Review

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Article

A Review on Adopting Blockchain and IoT Technologies for Fostering CE in the EEE Value Chain

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Abstract: With the continuous growth of electric and electronic appliances' usage, the waste produced with obsolete material (e-waste) has an increasing environmental impact. Also, the production of such appliances bears to increased consumption of natural resources and produces a multitude of toxic and hazardous substances, which typically are not properly treated. One of the approaches that may be adopted to reduce such problems relies on the circularization of the current linear model, commonly adopted in the Electric and Electronic Equipment (EEE) value chain. This includes recovering End-of-Life (EoL) products and reintroducing its parts, components, or raw materials into the value chain (e.g. semiconductors, circuit boards, raw metals, etc.), thus contributing to a more sustainable value chain. In this article, we present a state-of-art review that focuses on approaches and solutions for the EEE value chain traceability, and analyses the technologies that may be beneficial for promoting and implementing the Circular Economy (CE) model in this value chain.

Keywords: circular economy; traceability; BPMN; blockchain; IoT; electric and electronic equipment; EEE value chain

1. Introduction

Climate change is a current humanity concern, which is raised by deforestation, the enormous usage/burning of fossil fuels, and other human activities with a considerable impact on the environment. Most industrial and transport activities have a direct impact on the environment and are net contributors to the increase in the planet's average temperature. The EEE sector is a major contributor to this increase, due to the increasing exploitation of minerals and other raw materials, and the subsequent transport and industrial transformation, and also to the massive production of waste (e-waste). The global production of e-waste was around 53.6 million metric tons, in the year 2019, and is expected to be 74.7 million metric tons by 2030 [1].

In 2016, only 20% of 44.7 million metric tons found their way through recycling channels [2], while the rest ended up in dumpsites and landfills. These numbers are getting worse, because, according to the UN's Global e-waste Monitor 2020, in 2019, only 17.4% of 53.6 million metric tons of e-waste have been collected and recycled [3]. Moreover, inappropriate disposal of e-waste can lead to several social and environmental problems, since these products contain multiple dangerous substances to humans and the environment, including lead, cadmium, mercury, chromium, polyvinyl chloride, among others. Besides environmental concerns, e-waste also presents a significant economic loss and increases raw materials' scarcity. The transition to a CE can help to improve and optimize the EEE sector due to the substantial environmental and social impact of its products, which use multiple raw materials and a considerable amount of energy during the product life-cycle, namely during the production and use stages.

The EEE sector includes the manufacturing of all types of electric and electronic products, from TVs, microwaves, or cell phones, to desktops, laptops, etc. An electronic product, such as a smartphone, may be composed of 500 to 1000 different parts, from extremely small (micro components) to bigger

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parts (macro components) [4]. The demand for thinner gadgets increased the need for raw materials. From 2004 to 2014, the production of iron, cobalt, and lithium increased between 125% and 180% [4]. Different raw materials and minerals are used to build different components. From 83 stable elements in the periodic table (Figure 1), more than half of them are found in smartphones [5]. Most of them are easily available metals, such as iron and aluminum, but others are at risk of supply shortage. From a total of 17 rare earth elements, 16 are used in the production of smartphones [5,6]. Some of those materials are listed in the European Union (EU) list of critical raw materials[1].

Furthermore, smartphones also need conflict minerals (e.g., Tungsten, Tantalum, Tin, and Gold), whose designation is related to their origin areas, where human rights are not respected, being sometimes traded by armed groups. EU established new legal content in order to combat these issues [2].

Finally, it is also important to mention substances of concern, which have significant social or environmental impacts. The use of these substances is restricted on the EU market through Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation [3].

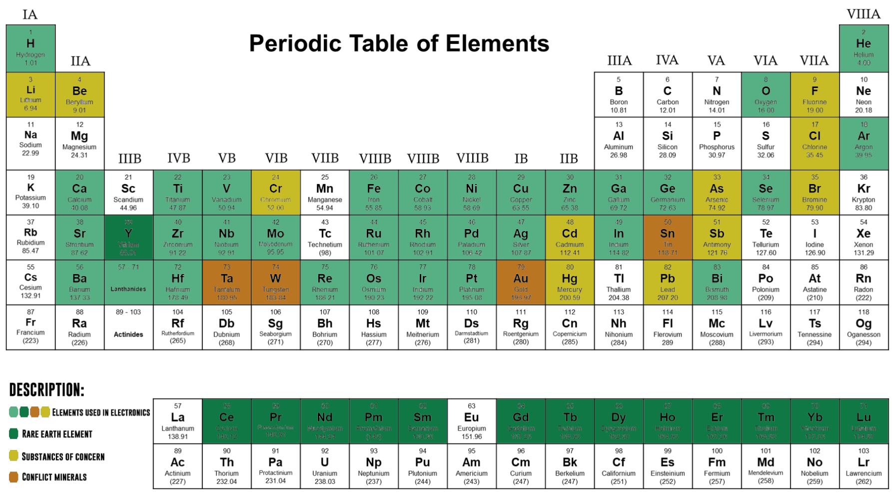

Figure 1. Smartphone periodic table (adapted from [5]).

One approach to reducing the harms that the EEE industry is causing to the environment is to explore CE applicability in this sector. CE is an economic model based on a business model that replaces the traditional linear "take-make-dispose" model by reducing, reusing, recycling, and recovering materials or components in the production and consumption processes [7].

To assess the environmental impact of every activity in the value chain, it is important to trace every relevant item in the value chain, such as any lot of raw material, electronic components, electric material, circuit boards, integrated circuits, etc. To accomplish this goal, a traceability platform is needed. The Blockchain technology (BCT) is already being used for traceability purposes. In a blockchain network, the transactions are stored in chronological order, creating a permanent and immutable data record, providing transparency in the value chain [8].

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1 Raw Materials Resilience: Charting a Path towards greater Security and Sustainability, European Commission, Brussels, September 2020, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474

2 Conflict Minerals Regulation, European Commission, Brussels, January 2021, https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/

3 Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02006R1907-20140410

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A traceability platform allows storing information about every item in any step of the value chain, thus allowing a physical item to be associated with a digital representation (its digital twin). Some traceability data may be collected through Internet of Things (IoT) devices, offering an easy, truthful and thoughtful way to handle data.

This article reviews the state-of-art of BCT to support CE in the EEE value chain, being used for storing data about important indicators needed to measure the sustainability of electrical and electronic equipments throughout the value chain. Moreover, the state-of-art regarding the IoT technology is also analyzed, since real-time data collection about every traceable item in the value chain is crucial to compute relevant operational metrics and indicators. Such tools are relevant for assisting decision-making at the business management level.

This article has the following structure. The next section presents the methodology adopted for identifying and selecting the literature review. Section 3 analyzes the EEE linear value chain and presents its generic business process model. In Section 4 a CE business process model for the EEE value chain is proposed. The proposed model is presented at a high abstraction level, identifying the main value chain activities and circularizing the previously linear value chain. Section 5 reviews the existing traceability platforms in the EEE value chain, and analyzes the main levers for CE in the EEE industrial sector. In Section 6 the technology enablers for CE in the EEE value chain are identified and analyzed. Finally, in Section 7 an analysis of the results is undertaken, and the conclusions are drawn in the last section, 8, with ideas for future work on the traceability of CE in the EEE value chain.

2. Materials and Methods

The goal of this research is to review traceability systems and technologies used in the EEE sector in order to enable the circularization of the EEE value chain. The research has been conducted between 24th of January and 31st of March 2022 using Google Scholar to search for results with a combination of the following terms: "Circular Economy", "Electric and Electronic Equipment", "Traceability System", "Blockchain-based traceability", "Blockchain", and "IoT". From the results obtained, and their relevant citations, we selected the ones indexed/published in Scopus, Elsevier, and Web of Science, published from 2003 onwards, for further analysis. To these papers, we added some technical reports, companies' white papers and technical blogs.

These materials has been individually analyzed based on the following steps:

- A manual title and abstract screening was performed and the manuscripts that were highly correlated with the topic under analysis have been considered for review.
- When it comes to blog opinions or other non-scientific items, it should present a different or unique perspective on a certain topic.
- Ambiguous or duplicated articles have been removed.

Finally, a total of 67 research items have been selected, including 52 scientific papers, 6 books, 3 technical reports, 2 MSc thesis, and 5 technical white papers or blog entries.

3. The EEE linear value chain

The EEE value chain is, nowadays, one of the biggest worldwide, involving several companies in several countries, with different industrial processes, starting in the mines and ending in the final consumer and waste. Some of these manufacturing processes assemble the final product, but most of them just produce some kind of intermediate part, such as transistors, chips, CPUs, circuit boards, integrated circuits, and many other electronic components.

The EEE production activities result in significant use of natural resources with consequent environmental damage, such as mining, transportation, energy consumption during manufacturing [9]. These activities must be traceable, in order to enable the measurement of their environmental and social impact.

According to [11], the currently predominant economic model is the Linear Economy (LE) model. Since the third industrial revolution, linear thinking has led to prosperity and economic growth in many parts of the world. Consequently, manufacturers have been oriented towards a business model that is based on a large use of materials and minimizes human labor costs. Automation, cheap materials, and the reduction of human labor costs are common reasons why recycling and reuse have been neglected. The search for cheap labor also leads to the transport of goods over long distances.

The "take-make-dispose" model, represented in Figure 2, is based on the assumption of high availability of materials and on the high regenerative capacity of the earth.

