data recorded, whereas the number of data sources is plotted logarithmically (Løvik et al., 2016).

Table 1
Data Quality Assessment Schema (Wolk-Lewanowicz et al., 2016). Qualitative judgment range defined for flows and composition, where the composition is related to all EEE (m-p, c-p, m-c, c-c, e-p, e-c, and e-m) and flows (PLACE ON THE MARKET, stocks, waste generated, and unofficial flows).

Data Quality Types	Qualitative judgement (flows)	Mean (flows)	Qualitative judgement (composition)	Mean (composition)	Weight
Highly confident	0–10%	5%	0–20%	10%	4
Confident	10–20%	15%	>20–50%	30%	3
Less confident	20–50%	35%	>50–100%	75%	2
Dubious	>50%	100%	>100%	200%	1

sources for the same data point are available, weighting criteria are applied to evaluate the quality and contribution of the sources (Wolk-Lewanowicz et al., 2016).

The data quality assessment is done by applying the ranges listed in Table 1 on a case by case basis, averaging the uncertainty and data quality per data point across all possible combinations of composition. The evaluation takes into consideration whether the data point is a result of measurements or samplings, estimations, and origin of references, among others. The decision on whether to include certain elements, components and/or materials is made by a data quality analysis of the information recorded. Furthermore, estimates are evaluated and extrapolated, where products share a similar composition (e.g., CRT TVs and CRT monitors). When using the composition information from similar products, the data quality is considered to be dubious. Therefore, this information is not considered in the consolidation as it hinders the results. Every data point was provided with a description of relevant information, such as any constraint or assumption taken when performing the consolidation. Fig. 2a provides an example of the data quality and uncertainties done for the composition and flows of the product.

The UNU product classification system is created to avoid using unstructured statistical classifications and to harmonize and correlate published information of products in the urban mine. The UNU keys are a ground-breaking classification framework system for describing EEE products (Balde et al., 2015). This framework system is constructed in a way that approximately 1000 different product types are grouped in a limited number of EEE product baskets (appendix A5). Products were grouped into 6 categories (Fig. 2b) according to average weights, comparable composition, end-of-life characteristics, and lifespan distributions (Balde et al., 2015). The UNU keys form a bridging function between the international trade statistics from Prodcom (2016), UN/COMTRADE (COMTRADE, 2019), the previous EU10, the current EU6 categories of the EU WEEE Directive (European Commission, 2012), and various lists in use by producer responsibility organizations in individual countries. The UNU key system provides the starting point for connecting product composition data to this product classification system, and the extension to end-of-life vehicles and batteries is a clear example of what can be achieved when using such harmonized and structured classifications. These classifications are suitable for calculating the composition of a basket of products (p-p) as performing material flow analysis of the raw material components in EEE and WEEE (eurostat, 2017). The representation of product flow placed on the market versus the flow of WEEE is usually not the same. Therefore, the lifespans of products should be considered. The lifespans of the products defined by the UNU keys are derived from country studies (Huisman et al., 2012) enhancing WEEE estimates. Furthermore, recently lifespan estimations became part of the implementing act for the EU WEEE Directive for measuring the collection rates (European Commission, 2017). Various numbers of records are documented per collection category in a harmonized and structured way using different sources and formats (Fig. 2b). It is necessary to correlate and aggregate published information using a clear, standardized classification system in a harmonized and replicable manner. A unified data model is created to describe the overall structure, management, quality and uncertainty of information of the urban mining data for secondary raw materials (Huisman et al., 2017b).

When recording and analyzing composition information in the urban mine, minimum requirements need to be defined and met to ensure a harmonized, structured methodology and to evaluate its quality, such as avoiding recycling of data, scoping issues, incomplete data, and combining data values (further details in appendix A4). The process of data collection is described in Fig. 3 (left box), and the minimum required criteria defined were a description of products in the original reference (e.g., computer, magnet, etc.), the similarity between the reference description (high, medium, low) and the predefined codes (list of components, materials and product classification, Appendix A6), the number of products/components in the batch and measurement method used.

