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Digitalization as an enabler of the Circular Economy of electronics

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Abstract

To facilitate the transition from a linear to a circular economy there is a need to develop digital tools that can provide comprehensive and useful data to enhance repair, remanufacturing, reuse, and recycling. This paper explains the typology of information key for such end, it discusses the current limitations and difficulties to implement methods in a digital platform, and a description of already existing digital solutions that will be further improved in the context of the DigiPrime project. A preliminary analysis of the availability and accessibility of information about electronics is required before the definition of a digital tool to support circular economy. First, the paper discusses the need of 'digitalized' end 'standardized' information of electronics to promote circular strategies. Then, diverse digitalization approaches by several teams of the Digiprime project are detailed. The paper concludes with a description of the next steps needed to align the diverse digitalization approaches and its potential contribution to improve the electronics sector.

Keywords: electronics; circular economy; printed circuit boards; repair; reuse.

1. Introduction

Circular economy aims to optimize the cycle of products and materials within the socio-technological system [1]. Within CE, maintenance, repair and reuse gain much more importance than recycling, which represents the last chance to close the cycle of materials in the economic systems. Some Original Equipment Manufacturers (OEMs), especially those active in business-to-business products, have already in place digital platforms to identify and order spare parts, access to the appropriate documentation, detect the machine error via online diagnosis, and start a repair request [2]. However, for business to consumer products, collecting information from products by third parties represents a bigger challenge as their information is not readily available in-house. Indeed, many of the latest EU ecodesign regulations on energy related products include new implementing measures where OEMs are obliged to provide technical information of the product, as for example an exploded diagram, which is key to facilitate maintenance, repair and reuse by third parties, as well as the declaration of the content of some specific materials [3]. As third-party repair and remanufacturing companies are due to have a more

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prominent role in the transition to a circular economy, it becomes evident the need to develop and implement digital tools that centralizes all the information available of the products, and provides comprehensive and useful data to streamline repair, remanufacturing and reuse [4,5].

All electrical and electronic products contain some electronic components, the printed circuit boards (PCBs). PCBs are a part highly customized by the OEMs and its complexity of the PCB varies depending on the functionalities of the product (even varies from one model to another model within the same product group). This is indeed one of the major limitations, even though there are standards for electronics (i.e IPC175x family) [6], the variability of this product is still enormous. As electronics are virtually contained in all electrical and electronic products, there is a great potential for the repair and reuse between sectors of some of the components contained, either at the PCB level or at the component level.

This paper starts by a short introduction about the existing limitations to repair and to prepare electronics for reuse. Then, it presents some examples of some digital approaches under development that can help overcome such difficulties, and therefore facilitate the circular economy of electronics. These tools, undergoing further developments within the DigiPrime project (https://www.digiprime.eu/), are aimed to enhance circular economy between at different levels of the same sector (i.e electronics used within an automobile) as well between several sectors (i.e. automotive industry, renewables). The tools presented focus specifically in the analysis of the components of the PCB. The assessment of the harvesting of the PCB from the product is out of the scope of the paper but might be included in a more advanced versions of the tools, especially in DoSE-LCADB which already includes some information (see section 3.3).

2. Limitations for repair, reuse and recycling of electronics

There are some existing limitations when aiming at repairing, reusing and recycling electronics. In this paper, we will focus on three of them: the location and assembly of the PCB within products, the identification of typologies of electronics and availability of information.

The first limitation is that related to the location and assembly of the PCB within an electrical and electronic product. Exploded diagrams of products indicating the location of the PCBs and the disassembly tasks involved for the harvesting of the PCBs from electrical and electronic products are not generally available. One possible limitation that hampers repair is the cost to separate the PCB using non-destructive methods [7]. The latest ecodesign regulations released include the obligation from the OEMs to provide information about the disassembly of products, in some cases, it also restricts the use of certain fixing techniques (i.e. rivets, bolt, adhesives) that hampers the non-destructive harvesting of components [8,9]. Technological advances have progressively reduced the cycle of use of components, thus obsolete components become difficult to find on the market. Components become obsolete after a few years from their introduction on the market. This makes research and introduction into the repair and regeneration processes of other components complex and expensive. A significant effort is needed in the initial disassembly of the products and selection of components that could be reused to carry out repairs or re-manufacturing, even before starting the troubleshooting, repair or regeneration and functionality tests according to activities that are currently carried out manually by expert technicians.

