City Research Online

City, University of London Institutional Repository

The Green Blockchains of Circular Economy

George Hatzivasilis [1,2,*] , **Sotiris Ioannidis** [3], **Konstantinos Fysarakis** [4] , **George Spanoudakis** [4]
and Nikos Papadakis [2]

1   Foundation for Research and Technology-Hellas, 70013 Heraklion, Greece
2   Department of Electrical and Computer Engineering, Hellenic Mediterranean University (HMU),
    71410 Heraklion, Greece; npapadak@cs.hmu.gr
3   Department of Electrical and Computer Engineering, Technical University of Crete, 73100 Chania, Greece;
    sotiris@ece.tuc.gr
4   Sphynx Technology Solutions AG, 6300 Zug, Switzerland; fysarakis@sphynx.ch (K.F.);
    spanoudakis@sphynx.ch (G.S.)
*   Correspondence: hatzivas@ics.forth.gr or hatzivas@hmu.gr; Tel.: +30-2810-391600

Abstract: Eco-friendly systems are necessitated nowadays, as the global consumption is increasing. A data-driven aspect is prominent, involving the Internet of Things (IoT) as the main enabler of a Circular Economy (CE). Henceforth, IoT equipment records the system's functionality, with machine learning (ML) optimizing green computing operations. Entities exchange and reuse CE assets. Transparency is vital as the beneficiaries must track the assets' history. This article proposes a framework where blockchaining administrates the cooperative vision of CE-IoT. For the core operation, the blockchain ledger records the changes in the assets' states via smart contracts that implement the CE business logic and are lightweight, complying with the IoT requirements. Moreover, a federated learning approach is proposed, where computationally intensive ML tasks are distributed via a second contract type. Thus, "green-miners" devote their resources not only for making money, but also for optimizing operations of real-systems, which results in actual resource savings.

Keywords: blockchain; federated learning; circular economy; green-miner; time-wise offloading; green computing

1. Introduction

A Circular Economy (CE) is composed as a regenerative ecosystem. The working period of current products is extended, and the consumption of new materials is confined [1,2]. Closed economy loops are established with resources being utilized over-and-over by different actors. The core phases of CE models typically can involve (i) long-lasting design, (ii) maintenance, (iii) repair, (iv) reuse, (v) remanufacturing, (vi) refurbishing, and (vii) recycling. The large-scale application of these CE aspects drives modern business models and economic transformation [3,4]. The CE review studies in [1,2] present the business principles of the new initiative. Further CE models and indicative examples are detailed in [3]. The survey in [5] examines the maturity of the most recent proposals (during 2019–2020). The enhanced collaborations between the involved entities in a CE lifecycle is considered of great importance, both for businesses that want to make the transition to circular operational models as well as for start-ups that are building their circular model from scratch [5]. Smart devices and the IoT ecosystem enable new forms of interaction and business models. The transformation of the traditional market into a service-oriented setting is now a fact. The integration of CE and IoT further promotes such data-driven service-oriented architectures (SoA) [5–7].

Today, the integration of emerging computer technologies is ongoing, such as the use of blockchains as distributed ledgers for the CE assets or as enablers of modern federated learning approaches. The blockchain technology started gaining ground as a cyber-cryptocurrency that was not controlled by any centralized authority [8]. Today,

there is a plethora of new application domains, with each one exhibiting different design properties [9,10]. In contrast to cryptocurrency mining, where we need to deploy a resource-expensive mechanism in order to verify the node/miner effort (i.e., block hashing), in the Circular Economy and Internet of Things (CE-IoT) field we mainly utilize blockchain as a ledger that records/logs the changes in the CE assets' status. Therefore, we need to promote a fast and efficient functionality. The active partners perform the cooperative business logic and accountability through smart contracts, while the chain verification is retained, simple, and fast. The goal is to offer a common view of the assets' state, with smart contracts providing share data with integrity, while enhancing the interoperability and transparency between the interacting partners. A CE can also involve small-medium enterprises (SMEs) that might not possess the skills or the resources [11] to perform the computationally heavy machine learning (ML) procedures that optimize the green operation of the installed services/equipment, such as the example in [12] where ML is utilized to improve the energy consumption of a data center and other relevant cases such as [13–15]. Thereupon, blockchaining is also promoted as an enabler for federated learning. The CE-IoT participants can assign the related tasks on smart contracts with miners performing part of the ML operations (i.e., training or model evaluation). Then, they send the results to the relevant beneficiaries. Once the contribution is validated, the miner is paid in gas (Ethereum or other cryptocurrency).