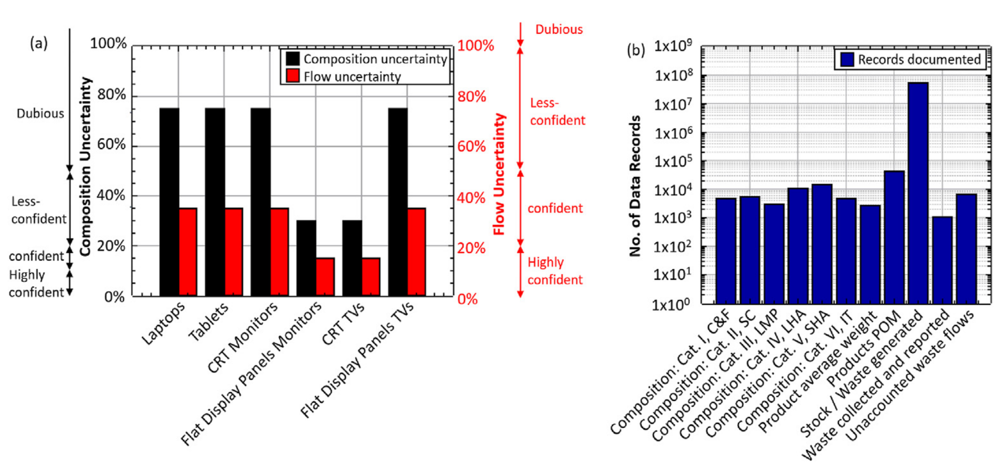

Fig. 2. (a) Data Quality Assessment Schema (Wolk-Lewanowicz et al., 2016); (b) Records documented for each category in Directive (2012)/19/EU (eurostat, 2017).

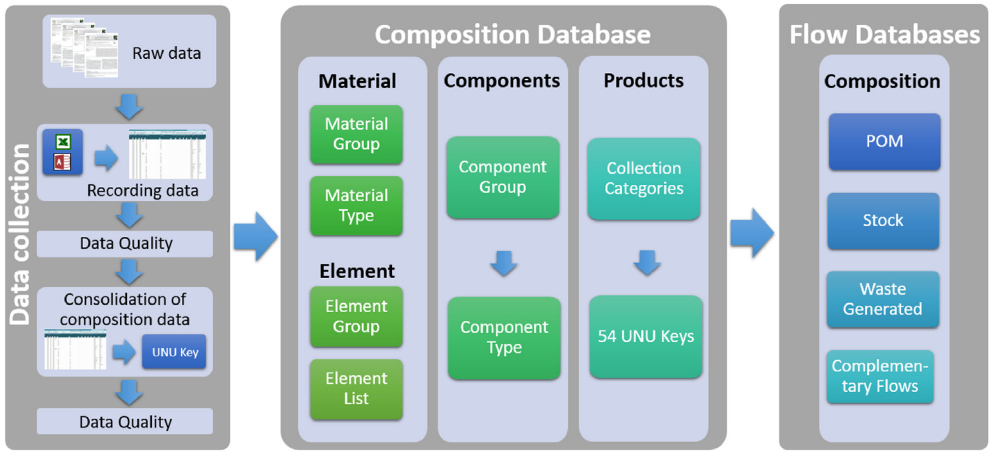

Fig. 3. Overview of the different steps applied in the methodology.

Furthermore, it defines whether the measurement was original or a citation. For example, if the reference states, the PCB data point is from "microcomputers, TVs, video cassettes recorders, etc" a low value is assigned as its very vague. If the reference state that the data point comes from clocks, it is considered medium as it does not specify its type, and if the description is detailed (laptop PCB, watch PCB) it is high. The datasets, which include measurements, will have a higher data quality and lower uncertainty than those which are only estimated. Each reference used when recording data, assessing data quality, performing the consolidation of composition and product flows, are assigned unique metadata allowing the data point attributes to be traceable (Fig. 3, left box). Metadata is a digital mean that uses descriptors which provide and describe information from other data sources and act as a label indexing purpose (van Straalen et al., 2015).