In order to reduce the disassembly and sorting costs of the components still in good condition, and to broaden the possibility of reusing even low-cost electronic boards, it could be useful to evaluate the use of automatic components selection tools and to identify how such information can be brought together in a digital form.

The second limitation is the identification of typologies of PCBs and components within electronics. A promising method to overcome such limitation is the use of imaging techniques. If data useful for unlocking innovative circular technologies are lost during the product value chain, one possibility is the direct extraction from the product using imaging techniques. As an example, Hayashi et al. developed imaging tools and algorithm to catch information from label of WEEE (in the paper labels from digital cameras are analyzed) [10]. Two important information details are detected in the analysis: the manufacturer and the camera model code. Especially for PCBs, the correct label recognition and reading are important steps to catch product information. Li et al focused on two key aspects of text recognition: binarization and final recognition of text objects using optical character recognition (OCR) engines [11]. Other applications of imaging techniques are the direct assessment of the product without reading the code, where imaging techniques applied to X-rays images of PCBs fragments are used in order to identify integrated circuits (ICs) [12]. In the literature, many examples of this standard method applied to PCBs are presented but nevertheless some limitations still occur. The most important one is the fact that the contrast in the image between the components and the background change from PCB to PCB and this make very difficult the elaboration of an 'universal' algorithm robust respect this very huge variability. Pramerdorfer et al identified this problem when investigating on electronics recycling and suggested to perform a classification by the type of PCB applying a feature matching approach [13]. By using several descriptors such as SIFT, SURF, ORB, BRISK, FREAK and AKAZE, they were able to reach high PCBs recognition rate robust to assess PCB damage. In any case, once data and knowledge are generated by sensors and camera, the most important challenge is to develop methods to properly exploit all the potential benefits. Section 3.2 explores methods to exploit data extracted from PCBs with sensors, camera, or visual analysis, both at PCB level and at component level.

The third limitation is the availability of information about the PCBs and components. When the PCB and the components are highly customized, information about functionalities and composition is hardly found. Thus, in general, information about the functionality and material composition is available only at the component level (i.e. capacitors, integrated circuits, resistors). In both cases, such documents are generally scattered and only available at the component manufacturer's website or in some specialized free accessible websites (i.e. alldatasheets.es, electronicsdatasheets.com, octorpart.com).

The component datasheet includes information about the current, voltage, as well as thermal, electrical, dynamic and static characteristics. It includes the package outline and the footprint with a clear description of the dimensions and the pins, as well. The availability of information about the use of components will allow understanding better if components may have been misused, heavily worn and damaged. This information could help make a more robust decision about the probability of future failures. For instance, components that have suffered irreversible damage due to sudden changes in current, liquids, heat, explosion would be completely unusable. Most of the manufactured chips (after 2006) have a security measurement one-time programmable (OTP) memory which limits their reuse. Information about OTP could be identified and collected together with the products and components that are unusable to recover raw/secondary materials. In the Digiprime project, the free access to advanced information about functionalities of a specific product will be addressed case by case to avoid any violation of property rights. This is because the more a product is customized, the more information is likely to be subject to property rights. Also data about advanced functionalities tends to be subject to property rights and is less accessible.

The most common available information on material content are the material declarations where manufacturers declare the presence or absence of certain (usually hazardous) substances in the component, as the Restriction of Hazardous Substances (RoHS) declaration and the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). The information given however has a limited use when aiming at quantifying the content of valuable materials to optimize the recycling of the PCBs. Complete Full Material Declaration (FMD) containing detailed information about the substance (generally disclosed with the Chemical Abstracts Service number), and their quantities are available in the so-called FMD, many times given using the IPC-1752A standard [14]. Due to the large number of type and sub-types of components, the data gathering of FMD requires intensive work on data mining, especially since there is not a unique platform where FMD are available.

The availability and accessibility to information about the functionalities and the material composition of the components are key to allow for their second life, as well as that of the PCBs and electr(on)ic products where they are contained.

3. Methods

3.1. Digitalization approach by e-repair

At the moment most of the repair and regeneration activities are carried out manually, but certainly the transition to digital can simplify some activities, preparatory to the circular economy not simply linked to our sector, but able to connect the entire ecosystem of electronic devices.