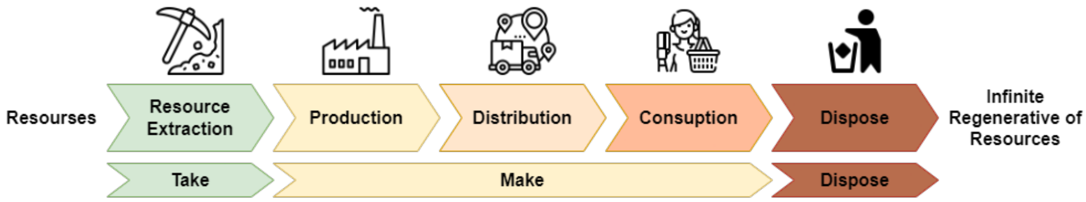

Figure 2. Linear Economy - “Take-make-dispose" model (adapted from [10]).

Although LE has been a great success in the last century, it has raised many concerns, as this model uses resources unsustainably, producing a large amount of waste that is harmful to the environment [10]. Within LE, population growth will require more and more resources to keep up with the demand generated by this growth. In addition to environmental impacts, there is a concern about non-renewable resources, as they are becoming scarce (including many metals, minerals, and fossil fuels) [10]. Furthermore, the price of these resources is rising and becoming unpredictable, leading to an increase in costs along the value chain and a higher price for the end consumer. Nowadays, the "take-make-dispose" pattern is still used by several value chains in different areas.

As mentioned before, the EEE value chain involves a huge number of participants that are spread all over the world. Figure 3, presents the inter-organizational business process model of the EEE value chain, by using the BPMN (Business Process Model and Notation) language. The model represents the generic linear EEE business process at a high level of abstraction. Thus, the main pool represents the main activities involved in the linear value chain, starting with the extraction of minerals and ending in waste. The participants involved in the value chain are represented as external participants. The participant responsible for carrying out an activity is represented by a message sent from the participant to the corresponding activity. An activity, at this inter-organizational level, represents a process internal to the company responsible for its execution. The internal processes of each of these companies can be complex and not very friendly to the environment.

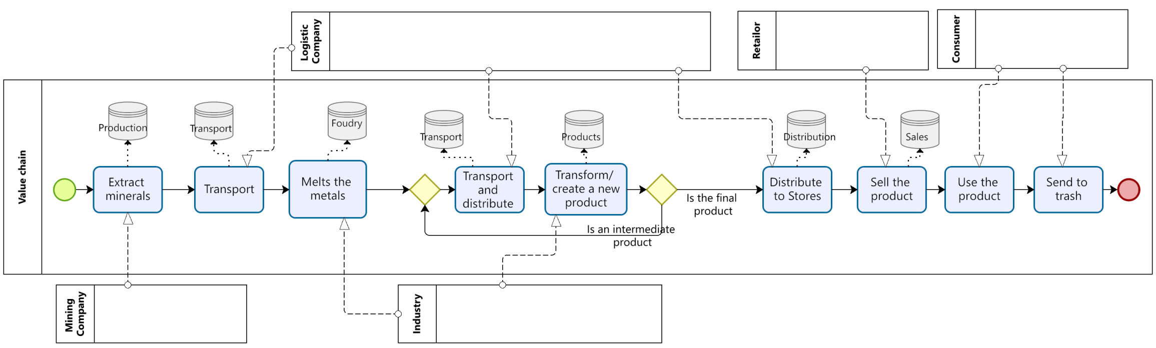

Figure 3. EEE Inter-organizational linear business process model.

As we can see in Figure 3 the process begins with the extraction of several types of minerals (first activity in the process), such as tin, silicon, cobalt, iron, copper, etc. by mining companies. After that, the minerals are transported for smelting, refining, or melting of metals, as represented in the second and third activities in Figure 3. Minerals are sometimes mixed together, meaning that they receive the raw material from different mines. Next, the metals (refined metal) are transported to the companies that create diverse components (fourth and fifth activities in Figure 3), such as chips, transistors, etc. Some companies create new products (final products or components) by using other products (components). The components are used as inputs for the creation of new components. This is represented by the loop between the two gateways in the business process represented in Figure 3).

After the final product is finished, it will be distributed by the stores to be sold to the final consumer who, after using it, can send it to the trash and thus produce electronic waste.

In the inter-organizational business process model presented here, five main types of participants are identified:

- *Mining companies* – This participant represents companies responsible for the exploration of mines from which minerals such as cobalt, tin, tantalum, silicon, and lithium, among many others, are extracted.
- *Logistic companies* – This participant represents companies responsible for transporting the materials. It may involve trucks, trains, boats, etc. The extraction of metals can be done in the most diverse parts of the world, so transportation is usually very long.
- *Industry* – This participant represents companies responsible for the fusion of materials (foundry) and industries responsible for the creation of all types of components such as chips, transistors, etc., or for the creation of new products such as computers, mobile phones, etc. Usually, in the construction of a EEE product, many industries of this type are involved. Each one is responsible for the manufacturing of a part or component, and the others are responsible for assembling such parts or components.
- *Retailer* – This participant represents companies responsible for distributing the products, or components, by the stores for selling them to the consumers.
- *Consumers* – This participant represents the final consumers who, after purchasing the product and using it, in the linear model, throw it away (represented in Figure 3 by the activity *Send to trash*).

The EEE sector contributes heavily to climate change. So, a more sustainable approach is necessary to minimize the environmental and social impacts of those products. To accomplish a more sustainable approach, it is important to know the environmental impact of each stage of the value chain and the material composition of each product or component [12].

When the objective is to trace a product in the value chain, it is necessary to store information about what happens in each one of these activities. This data collection is represented in Figure 3 by writing in the data stores by each of the activities, and it will be the responsibility of the company that performs the activity.

4. EEE Circular Value Chain

Mostly due to the scarcity of some minerals and the increasing use of e-products, due to the increase of population and technological advancements, society is challenged with their EoL management to reduce the environmental impact and save resources [13]. In a recent move towards a more circular process, there is a commitment to slowing and closing resources' loops [14].

CE promotes the circulation of resources, materials, and product components, to reuse them instead of discarding them. To achieve the goals of this economic system it is necessary, among other variables, to ensure the cooperation of all participants in the product value chain (producers and consumers), as well as a proactive improvement from product designers. The design must be thought to allow the easy replacement of a part or component of a product. Such initiatives are, most of the time, very challenging, given the complexity of e-product design and material composition [15].

The CE concept is a production and consumption model that contributes towards the transformation of the industry towards a more sustainable and environmentally friendly approach. This means trying to reduce the waste of materials, and recycling and reusing them throughout the value chain and production processes, aiming for innovation, economic growth, and the reduction of pressure on the environment [16].

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The concept of CE as a regenerative system, generally, is viewed as a necessity for sustainability that aims to reduce the waste of resources and maximize their efficiency and ecological sustainability, maintaining the value of products, materials, and resources in the CE as long as possible. This can be achieved through maintenance, repair, reuse, and recycling of products and materials [17].

4.1. EEE circular value chain: Generic business process model

CE is defined as a business model that can replace the linear economy or 'EoL' (End-of-Life) concept by reducing, reusing, and recycling resources that can be used again in the production-consumption process. To achieve this, the alternative to the "take–make–dispose pattern" needs to operate at different levels, with products, companies, and consumers at a micro-level; cities, nations, and beyond at a macro level [16].

Figure 4, represents, at a high level of abstraction, the circularization of the EEE business process model represented previously in Figure 3. As represented in Figure 3, to circularize the business process, it is necessary to involve new participants (or with different responsibilities), besides the ones already in the value chain, namely:

- *Customers* – Consumers play a very important role in circularizing the EEE business process because they can (and should): i) recover the product and use it again; ii) sell it to another consumer (and this new consumer can use it again); or iii) send it for recycling. Consumers can also choose to buy more sustainable products, encouraging manufacturers to invest in the production of products with less environmental impact. This way, consumers can fuel the circular economy.
- *Collector company* – is a new type of transport company, responsible for collecting the products sent for recycling and delivering these products to the recycling company.
- *Recycling and Recovery company* – it is a new kind of industry, responsible for cleaning and disassembling a product into components, and verifying if some components can be recovered and reused, or recycled. The recycling process of a EEE product can be very complex due to the high number of components and materials involved in creating the product.
- *Repair stations* – product repair shops are prepared to receive and repair products (or components) from consumers. Repair shops can repair, or replace, any component that breaks down and needs to be fixed. The ease of replacing a component (e.g., battery) in a product depends on the design of the product. So, to increase the circularity of a product, the product (and components) must be designed in such a way that it is easy to replace a component if it fails, without having to replace the entire product.

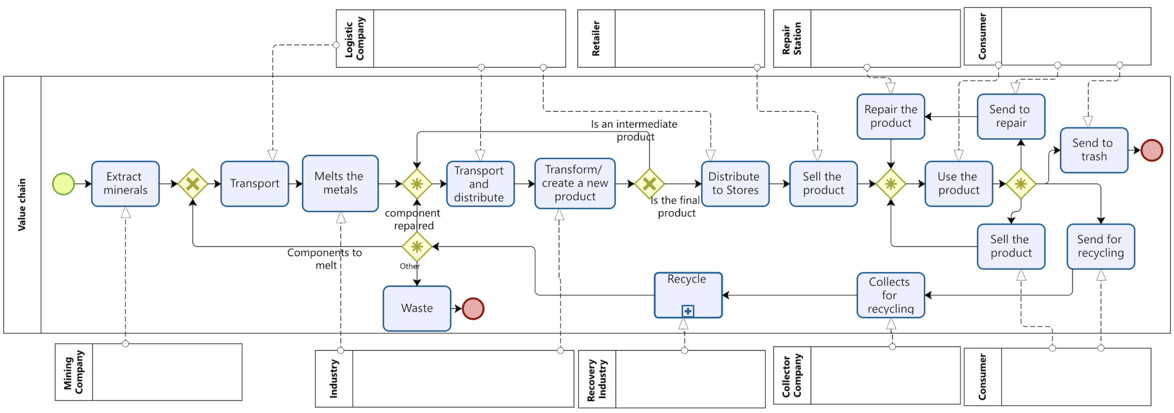

Figure 4. Generic business process model for CE in the EEE value chain.