Furthermore, consolidations of each UNU Key are created and an average mass fraction composition was calculated for all 54 UNU Keys separately and per collection category. The consolidation of a product key refers to integrating or merging various references for one dataset (Løvik et al., 2016). Different values for materials, components, and elements of the same UNU Key from different references are consolidated and a so-called average portrayal is created per UNU Key. Furthermore, general information is also considered for product-specific data when doing the consolidations of the product key. The general information of each portrayal contains composition information known and well documented from various sources such as the recovery of critical raw materials (Blengini et al., 2020; Rotter et al., 2013), dismantling studies, and chemical analysis (Lim et al., 2011; Sun et al., 2015).

Each portrayal consisted of different product levels (e-p, e-m, e-c, m-p, c-p, and p), which helped achieve a final mass balance on all different levels of the product. For instance, in the case of the m-p and c-p analysis, only material and component mass fractions (appendix A14-19) are considered from the analyzed product. An interlinkage between products and materials can be accomplished with the portrayals due to the strict predefined terminology due to the urban mine platform. That way, single components in a product over time (c-p (t)), such as the calculation of the average weight evolution over time of PCBs can be analyzed. This enables the harmonization of different datasets using sources, such as the EU WEEE Directive Article 7 common methodology (European Commission, 2012) and sampling campaigns from different countries (Huisman et al., 2017a). In the case where there is no information for certain elements, materials, and components and their product composition differ from other products, no data is assigned to the specific element, material and/or component being analyzed. The reason is that when performing the mass fraction consolidation of the element, material and/or component a clear distinction between measured zeros and lack of information has to be made. Most importantly, measured zeros are considered when performing the consolidation and therefore it would hinder the entire calculation producing unreliable data if the variables with no information were to be assigned a zero.

When there is no statistical data or quantitative assessment of uncertainty, data points available from the source like standard deviation or confidence intervals are implemented. Only then the references identified in the analysis are recorded and the average values for materials, components, and elements of the same product are calculated, an analysis is conducted to evaluate the quality of each data point to evaluate the level of confidence, ensure transparency and measure the uncertainty for each data level in a uniform manner. The quality of each consolidated data point is assessed by setting defined lower and higher quality limits. These quality limits are defined according to the following criteria (see also Table 1 and Fig. 2a): (1) Highly confident: Datasets resulting from reliable measurements. (2) Confident: Datasets resulting from data models, estimates, consolidation of reliable sources as well as datasets resulting from a medium-small to a large number of measurements. (3) Less confident: Datasets resulting from estimates, assumptions on various research articles, and single measurements. (4) Dubious: Datasets resulting from estimates, assumptions based on other research articles.

The quality criteria for the entire portrayal considered to conduct these assessments are the analysis of the characterization method used, the sample size, assumptions and estimates made, the models used for this estimation, the similarity between the product description and the UNU keys. A weighting criterion (Table 1) is assigned for each quality criterion to evaluate the type of data quality, the element, material, component, and product should be assigned. In the case that a data point is the result of estimation or general information is used, its data quality is considered to be dubious.

When the average composition mass fraction is calculated per UNU Key the data quality of each dataset is considered. For components or materials per UNU Keys (c-p, m-p) where no mass fraction composition is available, information on component or material of similar UNU Keys are used, and lower data quality is given (Løvik et al., 2017). For some materials and components where no specific information is available (aluminium alloy, stainless steel, and cables) general representative information (e.g.

external cables) containing previously known good quality data or resulting from confident sources are used. In some cases, dubious datasets or those data records with an unclear temporal scope (e.g. unknown year of market input or waste generation) are not considered as they could hamper the final result.

In conclusion, the assessment of data quality is performed for each dataset/data point, in all different levels with the products/flows, for all the UNU key portrayals and the different flow databases. These portrayals also provide a version control possibility since the outcomes are reviewed by multiple authors from different universities and time-stamped as the consolidation based on the available sources at a certain point in time. Especially since the portrayals are later multiplied with other data, this allows for the proper setting of a temporal scope to the combined data. The same procedure is used to evaluate the data quality while recording information is applied when performing the product composition consolidation. The data quality is assessed per UNU Key. It depends on the degree of representation of products in the UNU Key, the number of references, and the sample size.