The approach to digitalization in E-Repair has not simply been applied to the normal activities related to the management of the product from an administrative point of view and for its traceability during the work phases within the company. Four key point of digitalization are identified.

The first key point of digitalization in the more general process of the circular economy is to be able to create a value chain for the easy search and exchange of products and component useful for carrying out new repairs and regenerations. Based on the need to recover obsolete products and components, through a structured method, the Use Case 4 was activated within DigiPrime for the development of a database of obsolete components. This database has been structured to allow the creation of three types of actions:

- Insert an inquiry as applicant: Send a communication for the offer of obsolete products, to free the warehouse from unsold products, send back by the customer because they did not meet his expectations or other or even failures, without having to incur disposal costs by, for example, producers or dealers.
- Insert an inquiry as a bidder: send a request for an obsolete product/component to be acquired by the applicant (e.g. service provider, repairer).
- See requests received: create an automatic matching between supply and demand of the same type of item, which can send and automatic message to interested parties.

The items to undergo repair and reuse can be divided into three main categories: components (e.g. capacitors, display etc), spare parts (entire electronic boards or other parts of the products) and products to be used as a starting product for regeneration or as a product from which to extract the useful components to regenerate another products.

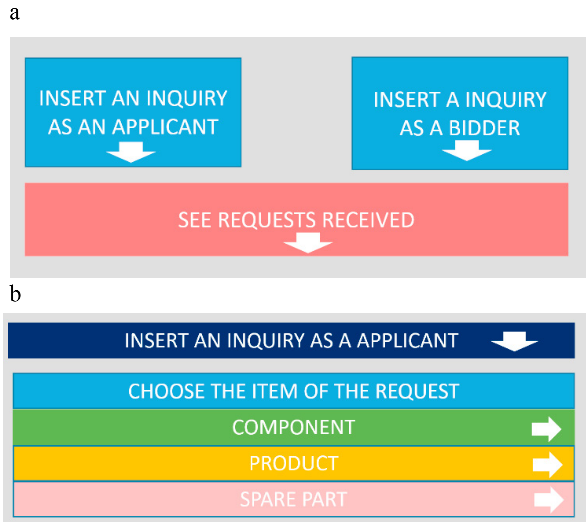


Fig. 1. Digitalization approach by e-repair. (a) description of the three possible actions; (b) description of the three categories of analysis.

The second key point is to create a shared knowledge for the identification of the most strategic obsolete items both in relation to their characteristics, functionality and their greater use on many different types of products and the possible difficulties in finding them on the market. The most challenging activity is to define a standardized method for defining the information necessary for the identification and classification of the items. At the moment a starting structure has already been created where some components have been evaluated, but we expect to analyze a greater number of items in order to define a use-case that takes into account most of the variables present on the various types of components.

The third point is to create an IT tool with a user-friendly interface, which simplifies data entry activities as much as possible, to create a virtuous model of information sharing and useful products of the circular economy.

The fourth key point is to facilitate the traceability of the obsolete product and the activities of shipment planning and logistics of obsolete items, at a European level, optimizing loads to reduce the environmental impact.

3.2. Digitalization approach by POLIMI

POLIMI uses two methods of exploiting data coming from a visual inspection of an End of Life (EoL) PCB with the objective of providing digital tool for the improvement of circular strategies and processes. The objective of the first method is to try to put a 'label' to the specific PCB concerning the field of application and the functionality. This is very important from a recycling point of view, since knowing the field of application and the functionality is important to have a first rough estimate of the material content (gold). This intuition is confirmed for example in [15] where the authors provide a classification of the metal content and the economic value of PCBs which varies according to the field of application: PC, mobile phone, TV, copy machine, fax machine PCBs and CPU component. Metal content is evaluated using traditional XRF and ICP-OES methods. The idea is to construct a knowledge-based classification scheme in order to properly classify the PCB. We try to extract some morphometric descriptors such as dimensions, ratio of different dimensions, weight, presence of characteristic components (for example special connectors of 'old models' of TV PCBs), used together to classify the electronic product. To construct this classification scheme, a total of nearly 60 PCBs have been considered and analyzed from a morphometric point of view. The role of digital data is crucial in this method. Input data used to the construction of the classification scheme are: the total weight, the ratio weight/total surface, the PCB shape (rectangular or not), the maximum side dimension, the ratio of maximum/minimum dimension. We use here the term 'digital' since these descriptors are easily extracted with image processing techniques or with other automatic tools (obviously the weight). The preliminary results of the application of the algorithm to a testing set of four PCBs (from automotive applications) is encouraging: three PCBs are correctly classified using only morphometric descriptors, the fourth one needs further investigation in terms of identification of characteristic components.