The circular economy also needs the active participation of government entities to, among other things, provide collection points for this type of product, making it easier for consumers to participate

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in the CE by recycling the products. Government entities can also create laws that prevent the disposal of this type of product, especially large electrical appliances.

4.2. End of Life practices & services

End of Life electronics should be managed by the Waste from Electrical and Electronic Equipment (WEEE) directive[4]. It says that the EoL of these devices is under the responsibility of producers and importers, those entities can either manage it individually or through a third party. The problem of the insufficient collection of e-waste is caused by the lack of data about the EoL devices, the value of unused and wasted devices, and data security issues [6].

As the process of creating a product is complex, involving the creation and assembling of many components, the process of recycling can be just as complex. Akcil et al. present a flow chart for metal recovery from E-waste (Figure 5). The presented schema is divided into *pre-processing* and *end-processing* [18]). *Pre-processing* refers to separating and sorting parts and materials for safe disposal and recovery processes. *End-processing* refers to all steps needed to recover secondary materials from processing scraps.

Pre-processing operation starts with removing polluting substances. The goal of this step is to comply with the pollution reduction requirements, such as those mentioned in Annex VII of the WEEE Directive. In the case of smartphones, selective treatment includes the removal of batteries, printed circuit boards and electric cables, and also plastics containing brominated flame retardants. Design features allowing an easy disassemble of a product listed in annex VII of the WEEE Directive are important to optimize this operation. Some design principles allow easier separation of parts, labeling them, and minimizing the number of materials used, and others help in the process of recycling, as is the case of recycling Lithium-ion (Li-ion) technologies.

After removing the most polluting materials, WEEE is separated into components. The scraps generated are separated into material outputs (e.g., gold scrap, copper scrap, printed circuit boards, plastics, etc.) that are sent to end-processing or to specialized companies that sort them better (e.g., various groups of copper).

In the case of smartphones, they are mainly made of aluminum and plastics. However, the main residual value of an electronic product comes from precious metals. The recovery of those types of materials from WEEE is the main goal of *End-processing*. In [6], an overview is provided on various recycling options for smartphones. The most known recycling route, in EU, for the recovery of metals is based on pyro-metallurgical methods, as illustrated in Figure 5. Several precious metals that have high recyclability rates can be recovered, for instance, copper, gold, silver, palladium, and tin [6]. Other critical materials are relevant for recycling but aren't efficiently recovered, such as tungsten, gallium, and indium.

Recycling and recovery of materials may be limited by the presence of certain substances and by technological issues. The development of advanced pre-treatment and recycling processes can increase efficiency. At the product design level, product design as such is crucial for enabling subsequent repair, refurbishment and recycling (such aspects as the ease of disassembly, ease of separation of components, etc.). This would make it easy to remove parts that can be reused and parts that contain precious metals, since documentation regarding the operations needed to access and remove the components or information about metals from high-risk areas, would exist. WEEE Directive, in art. 15 requires Member States to ensure that producers provide information free of charge about preparation for re-use and treatment in respect of each type of new EEE placed for the first time on the European Union market.

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[4] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02012L0019-20180704

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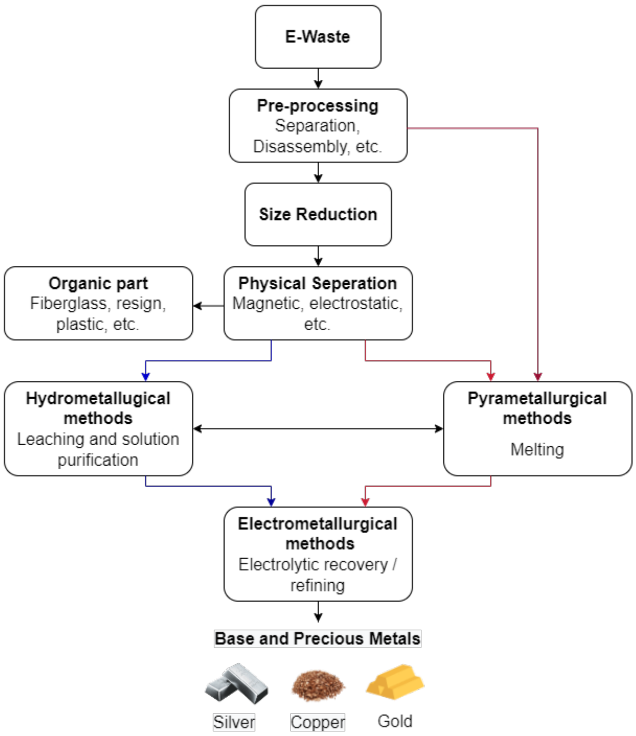

Figure 5. Scheme for recovery of precious metals (adapted from [18]).

4.3. *Circular Economy Levers in EEE industry*

The main levers for CE in any area are product design, digitization, regulations, or laws at a state level, and consumers who have already become aware that sustainability and the fight against global warming are not in line with consumption without rules and the linear economy, which throw away end-of-life products, not reusing or recycling them. Consumers will always have an active role to play in leveraging CE.

One of the levers for CE is *Circular product design*, which is a circular process for the design of a product. This is the phase where at least 70% of the total cost of a product is set, being one of the most important stages where commitments are made to reduce the environmental impact [19]. "Design for disassembly, reassembly, and recycling" aims to design EEE products that can be easily divided into components, to guarantee an efficient way of parts and material recovery within CE models [20]. The modular design consists of developing products' architectures with separable modules, which make the process of disassembly, reassembly, and recycling much easier, given that each module can be separated and attached as a group [21]. "Material selection" is a design option to incentivize the use of secondary raw materials [22], eco-friendly materials, and materials with high recyclability rates.

Digitization, through traceability systems, is another important lever for implementing CE. Nowadays, thanks to the advance in technology, manufacturers started to automate some processes through software and digital systems [23]. This automation enabled the creation of a bidirectional link between the physical world and the virtual one [24].

Governments may encourage companies to implement CE by issuing regulations [25] and through other economic incentives [26]. As mentioned earlier, the European Union has published a list of critical raw materials and a list of substances of concern, along with legislation to deal with these issues. These materials need to be managed carefully, in order to prevent and avoid social or environmental impacts.

Other levers include the need for maintenance and repair services, which are strategies to grow the life of EEE products [27]. Also, user-oriented Servitized Business Model (SBM), through product leasing, allows moving from the current 'replacement system' to the optimal one ('optimal usage' of

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products), given that leasing internalizes the life cycle costs to the manufacturer [28]. *SBM levers* focus on reverse logistics to close the value chains' cycle. Reverse logistics contains the processes of planning, implementing, and controlling material flows, and related information from the stage of consumption to the original stage efficiently to recapture value [29]. Usually, a second-hand EEE product can be supplied for individuals, collection sites, or from retailers [30]. Knowing how to implement a reverse logistics network is a complex problem, from defining the optimal sites, collection and inspection centers, re-manufacturing and recycling facilities [31].

The recollection modes, from business and domestic customers, are typically made at the end of lease or at the EoL of the product when the customer delivers it for assets recovery by municipal pick-ups and retail take-backs (such as buy-back, trade-back, etc.).

5. Traceability in the EEE value chain

Traceability mechanisms provide the ability to follow step by step and understand the story of a product. Through a IoT tag (e.g., QR Code, Barcode) it is possible to track a product along its value chain [32]. Traceability brings transparency, and it's a risk management tool, which [32,33]:

- Allows to follow each component at every stage of the value chain, identifying these components and their locations associated with their movements;
- Provides real-time tracing information of all activities from the production stage to the final consumer;
- Provides a historical record for traceability of components throughout the value chain;
- Offers the capacity to respond faster to potential supply chain risks, minimizing losses and product returns;
- Helps to improve the transparency of processes throughout the value chain, detect problems of a certain product, protect the brand from counterfeit products, etc.
- Allows that the information gathered to be used in the control and management of the different stages of production;
- Enables dynamic lot allocation, and optimization and control processes along the supply chain.

A traceability system can be beneficial to improve the relationship between business partners and between manufacturer and client, offering transparency about the product.

Product authenticity is also a benefit of traceability systems, since counterfeit products lead to huge economic losses to the companies, and may put at risk the overall value chain [34].

In order to comply with regulations, particularly warranties, returns, and costs, it's beneficial for EEE producers to have a manufacturing traceability solution.

The authors in [35] talk about an Industry 4.0 Smart Factory where the systems are interconnected and able to receive and send data from/to other systems. It is stated that there are systems/machines that help the implementation of traceability in each stage of production, from labeling the incoming goods into the facility (ex: Barcodes) to monitoring how the production runs and which components are needed to assemble a product. The author also states that there are machines capable of storing data from test results, movement of units throughout the production phase, etc.