2.2. An implementation example of the methodology: composition analysis of PCB

Thorough research of product composition and market trends is conducted when performing time-dependent composition analysis. An extrapolation is made using PCBs as a common denominator in the product, where no time-dependent information is available. As a result of reviewing data published in the literature (list of references in the appendix A34) and sampling done by third parties during the process of developing the model, it was found that the ratio between the mass of the PCB and the total mass of the product it is part of, is constant over time. Therefore, a decrease in the mass of the products will lead to a reduction in the mass fraction of PCBs over time. Consequently, when the mass of a product decreases or increases, the mass fraction of PCBs and their materials and composition is assumed to change as well.

Information acquired by independent data providers is sometimes necessary due to the lack of publicly available information. An advantage of information from third parties is the higher data quality as well as the benefit of more recent data. In the case that commercial third parties provide the product characterization, it is often necessary to aggregate the data with other sources to ensure confidentiality on one hand and reproducibility on the other hand by repeating this methodology.

Once the data recording and literature review are completed, it is found that for some EU-6 collection categories, more information is available than for others. Generally, more research is conducted in specific areas such as IT and screens in comparison to cooling and freezing (C&F) and large household appliances (LHA), where not much information is available. A total of 32,615 data records were documented, which correspond to 308 distinct publications. Of these distinct publications, only 93 of them performed original measurements (representing 30%), the remaining 215 mainly referring to values from other studies or estimations (representing 70%). It is important to emphasize that EEE composition is very dynamic, trend dependent, and reliant on the resources and materials that are available at a specific time.

In the case of PCBs, a total of 4051 composition data records from various products are recorded. From these data records, only a total of 2841 were measured and extracted from 48 studies. Fig. 4 illustrates the number of data records and sources per type of measurements recorded for PCBs.

Data records that have less-confident, confident, and/or highly confident data quality are consolidated, taking the average of all data sets per UNU Key. From all product and composition data records analyzed 14% are considered highly confident, 38% are considered confident, 39% are considered less confident, and 9% are considered to be dubious. Data records with dubious data quality are considered in the consolidation of information on a case by case basis and should be marked as dubious.

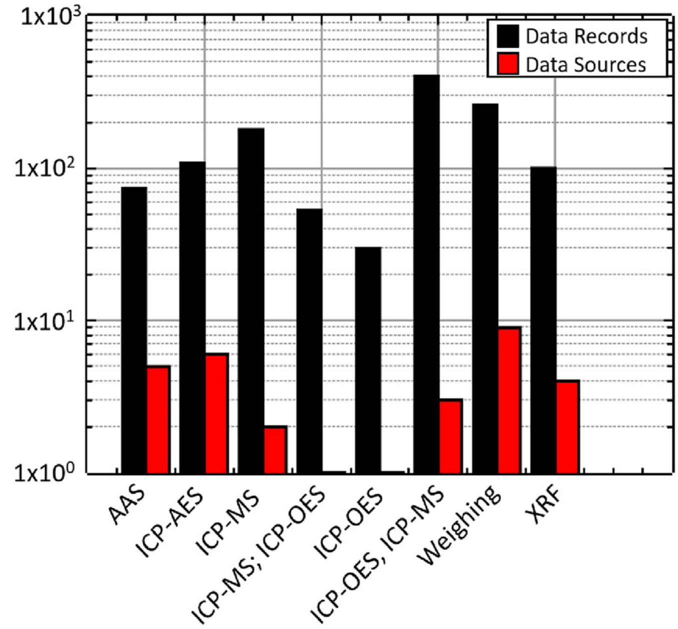

Fig. 4. Type of measurements, number of data records, and data sources recorded for PCBs. Measurements: atomic absorption spectroscopy (AAS), inductively coupled plasma atomic emission spectroscopy (ICP-AES), inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma atomic emission spectroscopy (ICP-OES), and X-ray fluorescence (XRF).