This first analysis is not enough to catch the residual value of the PCB based on the material content. To have a more precise estimate of the material content of the product, it is necessary to go further in the detail considering the specific material distribution inside electronic components. The fastest way to investigate the material content inside components is accessing its FMD. But, as already expressed in section 2, there are still two problems. The first is that the material declaration is not always available for all the components. The second one is that this documentation investigation would require a lot of time and work. Therefore, we need to find a simpler way to automatize the estimate of the residual value of the PCB. This can be done considering another aspect related to the product which is its level of standardization. This means that if we consider the electronic component from a mechanical point of view, describing it as a package, we discover that all the components could be classified inside few big classes of electronic packages. The following step is the construction of statistics related to the material distribution inside the components, investigating a huge set of material declarations. The process for the construction of our second algorithm and the material estimate method are summarized in Figure 2.

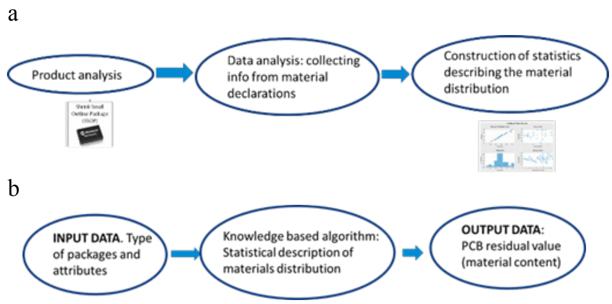


Fig. 2. Construction of algorithm for PCB value estimation. (a) Method used for the construction of the algorithm for the estimate of the residual value of a PCB and (b) Flow describing the application of the second algorithm for the estimate of the residual value of a PCB

'Input data' are of two kind: product 'typology' and product 'attributes'. In this second algorithm 'product' is referred to the electronic component (package). We focused our attention especially on integrated circuits (ICs) and on capacitors (electrolytic and polymeric ones). Attributes are mainly two: 'dimensions' and 'pin count'. Dimension are the component dimensions evaluated in the plane and out of the plane (thickness) and 'pin count' is the total number of metallic terminations of the component. The 'output datum' is related to the estimated amount of metals inside each components. One important aspect of this method is the fact that once the statistics have been constructed, all data are in digital form: in this way the calculation of the total material content can been easily performed implementing the statistics inside a calculation tool (for example Matlab). The output datum can for example been organized in a digital vector (string) whose components are the amount of the metals considered in the analysis: tot = [Cu Au Ag Al Fe Ni Zn Ta Sn]. Among these metals, copper (Cu) and gold (Au) are very important in the residual value estimate. For example, Arshadia et al. found Cu to be one of the most economic basic metals that should be recovered from most PCBs [15]. Moreover, the authors suggest to carry out a comprehensive study on the precious metals of different e-wastes, since the economic value of Au recovery is very high and recycling of other metals is less important than Au [11]. An example of the digital output of our method is reported below:

```
tot =
struct with fields:
max: 12.4389
mid: [3.2254e+03 10.3219 24.6200 0 0 0 0 0 0]
```

min: 8.2048

This is a digital structure: tot.mid is referred to the middle quantity of material (in mg). as previously explained each component of the vector is referred to a material. tot.max and tot.min are referred to the maximum and minimum amount of gold, considering the variance in a regression analysis.

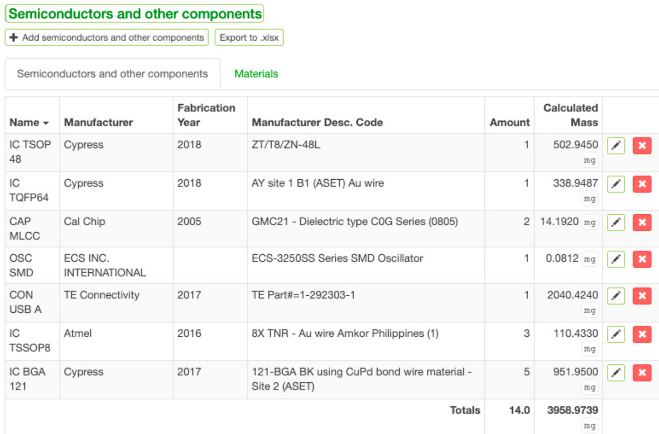
3.3. Digitalization approach by DoSE (ICTA-UAB)