Nowadays, with the globalization of value chains, the need for traceability has become more and more important, allowing to track a product all along its value chain [36]. In the EEE value chains, it's also necessary to track products and their components, ensuring their authenticity, to avoid forgeries. Traceability can also be seen as a step towards more transparency in the value chains [8].

Even though traceability systems offer several benefits to a supply chain, financial costs are also important factors, since gathering data from all devices in the production stages is very expensive. Some platforms have been proposed for traceability in the EEE value chain. Some of them are briefly described next and listed in Table 1.

Table 1. Summary of solutions for traceability and CE in the EEE value chain.

	Sustainable information management for Waste Electrical and Eletronic Equipment	Cloud-based system for Waste Electrical and Electronic Equipment	A traceability and auditing framework for electronic equip. reverse logistics based on blockchain	value chain transparency through blockchain-based traceability	Using IoT and Distributed Ledger Technology for Digital CE Enablement
Technology	RDBMS & RFID	RDBMS, QR Code, RFID	Blockchain, IPFS	Blockchain, RFID, LPWAN,QR Code	Blockchain, IoT technology
CE optimisation	✓	N\A	✓	✓	✓
IoT Integration	✓	✓	N\A	✓	✓
Traceability	✓	✓	✓	✓	✓
Features	SOA-based architecture, RFID technology	Web application	N\A	Several value chains are studied	IoT Geo-location
References	[37]	[38]	[39]	[40]	[41]

The authors in [37] suggested a case study on LCD TV WEEE to support a more sustainable WEEE management, proposing a generic global EEE information model and other EEE services. The conceptual information model proposed by the authors supports information gathering about the product and the data for recovery and re-manufacturing (factory information, tracing data, technological information for recovery and re-manufacturing, recovery/re-manufacturing-oriented design support information, legal, economic and ecological information) [37].

The authors in [38] presented a cloud-based system for WEEE, a Web application based on an Relational DataBase Management System (RDBMS) that can be used to track an EEE throughout its life cycle. The platform supports several features like adding a new product, managing, disassembling, and searching for products, etc. In each step of the product life cycle, the data are resumed or updated in the database. Additional information can be stored internally in the product itself (internal memory in the microcontroller or an RFID tag with memory and sensors) and sent to the cloud when the product changes its stage in the life cycle, using IoT capabilities.

In [39] the authors proposed a traceability and auditability platform for reverse logistics (RL) activities of EEE, with a special focus on mobile phones. The platform, based on a private blockchain, provides a functional implementation of several smart contracts (SmCs). Being based on SmCs, the presented solution offers automation in collecting, handling, and analyzing traceability information and events for the RL processes. BCT isn't suitable for storing a large quantity of data, so the author applied an off-chain storage approach by using the InterPlanetary File System (IPFS) to enable scalability and integrity for storing critical records of the RL events. Each stakeholder stores within IPFS all the important data of the RL operations in a Table of Contents (TOC), and after that the hashes of all individual records are stored on the blockchain. Therefore, instead of saving all the data directly on the blockchain, the system only saves the hashes of RL data on the blockchain [39].

The authors in [40] suggested a blockchain-based traceability solution to several value chains (including the EEE value chain). This technology can create transparency in the value chain via tracking and tracing. In this solution, to demonstrate the potential of BCT in traceability and value chain transparency, a solution was developed using the Microsoft Blockchain Workbench Platform (MBWP). The author explores several applications, in different value chains, and describes several IoT tools used for traceability, such as RFID tags, QR Codes, barcodes, and Near Field Communication (NFC) tags, GPS, etc.

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The authors in [41] proposed a combination of IoT and BCT that can lead to an improvement of circularity for EEE. The digital technologies that enable the creation of traceable supply chains for EEE could help to prolong product lifetime and retain materials value, creating a more valuable resource efficiency. The authors searched for a permissioned blockchain since it allows the introduction of an access control mechanism, which is important to accept transactions from authorized users. Among several solutions, Hyperledger Fabric has been selected, since it permits the creation of permissioned blockchain systems with several channels on the same node. The use of IoT devices can also help in this traceability, considering it's possible to retrieve data from materials, in terms of location, availability, geolocation, etc. [41].

The authors in [42] presented a traceability solution for automotive electrical system manufacturing through BCT and IoT technology. The process of manufacturing those systems is complex, involving thousands of parts, which need to be managed by various systems like Enterprise Resource Planning (ERP), centralized applications, etc. The importance of traceability in this sector comes with Autonomous driving (AD), especially for products that are safety-critical. Traceability can help to identify these products' components, in case of failures or in case of production problems. The authors have developed a blockchain-based traceability system using an Ethereum-based blockchain. Instead of using a conventional blockchain solution, such as integrating product data as primary transaction data and events, they have proposed a different approach by using ERC 1155[5] blockchain tokens. ERC 1155 introduced the capability to manage both types of virtual objects using the same smart contract. Several components in this industry are unique, needing separate tokens to link the component's unique Identifier (ID), status and production history. The application of ERC 1155 to this use case allows multiple tokens, which are needed to represent different products, and allows linking tokens with a URI, that can contain further product information.

Within the EEE industry, there is a concern regarding the introduction of counterfeit electronic parts. [43] states that traceability doesn't assure quality and performance once the component leaves the authorized value chain, regardless of the effectiveness and procedures used. Despite it is almost impossible to completely prevent counterfeit components from entering a supply chain, it is possible to reduce this occurrence by implementing "risk-based policies", as specified in the regulations, focusing on buying only materials from authorized suppliers.

6. Technology Enablers for CE traceability in the EEE value chain

Traceability systems, together with IoT, allow the EEE value chain to be smart and connected. These technologies can improve EoL activities by having always the information about the product, regarding its general condition, and the information about the components used before disassembly [44]. Traceability and IoT can also play an important role in Supply Chain Management (SCM), improving the quality and integrity of data and allowing advances in the context of reverse logistics for a faster and more sustainable use of WEEE. Traceability systems and IoT can improve a circular product design since all the data collected throughout the EEE life cycle can be used to trace all the products and their components [45,46].

6.1. Blockchain Technology

With regard to traceability systems, blockchain technology is one of the best and increasingly used alternatives to face the challenges posed by a global value chain [47]. Since the introduction of Bitcoin in 2008 [48], several blockchains have been applied in different scenarios involving value and supply chains [49–52]. Blockchains have several applications providing compliance, transparency, tracking, error reduction, payment processing, and many others [53].

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5 https://eips.ethereum.org/EIPS/eip-1155

A *Blockchain* is a distributed database that allows its participants to store information securely and in real-time. Distributed ledger technology (DLT) is the base layer of a blockchain. This technology offers a consensus mechanism that allows peer-to-peer transactions without the need for an intermediary to process and maintain the data generated by transactions. When a group of transactions is validated, a new 'block' can be created and added to the existing chain of blocks [54].

Distributed ledger technology is often misunderstood as a synonym for Blockchain, but it refers to the distributed and decentralized ledger of BCT. With DLT, a ledger can be maintained, authenticated, and secured without a central authority. As a result, copies of that ledger are distributed and maintained by the participants of the network [54].

Blockchains can have different types of permissions (refer to Table 2) and may be mainly characterized by their consensus protocol [55]. As there is no central authority to validate transactions, making sure that all network nodes are synchronized and have the same ledger, a *consensus protocol* is needed. A consensus protocol is an algorithm that allows all blockchain nodes to reach an agreement on committing information on a new block, ensuring that the new (latest) block has been added to the chain correctly [55]. Examples of blobkchain consensus protocols are Proof-of-Work (PoW), Proof-of-Stake (PoS) or Practical Byzantine Fault Tolerance (pBFT), among others [56].

One of the most known public blockchains is Bitcoin, which is purely used for the cryptocurrency with the same name. Bitcoin uses the PoW consensus mechanism, which is known for wasting too much energy [57]. There are, however, several other consensus mechanisms, which are applied in other blockchains, some of them trying to solve energy efficiency and other concerns [58].

Table 2. Blockchain permission types.

	Type of Permission	Read	Write	Commit
Open	Public permissionless	Anyone	Anyone	Anyone
	Public permissioned	Anyone	Authorized Participants	All or a group of participants
Closed	Consortium	Authorized Participants	Authorized Participants	All or a group of participants
	Private permissioned	Private Participants	Network Operator	Network Operator

Smart contracts are simple programs stored on the blockchain that run when certain conditions are met. Normally, they are used for executing agreements of which the participants can be certain of the outcome, without a third party [55]. Smart contracts can be seen as an "if-then statement" that is written into code on a blockchain. The network executes the action defined by the Smart Contract (SC) when the condition is met. These actions could be registering a product, transferring ownership, etc. When the transaction is completed, the blockchain is updated, meaning that the transaction cannot be changed [56].

6.2. Blockchain-based solutions for traceability and CE

When it comes to traceability solutions, it is essential that traceability information is accurate and easy to collect. At a base level, connectivity to all the machines and processes used in the production stage is needed to record every data element that is relevant for future decisions. EEE value chain crosses multiple players that are spread along the world, and a data storing technology that is secure and solves trustability issues among the stakeholders is mandatory.

A *Digital Twin* is a representation of a physical object that provides all the relevant information about that object in a digital way. While the real electronic product is going through the stages of the value chain, these different phases and processes should be recorded accordingly on a traceability system. To accomplish that, a digital twin of the real product is created to track and trace the product

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throughout its life cycle alongside its information (product identification, product name, etc.) [59,60]. According to [61], IoT can help record information from any product at any life cycle stage through devices that can ensure seamless tracking of the product. When this technology is combined with blockchain technology, this information becomes immutable and transparent.