For PCBs, 168 datasets are considered highly confident, 945 datasets are considered confident, 10,795 records are considered less confident, and 448 datasets are considered dubious. Appendix A10-13 illustrates the data quality analysis made for the list of elements, materials, and components analyzed and displayed. This structured approach allows for more elaborate sensitivity analysis and computation of error-propagation as illustrated in appendix A13 for 2016 WEEE Flows and the analysis of Cu in Cathode Ray Tubes TVs.

A data quality assessment is conducted for all the level of composition information (e-c, e-m, e-p, c-m, c-p, etc.) on products containing PCB. The content and concentrations (mg/kg and g) of elements found in PCBs in g for the year 2015 for all collection categories are shown in Appendixes A14-19, by applying the methodology and data quality assessment previously described.

3. Results and discussion

Information on products containing PCBs can be useful when analyzing areas such as future recovery rates, waste generated, and financial recovery of materials. In 2013 it was estimated that the profits resulting from the recycling of PCB in WEEE oscillated between € 1.79 billion to € 3.62 billion and for 2030 is predicted to increase to between € 2.95 billion to € 5.98 billion (D'Adamo et al., 2016). Fig. 6 illustrates the quantities of PCBs placed on the market from 1995 until 2020. It is important to note that information from 2016 to 2020 are extrapolations and therefore should not be taken as a certainty as they may vary due to change in technologies, material availability, and market trends. This type of information is crucial to showcase the importance of the recovery of materials and potential revenue that can be achieved and promote a more circular economy.

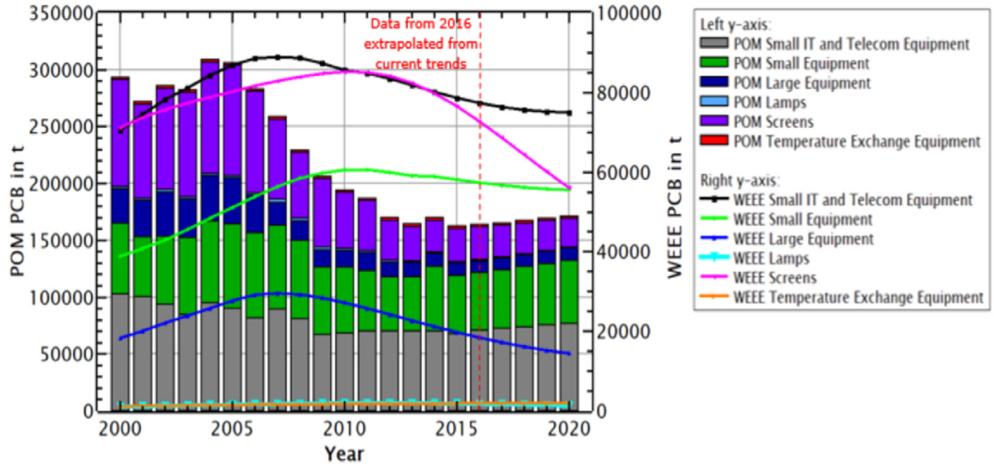

Fig. 5. The mass of PCBs place on the market in comparison with the mass of waste generated per collection category in tons per year in EU28 (c-f (t)). The right axis represents WEEE PCB in tons, and the left axis represents placed on the market PCBs in tons. For more information, visit the urban mine platform ("Urban Mine Platform," 2017).