DoSE® [16] has been designed as a part of the LCADB v.2 [17], an updated version of the lcadb.sudoe® data base developed in 2012 by the research group Sostenipra in partnership with the Universidad de Aveiro, Ecole des Mines d'Alès, Montepellier SupAgro, INRA, UdG, IRSTEA and CATAR Agro Resources. The new DoSE-LCADB database aims to provide better data to develop more robust inventories to perform better environmental life cycle assessments [18,19]. It contains two main sections, the DoSE which provides information of the material composition of over 250 components contained in printed circuit boards (PCB) and allows creating models of PCB contained in electr(on)ic products. Data for modeling the PCBs can be exported as an activity to LCADB® to create the life cycle inventory of an electr(on)ic product, exportable in Ecospold format which is widely used by commercial and non-commercial LCA software.

Within DoSE®, there are two main sections: the 'Semiconductor and other components' section, and the 'Printed Circuit Board' section. In the 'Semiconductor and other components' users can view/create the material composition of component. Data is available for 10 different typologies of integrated circuits, three typologies of capacitors, few typologies of inductors, resistors and connectors. In DoSE, each component is described in terms of mass (mg), dimension (cm), manufacturer, manufacturer description, and fabrication year. In addition, to provide robustness to data, it includes links to the manufacturer's websites, and an electronic copy of the datasheet and the FMD. All these documents were accessed in on-line free websites and include a clear reference to the source of data.

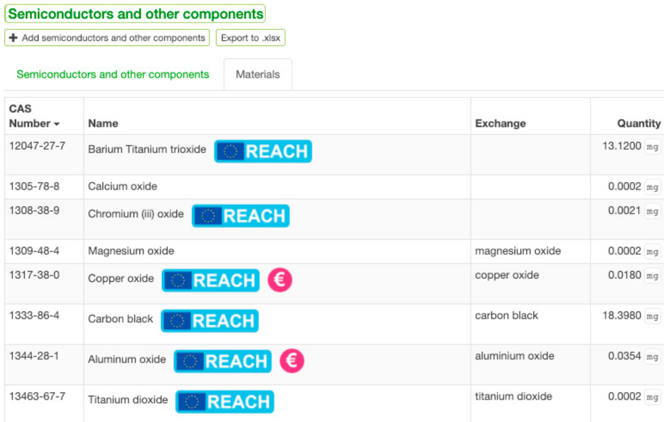
The 'Printed Circuit Board' section includes a table with the list of PCBs generated. For each PCB, the database includes a description of the PCB (dimensions, mass, typology of the PCBs), pictures of both sides of the PCBs, and information about the product or part where the PCB was taken. It also includes a description of the disassembly procedures and scheme to harvest the PCBs, which has been generated by the user by performing the disassembly of products to harvest the PCB. The description includes as well an estimated of the lifetime of the product (in months) and a section to add a short description of the method used. In general, data about lifetime is collected from on-line published report and do not violate any proprietary rights.

In the latest section of the description, users can view the components in an already existing PCB in DoSE-LCADB (see Fig 3) or add the components identified in the PCB based on a prior human visual inspection. The section includes a drop-down selection bar where the components already available in the 'Semiconductors and other components' section of DoSE-LCADB can be selected to model the PCB. The material composition of the PCB (see Fig 4) generates automatically as components are included in the inventory. Once the PCB is modelled, the dataset of the component and the material composition generated can be exported in excel format to allow performing further calculations, or exported as an activity to the LCADB® to generate a LC inventory of the product. The generated is useful to further assess the potential environmental impact and the economic value of electronics. Compared to other LC databases available, DoSE contains information on the disassembly of the PCBs and the lifetime of the product, all useful when assessing the repair and reuse of electronics.