BCT has been applied in different commercial scenarios, including in reverse logistics and value chains [40,41]. However, we could find very few studies on the use of BCT in the EEE value chain. The adoption of BCT would be useful and bring many benefits, such as compliance, transparency, tracing, tracking, immutability, etc. [53]. In addition, blockchain-based systems provide real-time data and SC technology to suit the needs of their users, and can be integrated with other technologies, such as Big Data, Artificial Intelligence (AI), IoT, etc.

Some characteristics of BCT have motivated the development of blockchain-based platforms dedicated to the logistics sector, such as TradeLens[6], DataPorts[7] and LACChain[8].

Alves *et al.* also refer to alternative blockchain-based solutions for CE [60]. For example, Circularise, Vechain, and Waltonchain, which use public blockchains with permissionless user profiles; and Everledger and Ambrosus, which use private/consortium blockchains with permissioned user profiles.

Hyperledger[9] is an open source community that pursues the development of stable frameworks, tools, and libraries for enterprise blockchain deployments. One of these tools is Hyperledger Fabric. Under this private blockchain technology, the confidentiality of the data stored on the ledger is assured. One feature that is noteworthy is the "channels" functionality, where nodes can only share and access information in the channels in which they have permission [60]. This architecture allows sharing information between nodes connected to a given channel, protecting the private data from other nodes outside the channel.

The Hyperledger Fabric, here used as an example of a private / consortium permissioned blockchain framework, brings some advantages, such as:

- *Permissioned network* – Hyperledger Fabric allows deploying blockchain-based solutions that are not publicly accessible. Different permissions may be assigned to different users, and only registered users may access the blockchain and act within the assigned permissions.
- *Confidential transactions* – The data handled in a transaction is shared and viewable only among the users/organizations that are involved in the transaction.
- *Pluggable architecture* – Hyperledger Fabric's consensus protocols are pluggable, meaning that it is possible to modify/configure different consensus protocol implementations. Hyperledger Fabric supports different consensus protocols such as CFT (crash fault-tolerant) or BFT (byzantine fault-tolerant), among others.
- *Easy to get started* – Hyperledger Fabric supports different SC known programming languages, instead of custom languages, as is the case of Ethereum.

The use of BCT also provides several features and characteristics that can be seen as advantages/benefits when used in value chains comprising several participants spread along the world [55,58]. *Decentralization* is one of those features. *Decentralization* means that the blockchain doesn't rely on a central authority. The data is stored in a distributed/ decentralized way without being controlled by a third party. *Immutability*, is an intrinsic feature of BCT and is related to the fact that it is near impossible to change previously registered data. *Pseudonymity* is another advantage since it avoids identity exposure in the network through encrypted addresses. *Autonomy* refers to the fact that nodes in the system can safely manage data, so the purpose is to trust in the system instead of

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6 https://www.tradelens.com/
7 https://dataports-project.eu/
8 https://www.lacchain.net/home
9 https://www.hyperledger.org/

an entity. And, *Transparency* is one of the key characteristics of distributed ledger systems, as any node can consult the data records.

In a blockchain, the data manipulated in transactions is stored in blocks, which are chained in a distributed and immutable ledger. The data is transparently available to the participants. This information-sharing improves product trace and track in value chain scenarios [62]. Through DLT it is possible to trace and track a product throughout its life cycle, transfer of ownership, etc. In the case of an emergency, it is easy to identify and trace all history of events that cause a problem and take immediate action. BCT can store data about the origin of a product, components, processes, and entities, and all related transactions. This data is traceable and verifiable by the participants of the network. This can lead to the application of sustainability criteria for materials, products, suppliers, and many other aspects, as well as the design of a more sustainable logistics and internal network [41].

6.3. IoT Technologies

Traceability is in high demand in many industrial sectors, including not only logistics but also manufacturing, because it enables effective tracking and, if necessary, a safe and transparent item recall. There are several examples in the literature, where products' traceability has been introduced in distinct application domains, cf. food value chains [63], pharmaceutical industries [64,65], agriculture [66], fishery [8], etc. The literature also suggests that, the integration of IoT and BCT technologies fosters the value chain's productivity BCT [66].

Traceability technologies allow items to be identified and traced along their value chain, from maker to customer. IoT provides the technology tools required to bridge the gap between the physical and digital worlds, consisting of web-enabled intelligent devices that gather data from their surroundings using embedded systems, which include CPUs, sensors, and built-in communications. By connecting to a IoT gateway or other edge devices, IoT devices may share the data they acquire in the cloud. Nowadays, IoT technologies are more than just items that can interact; they are part of a larger ecosystem that goes beyond just connection. Platforms like Microsoft Azure, IBM Bluemix, AWS Cloud, provide a variety of services that foster interaction with IoT technologies. Since these devices generate a vast amount of data, machine learning techniques can be used at the edge to reduce data dimensions and add cost-effective smart features.

The use of low-cost IoT devices to track and trace is a common approach in different IoT-based applications, and value chain traceability is no exception [67]. In the case of the food [63] and pharmaceutical [65] value chains, extra attention regarding product traceability is needed. This may include the acquisition of distinct environmental parameters, such as temperature and relative humidity, not only during the production stage, but also during distribution, thus increasing safety and quality control, and thus adding value to the products, e.g., at any stage of the value chain these environmental parameters can be consulted, just before a deal is made.

Figure 6 presents a general IoT traceability model that includes the production stage and all the operations and logistics stages. The proposed model, c.f. Figure 6, depicts the six main steps, having in mind the EEE value chain presented in this document, as follows:

- *Create*: Production of EEE goods or components with the integration of IoT-readable tags during the manufacturing process;
- *Read*: Read the tag data within a specific stage of the value chain;
- *Communicate*: data communication from the IoT devices in the assembly line must guarantee high interoperability;
- *Aggregate*: Reorganizes multiple data formats and ensures data consistency. This stage confirms that the dataset is complete and disseminates it into one or multiple places;
- *Consult*: Platform management for business or supply chain, manufacturing, and other related services;

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- *Analyze (Visualization)*: Business operation management that integrates with traceability system, reporting, manufacturing, and other related activities (ex: ERP & Manufacturing Resource Planning (MRP));
- *Analyze (Augmented Intelligence)*: Enhances human interaction. Augmented intelligence involves people and machines working together, using their strengths to accomplish significant business value.

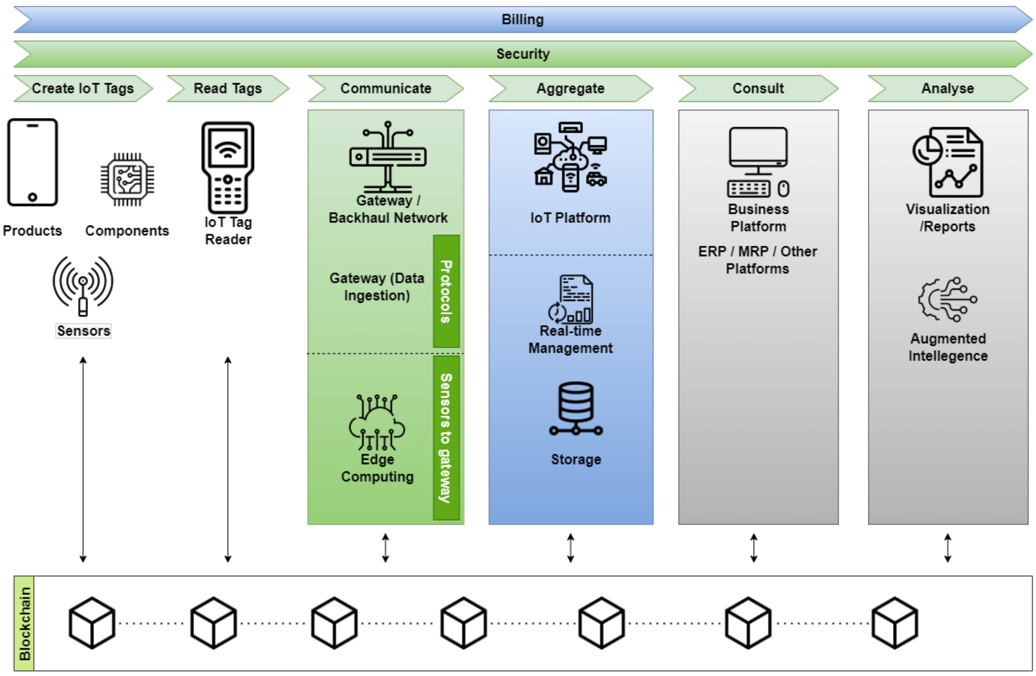

Figure 6. Generic IoT traceability model for the EEE value chain.

Information technology changed the way that companies manage their manufacturing processes. Digital traceability provides remarkable benefits such as accuracy, security, efficiency, and contractility [68]. *Automatic identification (auto-ID)* provides the ability to track and trace objects throughout its supply chain by reading and transferring data with low, or without, human intervention. While auto-ID technologies allow automatic tracking, the most commonly used technologies on supply chains are barcode, Radio Frequency IDentification (RFID), Real-time Locating System (RTLS) and Global Positioning System (GPS). These technologies have distinct features and can be adopted for different purposes:

- *Barcode*: consists of a printed image tag with black lines and white spaces that can be read by an optical scanner. Normally, barcodes are applied to products to speed up their identification. Nowadays, different types of barcodes are commonly used, e.g., QR-Code and Datamatrix, which provide increased data capacity. This technology is the most used auto-ID in the world. On the other hand, they present poor data security, high deterioration over time, and are read-only tags.
- *RFID*: Radio Frequency IDentification, uses radio waves to energize a chip-based tag and to communicate a unique serial number (with additional information in specific cases) about an item. A reader can simultaneously interrogate multiple tags, that can also be rewritten and encrypted.
- *RTLS*: provide the location of items or people in real-time. The information provided by this type of device can include the location, speed, temperature, and other information. There are several examples of the application of this technology, such as tracking vehicles, etc.
- *GPS*: provides the ability to remotely track any object in the world in real-time. This technology is beneficial to track vehicles and shipping in logistic activities.