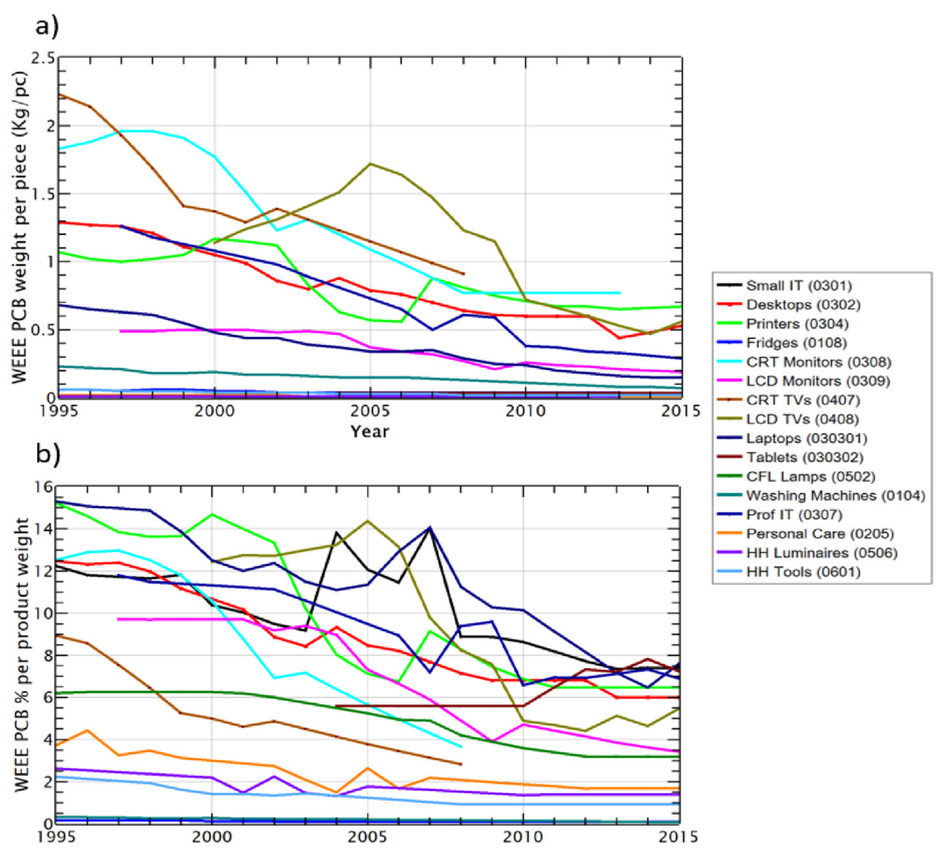

Fig. 6. WEEE PCB contribution 1995–2013 per UNU Keys is shown a) in kg and b) in % linked to the market input (c-p (t)). More information in ("Urban Mine Platform," 2017).

To analyze the evolution of elements in PCBs over time, it is necessary to understand the flows of materials and components that are part of PCBs and products that contain PCBs. To quantify volumes placed on the market and WEEE generated, the common methodology developed by Magalini et al. has been used, which results in the quantification of PCBs per collection category for EU28 placed on the market versus WEEE generated (Fig. 5) (Magalini et al., 2014).

The mass of PCBs both placed on the market and WEEE generated have a constant decreasing trend mainly due to miniaturization and the facing out of some products from the market (Fig. 5). In the case of the screens' collection category, the change in technology and its effects is very evident. A decrease in sales of CRT screens and PCBs contained in this type of products is apparent with the introduction of flat screens in the market. This type of change affects not only the product size but their composition as well and subsequently also their recyclability and value. For recycling companies, the treatment costs for these products can become higher than their revenues, like in the case of CRT screens, and therefore in most developing countries, this type of equipment is disposed of in landfills without any treatment.

In the case of the collection category of IT and telecom, an increase of 26% of waste generation of PCBs in weight is observed between the years 2000–2007, primarily from products introduced in the market before 2000. A decrease in weight of 15.5% (2007–2019) can be observed mainly due to miniaturization as products become lighter. For lamps, constant market input and waste generation is observed. Moreover, for temperature and exchange equipment and large household appliances, both market input and waste generation present a decreasing trend.

The analysis of the number of PCBs placed on the market in comparison with the amount of WEEE generated per collection schemes (temperature exchange, screens, lamps, large equipment, small equipment and small IT and telecom) can be found in appendix A22-27.

When comparing Figs. 6 and 5, it can be concluded that due to the decrease of the share of PCB contributions to the product over time, caused by miniaturization trends, both its placed on market and WEEE generated weight decreases with the years. As a result, the Au concentration in PCBs has decreased (Fig. 7a), making the recyclability of product and components more challenging. However, changes in technology should also be considered when doing this type of analysis. It is challenging to foresee new types of technologies or type of CRM will be required for their production, but future trends can be estimated taking into consideration the type of the component (for example PCBs) and importance of the element in regards to a product or component, for example, Au being one of the best conductive materials, corrosion resistance, the most malleable and ductile metal (Lah and Trigueros, 2019).