Semiconductors and other components
+ Add semiconductors and other components | Export to .xlsx
Semiconductors and other components | Materials

Name	Manufacturer	Fabrication Year	Manufacturer Desc. Code	Amount	Calculated Mass
IC TSOP 48	Cypress	2018	ZT/T8/ZN-48L	1	502.9450 mg
IC TQFP64	Cypress	2018	AY site 1 B1 (ASET) Au wire	1	338.9487 mg
CAP MLCC	Cal Chip	2005	GMC21 - Dielectric type C0G Series (0805)	2	14.1920 mg
OSC SMD	ECS INC. INTERNATIONAL		ECS-3250SS Series SMD Oscillator	1	0.0812 mg
CON USB A	TE Connectivity	2017	TE Part#=1-292303-1	1	2040.4240 mg
IC TSSOP8	Atmel	2016	8X TNR - Au wire Amkor Philippines (1)	3	110.4330 mg
IC BGA 121	Cypress	2017	121-BGA BK using CuPd bond wire material - Site 2 (ASET)	5	951.9500 mg
			Totals	14.0	3958.9739 mg

Fig. 3. Example of the list of components included in the 'Printed Circuit Board' section of DoSE®.


Semiconductors and other components
+ Add semiconductors and other components | Export to .xlsx
Semiconductors and other components | Materials

CAS Number	Name	Exchange	Quantity
12047-27-7	Barium Titanium trioxide REACH		13.1200 mg
1305-78-8	Calcium oxide		0.0002 mg
1308-38-9	Chromium (iii) oxide REACH		0.0021 mg
1309-48-4	Magnesium oxide	magnesium oxide	0.0002 mg
1317-38-0	Copper oxide REACH €	copper oxide	0.0180 mg
1333-86-4	Carbon black REACH	carbon black	18.3980 mg
1344-28-1	Aluminum oxide REACH €	aluminium oxide	0.0354 mg
13463-67-7	Titanium dioxide REACH	titanium dioxide	0.0002 mg

Fig. 4. Example of the material quantities included in the 'Printed Circuit Board' section of DoSE®.

4. Next steps to advance in the digitalization of electronics

As each of the partners have approached digitalization from diverse perspectives. First, there is a need to identify how the information generated by those three approaches could be merged into a more robust and useful digital tool. To do so, it is important to identify or generate a common ontology between the diverse research teams, the industrial partners and IT programmers. This shall be done by setting up basic concepts as repair, reuse, and recycling, as well as component, part, product, by taking into account the already existing standards [20].

A second step is to establish information priority-setting for the manufacturers, third party repair and reuse companies as well as research teams. The objective is to identify key information for repair, reuse and recycling, to establish their importance from the diverse perspectives and to define as well the level of data accessibility. In the case of obsolete components/products, the resulting digital tool will facilitate their exchange between companies (for example Manufacturers as BIDDERS and service providers as APPLICANTS) across Europe. This system will also allow companies (manufacturers or dealer) that have obsolete products and components, or those that have returned from the market (for example new but with an open box, used or broken), to free up space in the warehouse avoiding incurring costs for disposal, promoting a good practice of reuse. While service providers will be able to enter requests for specific components that they consider strategic for repair and remanufacturing.

Some other features that are due to be further explored during the development of the new digital tool include to:

- Create a standardized methodology, applicable to a wide range product groups to identify a component and its functions.
- Create a classification of both products and components into specific search categories.
- Map the components contained in a selected product group and their functionalities to facilitate the identification and data harvesting. The list of product groups might be expanded as to facilitate the future search of the targeted component and the matching from product to component and vice versa.
- Define a list of the most strategic obsolete components according to their age and availability on the market.
- Define the level of data accessibility, especially data on use. The accessibility of data can vary from free public accessibility to consortia or project accessibility.

5. Conclusions

For the transition to a circular economy, all the strategies are equally useful as they optimize the loops for products and materials. According to the 2020 Circular Economy Action Plan [21], repair and reuse need to be further promoted as they report the greatest environmental saving. In addition, recycling shall continue play an important role as all products when they reach their end of life will need to undergo mechanical and chemical processes to ensure an optimal material recovery. Digital tools to support all of these strategies need to be further advanced, as they have the potential to streamline useful information to guarantee the optimal use of products and materials. This paper has already presented some of the current limitations to close the loop of electronics and suggested three digital tools conceived to overcome such limitations within the Digiprime project. Some key steps to advance towards the digitalization of CE is to identify/create a common ontology between the partners involved, aligned with already existing standards, and set up information priority setting to ensure the availability and accessibility of useful information.

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