There are other IoT communication technologies that can be adopted for traceability, such as Near Field Communications (NFC), Low Power Wide Area Network (LPWAN), SigFox, NB-IoT, and Bluetooth that are introduced and compared in detail in [60]. Those technologies, notably RFID, NFC, and BLE, have been important in the growth of the smart tag market. Typically, these smart tags demand additional sensory information, such data as ambient temperature/humidity, acceleration, geolocation, and other data, that can be used to effectively improve the traceability of specific value chains. Moreover, the adoption of mobile devices as readers enhances the cost-benefit of this approach, since most of the effort will be on developing software applications that are integrated with those devices using Service Oriented Architecture (SOA) or Micro-services Architecture.

The value chain of any product is dependent on a series of processes that are interconnected and need to be traced. If one fails, e.g., operations fail, transport delays, and product quality issues, the business value chain may be severely impacted, resulting in increased costs. IoT technologies are therefore key technological enables, that naturally deal with such complexity, enabling the value chain management in real-time and thus fostering circularity in the product life-cycle. The adoption of IoT devices as tracing elements, among with business analytics tools, can provide continuous improvement in the value chain and thus reduce operational inefficiencies. Major benefits of adopting IoT traceability in the EEE value chain include: i)*Transparency*, problems may be identified in real-time; ii) *Transportation optimization*, transportation can be improved throughout time and cost reduction, e.g., delivery routes optimization; iii) *Operational efficiency*: IoT technologies are less prone to errors than humans, resulting in a reduced operational cost, e.g., inventories, transportation, etc.

7. Discussion

The current LE model in the EEE industry needs to move towards a more sustainable and environmentally friendly paradigm that reduces the intensive use of natural resources, energy consumption, and the production of waste. The CE model tackles these issues by circularizing the value chain, maintaining the resources in the value chain as long as possible.

The proposed CE business model for the EEE value chain, depicted in Figure 4 (Subsection 4.1), provides an insight on how the EEE industry can be moved towards a CE model. The proposed model has some new activities in the value chain, such as the recycling and reusing value chain activities, providing the ability to prolong the use of raw materials and electronic components in the value chain by re-introducing them again in the production of new products.

The proposed CE model brings, on one hand, the advantages of reusing natural resources, recycling some components of older products, and other benefits. On the other hand, the model raises some challenges to overcome, such as the involvement of the stakeholders in the traceability platform, avoiding the introduction of counterfeit products in the value chain, and some materials have low recyclable rates, as addressed in subsection “End of Life practices & services", some recycled plastics aren’t feasible to be used in electrical parts, and the recovery phase of materials can be challenging when dealing with e-waste from different types of EEE [6].

Traceability platforms are an essential requirement of CE, as they allow tracing a product back to its constituent components and materials, together with the activities that built each of them. This provides the final consumer with information about the social and environmental impact of producing a product, enabling them to choose products with less impact. In Section 5, some platforms for traceability in the EEE value chain have been identified and presented in Table 1.

Blockchain and IoT technologies can change the way companies operate value/ supply chain processes, providing the ability to trace and track an object throughout the chain. Blockchain, in this context, refers solely to a distributed way of registering and sharing information. As mentioned in Subsection 6.1, blockchain is a distributed ledger technology, which may be used, and has been used, in cryptocurrencies, but is above the ethical, financial and other problems raised by these.

Blockchain and IoT technologies combined can offer automation in the identification of products, components, and materials, traceability of those items, data immutability, and transparency in activities and product use along the value chain. This enables a risk management tool that can be used to identify production failures or logistics risks in supply chains, but also an environmental and social impacts traceability tool. These technologies provide several benefits, such as the ones mentioned in section "Technology Enablers for CE traceability in the EEE value chain", but they can also bring some challenges.

The main technical challenges raised by BCT are [69], [70]:

- *Security*: Public blockchains, such as the ones used in cryptocurrencies, don't allow users to have different permissions, and also private transactions are not supported. Also, public blockchains, typically based on PoS or PoW consensus protocols, can suffer a 51% attack, if this percentage or more of nodes coordinate their efforts to attack the network. Normally, private and consortium blockchains support users with different permissions or different roles, and private channels. This provides greater security mechanisms and private transactions, but the associated consensus mechanisms can have a lower tolerance to attacks.
- *Scalability*: Particularly in public blockchains it can be a problem. Although a greater number of miners increases security and decentralization, with a greater number of transactions coming through, the transaction time increases and therefore reduces the transaction throughput, threatening scalability.
- *Transaction cost*: Public blockchains are typically based on rewarding the miners for their work or their staking power on participating in the consensus mechanism. Public networks are commonly associated with cryptocurrencies, which are created in committing transactions. Consequently, this brings transaction costs. If private blockchains are adopted, this cost is negligible.
- *Power consumption*: Some blockchains, as mentioned before, have compute-intensive consensus mechanisms, such as PoW. These blockchains carry an enormous carbon footprint, because of the energy spent in computing power when trying to commit transactions. Despite this problem in PoW, nowadays, there are several other options that don't depend on power consumption, such as the blockchains based on PoS protocols or the ones available for Hyperledger Fabric.

For implementation purposes in the EEE value chain, there are some specifications or properties that are best suited. Since all the value chain participants within the EEE value chain can create a consortium, the optimal option is a private blockchain [41].

Also, IoT technologies present some challenges in their adoption for traceability in a value chain, despite the benefits provided. The deployment of these technologies doesn't guarantee direct benefits for business operations. Some aspects are non-technical and others are more technical challenges. On one hand, non-technical challenges include factors that slow the adoption of these technologies, such as [71]:

- The lack of understanding of these technologies among business owners, that can be reluctant when it comes to invest in new technologies and suffer the consequence of first comers, due to the lack of industry standards and practices.
- Legacy ERP tools used worldwide don't support the integration of these new technologies, impacting their constraints, due to the increased cost of adapting these tools.
- The operators of the value chain need to be trained, since the integration of these technologies requires new technical skills and an understanding at a macro level of the business-related activities.

On the other hand, some technical challenges that IoT adoption faces are:

- *Scalability* is one of the main challenges in the implementation of IoT technology with BCT for traceability, since a product value chain needs to stay responsive through changes, and to be subject to continuous improvement.
- *Interoperability* among heterogeneous devices inside the network, but also for the federated computing environment. The need for standardization practices must be considered to promote integration among such heterogeneous IoT networks, enabling a more efficient federated computing paradigm.

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8. Conclusion

Being the EEE industrial sector one of the biggest sectors in the world, today, it is an urgent matter to foster the adoption of CE in the EEE value chain. The CE is one of the most promising models for value chain sustainability development, providing the continuous reuse of materials and resources, allowing the reduction of e-waste production and of natural resources usage. The adoption of a CE business model requires applications that allow data collection for tracing products, and measuring their social and environmental impact, enabling the assessment of circularity. As addressed in this article, the combination of blockchain and IoT technologies is promising to fit the needs of traceability and CE.

Nevertheless, the use of IoT and BCT may raise some challenges, which foster ideas for future work. One of these challenges is related to reading the data from IoT devices (e.g., temperature, humidity). These readings generate large quantities of information, which cannot be all put into a blockchain. They need to be stored in high-performance databases, such as time-series databases, for pre-processing or filtering, before selecting the relevant data for storing in the blockchain. Another challenge is related to the implementation of digital twins.

A traceable item can be a single product item (with a serial number) or a product lot (e.g., semiconductors). This brings more challenges to the implementation of traceability solutions, as the value chain activity may not involve an entire lot in the production of an EEE.

The use of blockchain for traceability and CE in the EEE value chain has also benefits when compared with other solutions. As the value chain involves many participants, having traceability information on a decentralized network with immutability guarantees is of great importance. Transparency is another key advantage of BCT, as any participant can consult the recorded data on the ledger, allowing auditability for traceability purposes.

Some blockchains, typically the ones used for cryptocurrencies, also present their own challenges, such as energy consumption or transaction costs. Nevertheless, for supporting traceability and CE models, there are other blockchain technologies, which don't carry the problems of cryptocurrencies. Hyperledger Fabric is an example of a BCT that uses a relatively rapid, non-energy burning, consensus protocol, and that provides several tools for implementing security policies with access control and private channels [69].

In a CE model, the loop is closed by the final consumer, since they are responsible for delivering the EoL EEE equipment for recycling purposes. An incentives' or gamification system to engage the final consumer in participating in the process may be required, since their participation is crucial for the CE model to work properly.