The contribution of PCBs in the absolute value in kg and percentage of a product as a function of time for relevant UNU Keys from 1995 until 2015 is shown in Figs. 6a and 4. The analysis of PCBs contribution in WEEE from 1995 to 2013 per collection schemes (temperature exchange, screens, lamps, large equipment, small equipment, and small IT and telecom) can be found in appendix A28-33.

From the analysis made of PCBs over time, it can be observed that its contribution in most EEE is decreasing over time. This is mainly the result of the miniaturization of products and technological advancements. The trend of miniaturization (Schaller, 1997) is reflected by the products becoming smaller (Jung et al., 2003). Furthermore, more and more components, which used to be separately placed on a PCB, such as sensors, the electronic evaluation units or microcontrollers, are integrated all together into one single component (Jillek and Yung, 2005) or embedded into the PCB (Palm et al., 2005) reducing the size of the components. This trend affects not only the size of the components in products but also their energy consumption and ultimately the material concentration within the components as well. Moreover, it can be observed that the introduction of LCD screens to the market affected the sales of CRT screens and, therefore, PCB component sales in the corresponding product (Fig. 6a and b). This results in an increase for PCBs in LCD screens and a decrease in PCBs in CRT screens due to change in technology.

As an example, the evolution over time of the contribution of selected elements in PCBs used in screens is analyzed (Fig. 7a–d). The elemental mass fraction expressed in mg is shown per kg of PCBs as a function of time from 1990 to 2020. Data from the year 2016–2020 have been extrapolated from previous years. The elements displayed in Fig. 6 are selected due to their relevance in PCBs as well as their economic value. Among them are precious metals (Ag, Au, Pd, and Pt), Rare Earth Elements (Ce, Dy Eu, Gd, La, Nd, Pr, and Tb), special metals (Co, Ga, Ge, and Ta), and hazardous base metals (Pb, Sb, Sn, and Zn). Throughout the years (Fig. 7), the concentration of elements like Sn and Pb is greater than precious