While our approach is applicable for a wide spectrum of CE-IoT applications, in this study we demonstrate the operation of blockchaining in the field of Information and Communications Technology (ICT). The CE assets in this domain may include any computer device and their counterparts. Specifically, we monitor the infrastructure of a medium-scale Internet provider in Cyprus, called Cablenet. The main monitoring and decision-making setting is presented in [16,17], where we detailed a complete circular scenario and the implementation of an enhance recycle-reward and e-waste management service. The CE-IoT framework is managed by an efficient and scalable multi-agent system, where the agents collect data from IoT-monitors and are abreast of the assets' **Location, working Condition, and Availability (LCA)** properties. The main contributions of this paper include the following:

- An upgrade of the original CE-IoT blockchain with the principles of the HYPERLEGER project (https://www.hyperledger.org/, accessed on 23 July 2021) and its utilization by multiple actuator types;
- The incorporation of federated ML and the development of the "green-mining" concept;
- An extension of the main federated ML protocol and introduction of the "time-wise ML data offloading technique" that overcome the underlying obstacles, enhance confidentiality and privacy, and make the use of ML in blockchain cost-efficient.

Section 2 presents related works. Then, Section 3 details the operation of the core blockchain as well as the enhanced green computing functionality of CE-IoT with ML and the potential of federated learning with blockchains. Section 4 discusses the overall results and refers to future work. Finally, Section 5 concludes this work.

2. Materials and Methods

Related Works—CE Studies, Trends, and Applications

The researchers in [18–20] try to analyze and understand the factors that are affecting the consumption in the context of CE ecosystems in general. Circular solutions are gaining great attention from researchers these days. The digital transformation of the economy is considered a main driver of CE, with the data-driven approaches gaining ground.

Several reviews are now presenting new business models and novel applications concerning CE strategies [1–3]. More-and-more traditional markets are transformed into service-oriented ones, with the CE and IoT integration promoting data-driven settings [6,21]. The proposed solutions are overarching a wide range of industrial domains.

Manufacturing and Industry 4.0 are such prominent domains for CE [22–27]. The main goal here is to enhance intelligence and visibility into digital assets. The management

of the supply chain is also important [28,29]. The use of blockchain, Big Data analytics, and Artificial Intelligence (AI) is applied in an attempt to improve the transparency and traceability of products throughout their working lifetime (e.g., [29–35]). Similarly with our study, globalization and the concepts of reuse, remanufacture, and recycle are examined under the sponsorship and support of the United Nations (UN).

The automobile industry is another prominent sector of CE. Danish research [36] records that on a daily basis, an arbitrary (personal) car transports around 1.4 people on average, while for 23 h it is parked. The spare seats are of great importance for ride-sharing applications. GoMore [37] enables the driver to ask other people to join a ride on a planned route and share some costs. Such approaches increase the persons that are onboard per car and decreases the vehicles on the street. More than 1 million users are utilizing this service, resulting in around 300,000 seats in Denmark alone. GoMore is a chief company in Europe incorporating peer-to-peer car condo and ride-sharing and the main commercial enterprise for this business in Scandinavia.

Michelin deployed a leasing service for truck fleets in Europe [38]. Specifically, it leases services concerning the trucks' tires per kilometer. The fleet fee depends on the vehicle type and the traversed distance. The Fleet Solutions [38] are decreasing the risk for varying costs, which involve unexpected damages from owning the tires, differences in tire performance, and purchase fees. Thus, Michelin absorbs some risks, without a client having to pay a permanent price for the tires and their change afterwards.