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Abbreviations

The following abbreviations are used in this manuscript:

BPMN	Business Process Model and Notation
CE	Circular Economy
EEE	Electric and Electronic Equipment
WEEE	Waste from Electrical and Electronic Equipment

IoT	Internet of Things
DLT	Distributed ledger technology
BCT	Blockchain technology
PoW	Proof-of-Work
PoS	Proof-of-Stake
ERP	Enterprise Resource Planning
AI	Artificial Intelligence
GPS	Global Positioning System
VM	Virtual Machine
RFID	Radio Frequency IDentification
NFC	Near Field Communications
REST	Representational State Transfer
AD	Autonomous driving
auto-ID	Automatic identification
MRP	Manufacturing Resource Planning
CPU	Central Processing Unit
LE	Linear Economy
Li-ion	Lithium-ion
Li-poly	Lithium polymer
EU	European Union
EoL	End-of-Life
SBM	Servitized Business Model
SCM	Supply Chain Management
SC	Smart Contract
RTLS	Real-time Locating System
LPWAN	Low Power Wide Area Network
SOA	Service Oriented Architecture
RDBMS	Relational DataBase Management System

References

1. Rajesh, R.; Kanakadhurga, D.; Prabaharan, N. Electronic waste: A critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. *Environmental Challenges* **2022**, *7*, 100507. https://doi.org/https://doi.org/10.1016/j.envc.2022.100507.
2. Baldé, C.P.; Forti, V.; Gray, V.; Kuehr, R.; Stegmann, P. *The global e-waste monitor 2017: Quantities, flows and resources*; United Nations University, International Telecommunication Union, and International Solid Waste Association, 2017.
3. Forti, V.; Baldé, C.P.; Kuehr, R.; Garam, B. *The Global E-waste Monitor 2020 – Quantities, flows, and the circular economy potential*; United Nations University/United Nations Institute for Training and Research, International Telecommunication Union, and International Solid Waste Association, 2020.
4. Wiens, K. Smartphone Repairs You Can Do on Earth Day, 2014.
5. Jardim, E. From smart to senseless: The global impact of 10 years of smartphones. *Washington: Greenpeace Inc* **2017**.
6. Manhart, A.; Blepp, M.; Fischer, C.; Graulich, K.; Prakash, S.; Priess, R.; Schleicher, T.; Tür, M. *Resource efficiency in the ICT sector*; Greenpeace eV, 2016.
7. Limata, P. Speculating on the application of blockchains in the circular economy. CERBE Working Papers wpC32, CERBE Center for Relationship Banking and Economics, 2019.
8. da Cruz, A.M.R.; Cruz, E.F. Blockchain-based Traceability Platforms as a Tool for Sustainability. In Proceedings of the 22st International Conference on Enterprise Information Systems (ICEIS 2020). SciTePress, 2020, Vol. 2, pp. 330–337.
9. Gu, Y.; Wu, Y.; Xu, M.; Mu, X.; Zuo, T. Waste electrical and electronic equipment (WEEE) recycling for a sustainable resource supply in the electronics industry in China. *Journal of Cleaner Production* **2016**, *127*, 331–338. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.04.041.
10. Wautelet, T. Exploring the role of independent retailers in the circular economy: a case study approach. Master's thesis, eufom European University for Economics & Management, 2018. https://doi.org/10.13140/RG.2.2.17085.15847.
11. Foundation, E.M. Towards the circular economy, 2015.

12. Ongondo, F.; Williams, I.; Cherrett, T. How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Management* **2011**, *31*, 714–730. https://doi.org/https://doi.org/10.1016/j.wasman.2010.10.023.
13. González, X.M.; Rodríguez, M.; Pena-Boquete, Y. The social benefits of WEEE re-use schemes. A cost benefit analysis for PCs in Spain. In Proceedings of the Waste Management, 2017, Vol. 64, pp. 202–213. https://doi.org/https://doi.org/10.1016/j.wasman.2017.03.009.
14. Bocken, N.M.P.; de Pauw, I.; Bakker, C.; van der Grinten, B. Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering* **2016**, *33*, 308–320, [https://doi.org/10.1080/21681015.2016.1172124]. https://doi.org/10.1080/21681015.2016.1172124.
15. Atlason, R.; Giacalone, D.; Parajuly, K. Product design in the circular economy: Users' perception of end-of-life scenarios for electrical and electronic appliances. *Journal of Cleaner Production* **2017**, *168*, 1059–1069. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.09.082.
16. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling* **2017**, *127*, 221–232. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.09.005.
17. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.; Hultink, E.J. The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production* **2017**, *143*, 757–768. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.048.
18. Akcil, A.; Erust, C.; Gahan, C.S.; Ozgun, M.; Sahin, M.; Tuncuk, A. Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixiviants – A review. *Waste Management* **2015**, *45*, 258–271. Urban Mining, https://doi.org/https://doi.org/10.1016/j.wasman.2015.01.017.
19. Kumar, S.; Putnam, V. Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors. *International Journal of Production Economics* **2008**, *115*, 305–315. Institutional Perspectives on Supply Chain Management, https://doi.org/https://doi.org/10.1016/j.ijpe.2007.11.015.
20. Mandolini, M.; Favi, C.; Germani, M.; Marconi, M. Time-based disassembly method: how to assess the best disassembly sequence and time of target components in complex products. *The International Journal of Advanced Manufacturing Technology* **2018**, *95*, 409–430. https://doi.org/10.1007/s00170-017-1201-5.
21. Yang, Q.; Yu, S.; Sekhari, A. A modular eco-design method for life cycle engineering based on redesign risk control. *The International Journal of Advanced Manufacturing Technology* **2011**, *56*, 1215. https://doi.org/10.1007/s00170-011-3246-1.
22. Kim, J.; Hwang, Y.; Park, K. An assessment of the recycling potential of materials basedon environmental and economic factors; case study in South Korea. *Journal of Cleaner Production* **2009**, *17*, 1264–1271. Advances in Life-Cycle Approaches to Business and Resource Management in the Asia-Pacific Region, https://doi.org/https://doi.org/10.1016/j.jclepro.2009.03.023.
23. Nistor, S.; Wu, J.; Sooriyabandara, M.; Ekanayake, J. Capability of smart appliances to provide reserve services. *Applied Energy* **2015**, *138*, 590–597. https://doi.org/https://doi.org/10.1016/j.apenergy.2014.09.011.
24. Batty, M. Digital twins. *Environment and Planning B: Urban Analytics and City Science* **2018**, *45*, 817–820, [https://doi.org/10.1177/2399808318796416]. https://doi.org/10.1177/2399808318796416.
25. Favot, M.; Veit, R.; Massarutto, A. The ratio of EPR compliance fees on sales revenues of electrical and electronic equipment in Italy. A circular economy perspective. *Resources, Conservation and Recycling* **2018**, *135*, 34–37. Sustainable Resource Management and the Circular Economy, https://doi.org/https://doi.org/10.1016/j.resconrec.2017.06.012.
26. Gnoni, M.G.; Mossa, G.; Mummolo, G.; Tornese, F.; Verriello, R. CIRCULAR ECONOMY STRATEGIES FOR ELECTRIC AND ELECTRONIC EQUIPMENT: A FUZZY COGNITIVE MAP. *Environmental Engineering & Management Journal (EEMJ)* **2017**, *16*.
27. Intlekofer, K.; Bras, B.; Ferguson, M. Energy Implications of Product Leasing. *Environmental Science & Technology* **2010**, *44*, 4409–4415. https://doi.org/10.1021/es9036836.
28. Tasaki, T.; Hashimoto, S.; Moriguchi, Y. A quantitative method to evaluate the level of material use in lease/reuse systems of electrical and electronic equipment. *Journal of Cleaner Production* **2006**, *14*, 1519–1528. Product Service Systems: reviewing achievements and refining the research agenda, https://doi.org/https://doi.org/10.1016/j.jclepro.2006.01.020.