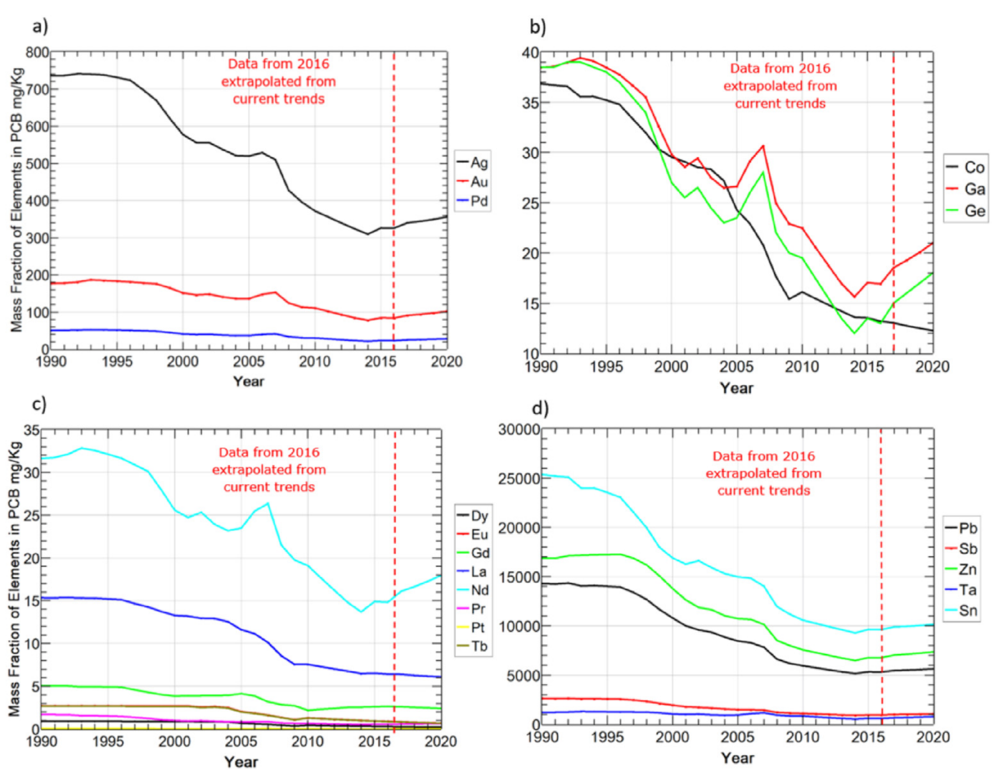

Fig. 7. Selected elements in PCBs over time (e-c (t)) of WEEE generated from 1990 to 2020 for the Collection Category of Screens, e-c of a) precious metals, b) Rare Earth Elements, c) special metals d) base and/or hazardous metals. For more information visit the urban mine platform ("Urban Mine Platform," 2017).

elements like Ag, Au, and Pd in PCBs. Most components found on a PCB have a solder connection, and the solder material consists of an Sn mix, previously including Pb. Given that the use of Pb was forbidden due to its toxicity in many countries worldwide the use of solder containing Pb has decreased drastically (Fig. 7d, black line) for the use in PCBs.

The decrease in the concentration of Au in PCBs observed in Fig. 7a, is the result of some products made obsolete and due to miniaturization (Adie et al., 2017). A slight increase in the gold content in PCBs between 2005 and 2006 is observed perhaps due to change in technology such as the mass fabrication of LCD monitors and TVs. This type of equipment contains gold contacts in the control boards surrounding the display. The reduction of concentration for Ga and Ge illustrated in Fig. 7b could be attributed to the rapid increase of miniaturization and its substitution in the microchips by silicon devices technology, which provides the possibility to highly integrate many devices on PCBs. Elements displayed in Fig. 7c and d maintain a constant decreasing trend due to miniaturization except for Nd, whose increase could be attributed to sales, change in technology and increase-of drivers in screens.

As presented, this unified data model methodology allows the harmonization of information for various flows and product levels of EEE in a structured and comprehensive manner. Information such as the one presented in this study can be used to perform analysis on economic opportunities for recyclers when recovering materials from products ('D'Adamo et al., 2019). This methodology can be reproduced for different sectors (e.g., vehicles and batteries) and allows for the information to be updated when new information is obtained, as well as to expand the timescale. As a result, an improvement in the knowledge of SRM in the urban mine can be achieved, allowing measurements such as resource availability, potential recovery, and a material flow analysis.

4. Conclusion

Some of the main challenges found when analyzing compositional data, are: (1) the lack of harmonization regarding the level of detail, aggregation of data and terminology, (2) the identification of relevant and valuable materials and components, (3) the analysis of datasets using confidential information from data providers due to confidentiality issues and (4) the analysis of data quality 5) lack of uniformity of the bill of materials among various sources. When consolidating composition information, the usage of a harmonized terminology is a prerequisite for a more reliable prospection of end-of-life data for each system level. This enables a unified data model with the advantage to be able to analyze, quantify and track data for each product level (e-p, e-c, e-m, c-p, c-m, m-p, p, p-p, p-f, and c-f), which is demonstrated in the case of PCBs. Before the implementation of this methodology, it was not possible to conduct these kinds of analyses. The methodology enables an improvement in the harmonization and statistics to obtain valuable information on the urban mine. The analysis illustrated employing the PCB compositions provides a base for more structured, comprehensive, and reproducible analysis. Furthermore, a comparison can be drawn in the use of critical raw materials in various products over time having social, economic and environmental importance. Using historic trends can help monitor and foresee future trends in the usage of materials on EEE. Lastly, analysis and quantification of the composition of products and evaluation of resource availability of secondary raw materials, potential recovery quantification in the urban mine can be conducted. This type of information provides policymakers with relevant information to make informed decisions to promote a transition to a more circular economy encouraging the use of secondary raw materials, promote recovery and secure material supply. Recyclers can make more informed investment decisions and producers can be more transparent in regards to product compositions and materials currently being used. Furthermore, it will allow universities and research institutes to gain access to more harmonized and more detailed data on product composition for their assessments of the urban mine and future recycling technologies.

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127164.

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