29. Farooque, M.; Zhang, A.; Thürer, M.; Qu, T.; Huisingh, D. Circular supply chain management: A definition and structured literature review. *Journal of Cleaner Production* **2019**, *228*, 882–900. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.04.303.
30. Kissling, R.; Fitzpatrick, C.; Boeni, H.; Luepschen, C.; Andrew, S.; Dickenson, J. Definition of generic re-use operating models for electrical and electronic equipment. *Resources, Conservation and Recycling* **2012**, *65*, 85–99. https://doi.org/https://doi.org/10.1016/j.resconrec.2012.04.003.
31. Alumur, S.A.; Nickel, S.; da Gama, F.S.; Verter, V. Multi-period reverse logistics network design. *European Journal of Operational Research* **2012**, *220*, 67–78. https://doi.org/https://doi.org/10.1016/j.ejor.2011.12.045.
32. Zhang, T.; Kraisintu, K. The role of traceability in sustainable supply chain management. Master's thesis, Chalmers University of Technology, Göteborg, Sweden, 2011.
33. Traceability in the production of electronics, 2017, https://en.elhurt.com/traceability-in-the-production-of-electronics/.
34. Giannakis, M.; Papadopoulos, T. Supply chain sustainability: A risk management approach. *International Journal of Production Economics* **2016**, *171*, 455–470.
35. Richardson, H. Traceability for electronics manufacturing, 2020.
36. Oliveira, J.; Lima, J.E.; da Silva, D.; Kuprych, V.; Faria, P.M.; Teixeira, C.; Ferreira Cruz, E.; Rosado da Cruz, A.M. Traceability system for quality monitoring in the fishery and aquaculture value chain. *Journal of Agriculture and Food Research* **2021**, *5*, 100169. https://doi.org/https://doi.org/10.1016/j.jafr.2021.100169.
37. Li, W.; Chao, K.M.; Jin, G.; Xia, K.; Gao, L. Sustainable information management for Waste Electrical and Eletronic Equipment. In Proceedings of the Proceedings of the 2012 IEEE 16th International Conference on Computer Supported Cooperative Work in Design (CSCWD), 2012, pp. 875–881. https://doi.org/10.1109/CSCWD.2012.6221924.
38. Capecci, S.; Cassisi, E.; Granatiero, G.; Scavongelli, C.; Orcioni, S.; Conti, M. Cloud-based system for waste electrical and electronic equipment. In Proceedings of the 2017 13th Workshop on Intelligent Solutions in Embedded Systems (WISES), 2017, pp. 41–46. https://doi.org/10.1109/WISES.2017.7986930.
39. Dasaklis, T.K.; Casino, F.; Patsakis, C. A traceability and auditing framework for electronic equipment reverse logistics based on blockchain: the case of mobile phones. In Proceedings of the 2020 11th International Conference on Information, Intelligence, Systems and Applications (IISA, 2020, pp. 1–7. https://doi.org/10.1109/IISA50023.2020.9284394.
40. Sunny, J.; Undralla, N.; Madhusudanan Pillai, V. Supply chain transparency through blockchain-based traceability: An overview with demonstration. *Computers & Industrial Engineering* **2020**, *150*, 106895. https://doi.org/https://doi.org/10.1016/j.cie.2020.106895.
41. Magrini, C.; Nicolas, J.; Berg, H.; Bellini, A.; Paolini, E.; Vincenti, N.; Campadello, L.; Bonoli, A. Using Internet of Things and Distributed Ledger Technology for Digital Circular Economy Enablement: The Case of Electronic Equipment. *Sustainability* **2021**, *13*. https://doi.org/10.3390/su13094982.
42. Kuhn, M.; Funk, F.; Franke, J. Blockchain architecture for automotive traceability. *Procedia CIRP* **2021**, *97*, 390–395. 8th CIRP Conference of Assembly Technology and Systems, https://doi.org/https://doi.org/10.1016/j.procir.2020.05.256.
43. DiMase, D.; Collier, Z.A.; Carlson, J.; Gray, Jr, R.B.; Linkov, I. Traceability and Risk Analysis Strategies for Addressing Counterfeit Electronics in Supply Chains for Complex Systems. *Risk Anal* **2016**, *36*, 1834–1843.
44. Ilgin, M.A.; Gupta, S.M. Recovery of sensor embedded washing machines using a multi-kanban controlled disassembly line. *Robotics and Computer-Integrated Manufacturing* **2011**, *27*, 318–334. Translational Research – Where Engineering Meets Medicine, https://doi.org/https://doi.org/10.1016/j.rcim.2010.07.016.
45. Favi, C.; Marconi, M.; Germani, M.; Mandolini, M. A design for disassembly tool oriented to mechatronic product de-manufacturing and recycling. *Advanced Engineering Informatics* **2019**, *39*, 62–79. https://doi.org/https://doi.org/10.1016/j.aei.2018.11.008.
46. Choi, T.M.; Chen, Y. Circular supply chain management with large scale group decision making in the big data era: The macro-micro model. *Technological Forecasting and Social Change* **2021**, *169*, 120791. https://doi.org/https://doi.org/10.1016/j.techfore.2021.120791.
47. Agrawal, T.K.; Kumar, V.; Pal, R.; Wang, L.; Chen, Y. Blockchain-based Framework for Supply Chain Traceability: A Case Example of Textile and Clothing Industry. *Computers & Industrial Engineering* **2021**.
48. Nakamoto, S. Bitcoin: A Peer-to-Peer Electronic Cash System, 2008.

49. Caro, M.P.; Ali, M.S.; Vecchio, M.; Giaffreda, R. Blockchain-based traceability in Agri-Food supply chain management: A practical implementation. *2018 IoT Vertical and Topical Summit on Agriculture - Tuscany, IOT Tuscany 2018* **2018**, pp. 1–4. https://doi.org/10.1109/IOT-TUSCANY.2018.8373021.
50. Tian, F. A supply chain traceability system for food safety based on HACCP, blockchain & Internet of things. *14th International Conference on Services Systems and Services Management, ICSSSM 2017 - Proceedings* **2017**. https://doi.org/10.1109/ICSSSM.2017.7996119.
51. Alves, L.; Cruz, E.F.; Rosado Da Cruz, A.M. Tracing Sustainability Indicators in the Textile and Clothing Value Chain using Blockchain Technology. In Proceedings of the 2022 17th Iberian Conference on Information Systems and Technologies (CISTI), 2022, pp. 1–7. https://doi.org/10.23919/CISTI54924.2022.9820241.
52. da Cruz, A.M.R.; Santos, F.; Mendes, P.; Cruz, E.F. Blockchain-based Traceability of Carbon Footprint: A Solidity Smart Contract for Ethereum. In Proceedings of the 22st International Conference on Enterprise Information Systems (ICEIS). SciTePress, 2020, Vol. 2, pp. 258–268.
53. Tapscott, D.; Tapscott, A. How blockchain will change organizations. *MIT Sloan Management Review* **2017**, *58*, 10.
54. Michael, J.; Cohn, A.; Butcher, J.R. Blockchain technology and Regulatory Investigations. *Practical Law - The Journal* **2018**, pp. 35–44.
55. Lin, I.C.; Liao, T.C. A survey of blockchain security issues and challenges. *Int. J. Netw. Secur.* **2017**, *19*, 653–659.
56. Laurence, T. *Blockchain for dummies*; John Wiley & Sons, 2019.
57. de Vries, A.; Stoll, C. Bitcoin's growing e-waste problem. *Resources, Conservation and Recycling* **2021**, *175*, 105901. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105901.
58. Zheng, Z.; Xie, S.; Dai, H.N.; Chen, X.; Wang, H. Blockchain challenges and opportunities: A survey. *International Journal of Web and Grid Services* **2018**, *14*, 352–375.
59. Huang, S.; Wang, G.; Yan, Y.; Fang, X. Blockchain-based data management for digital twin of product. *Journal of Manufacturing Systems* **2020**, *54*, 361–371. https://doi.org/https://doi.org/10.1016/j.jmsy.2020.01.009.
60. Alves, L.; Cruz, E.F.; Lopes, S.I.; Faria, P.M.; da Cruz, A.M.R. Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: A review. *Waste Management & Research* **2022**, *40*, 3–23, [https://doi.org/10.1177/0734242X211052858]. PMID: 34708680, https://doi.org/10.1177/0734242X211052858.
61. Fei, T.; Jiangfeng, C.; Qinglin, Q.; Zhang, M.; Zhang, H.; Fangyuan, S. Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology* **2018**, *94*, 3563–3576.
62. Nandi, S.; Sarkis, J.; Hervani, A.A.; Helms, M.M. Redesigning Supply Chains using Blockchain-Enabled Circular Economy and COVID-19 Experiences. *Sustainable Production and Consumption* **2021**, *27*, 10–22. https://doi.org/https://doi.org/10.1016/j.spc.2020.10.019.
63. Grecuccio, J.; Giusto, E.; Fiori, F.; Rebaudengo, M. Combining Blockchain and IoT: Food-Chain Traceability and Beyond. *Energies* **2020**, *13*. https://doi.org/10.3390/en13153820.
64. Ambrosus. Ambrosus whitepaper, 2018.
65. Botcha, K.M.; Chakravarthy, V.V.; Anurag. Enhancing Traceability in Pharmaceutical Supply Chain using Internet of Things (IoT) and Blockchain. In Proceedings of the 2019 IEEE International Conference on Intelligent Systems and Green Technology (ICISGT), 2019, pp. 45–453. https://doi.org/10.1109/ICISGT44072.2019.00025.
66. Chun-Ting, P.; Meng-Ju, L.; Nen-Fu, H.; Jhong-Ting, L.; Jia-Jung, S. Agriculture Blockchain Service Platform for Farm-to-Fork Traceability with IoT Sensors. In Proceedings of the 2020 International Conference on Information Networking (ICOIN), 2020, pp. 158–163. https://doi.org/10.1109/ICOIN48656.2020.9016535.
67. Prato, A.; Mazzoleni, F.; Schiavi, A. Metrological traceability for digital sensors in smart manufacturing: calibration of MEMS accelerometers and microphones at INRiM. In Proceedings of the 2019 II Workshop on Metrology for Industry 4.0 and IoT (MetroInd4.0 IoT), 2019, pp. 371–375. https://doi.org/10.1109/METROI4.2019.8792906.
68. Budak, A.; Ustundag, A.; Kilinc, M.S.; Cevikcan, E., Digital Traceability Through Production Value Chain. In *Industry 4.0: Managing The Digital Transformation*; Springer International Publishing, 2018; pp. 251–265. https://doi.org/10.1007/978-3-319-57870-5_15.

doi:10.20944/preprints202302.0040.v1

69. Agbo, C.C.; Mahmoud, Q.H. Comparison of blockchain frameworks for healthcare applications. *Internet Technology Letters* **2019**, *2*, e122, [https://onlinelibrary.wiley.com/doi/pdf/10.1002/itl2.122]. https://doi.org/https://doi.org/10.1002/itl2.122.
70. Zhang, S.; Lee, J.H. Analysis of the main consensus protocols of blockchain. *ICT Express* **2020**, *6*, 93–97. https://doi.org/https://doi.org/10.1016/j.icte.2019.08.001.
71. Jabbar, S.; Lloyd, H.; Hammoudeh, M.; Adebisi, B.; Raza, U. Blockchain-enabled supply chain: analysis, challenges, and future directions. *Multimedia Systems* **2021**, *27*, 787–806. https://doi.org/10.1007/s00530-020-00687-0.