In French, Alstom produced the HealthHub—a protection system that monitors the health of railway components and predicts system failures [39]. Analytics are utilized in order to prolong and retain the working lifetime of trains, signaling equipment, and infrastructure assets. Therefore, it captures the degree of performance of train components, such as the brake pads, the wheels, or the put on-and-tear-inclined pantograph carbon strips (a framework that transfers current to railways from overhead wires) and diagnoses their status.

The MAN Truck and Bus [40] is one of the main international manufacturers of transport and commercial vehicle to businesses. The German company provides advice services and support for vehicle design for fleets, infrastructure, operations, maintenance, and carrier. It has started a data-driven service to help bus fleets and commercial trucks to comply with the low-carbon transportation initiatives. This involves battery swapping and charging infrastructure issues, variety, making plans, loading and capacity planning, as well as air-conditioning and heating demands.

The food industry is another main sector that can benefit from a CE [41]. In [42], an IoT installation in the food processing industries monitors and facilitates the transportation services amongst the supply chain. This also includes the advancement of the underlying packaging processes along with designs that support recycling and low new material usage. In [43], the IoT enhances the traceability of goods and ensures food safety for the customers. In [44], an IoT-based monitoring system is implemented and supports the food quality control procedures from the production to the consumption stages. Furthermore, information dissemination on IoT ecosystems can help a company in administrating its operations and achieve sustainable business practices [41–44]. For example, in [45], the researchers built a system dynamics model that gathers information for the food industry supply chain and evaluates the environmental impacts of reverse logistics operations, enhancing the overall green performance. The researchers in [46] implement an interactive seed library that mentions the stories of culturally diverse urban food growers and inter-links the environmental sensors of their gardens. Therefore, the overall solution tries to promote more sustainable food practices in cities.

Banking and insurance sectors have been also benefitted by CE initiatives. The IoT, AI, deep learning, and Big Data analytics are advancing Financial Technology (FinTech) and enable the creation of augmenting and smart banking services [47,48]. Relevant products may include product leasing, peer-to-peer provisioning, upcycling, zero-waste, remanufacturing, or reverse manufacturing [49]. In general, banks are trying to utilize

the new technologies and adapt their role in the CE landscape by defining a common understanding of CE amongst the various stakeholders, establishing widely accepted guidelines for CE finance, providing credit to relevant businesses, adjusting the current finance models to fit into the CE world, implementing green banks, as well as training their staff and creating a culture of green operation, material reuse, and waste decrement [50,51]. Banks, venture capital groups, private equity foundations, and others in the financial domain are exhibiting increasing enthusiasm for such opportunities, driven by the potential for financial returns related with less exposure to linearity risks, lower resource dependency, as well as the ability to comply with the stakeholders' expectancies [52–54]. The study in [55] proposes the use of blockchains and cryptocurrencies as a modern mean to retain sustainability by empowering the creation of community-based incentive systems on a variety of platforms. Such platforms are gradually connected and build new "token economies", with tokens circulating within and between them. The goal is that the new income sources will be able to mitigate unsustainable operations on a large scale.

Several research proposals are suggested as well, e.g., [56,57]. SmartTags utilize the GS1 barcode standard and build a product passport. Through these labels that are printed on products, data exchange is enabled for the modern CE settings including unique asset identification, as well as the tracking of collecting, reading, and sensing parameters.

Other IoT solutions are materializing solutions for household waste source separation, promoting the sustainable waste management in China [56]. These technologies are trying to predict and explain peoples' behavior that is required for source separation at the household level. By monitoring and evaluating accountability rules, several aspects of the waste management cycle are improved.

3. Results—The CE-IoT Blockchain and Federated Learning

3.1. The Core CE-IoT Blockchain

We utilize the CE-IoT permissioned-blockchain in order to record and trace the assets' status. An initial version of the proposed blockchain solution was presented in [17]. In this work, we adopt the method in [17] within a real-life scenario where multiple actuators are used. The current setting also complies with the guidelines and directives of the HEYPERLEDGER project, which constitutes an umbrella initiative for blockchain research.

3.1.1. Motivating Example

Figure 1 illustrates an emulated iteration of the CE-IoT loop. As aforementioned, our organization (Cablenet) uses its equipment to serve end-customers. When the system is upgraded, the related machinery is sold to start-ups in the UK. Similarly, these companies can re-sell the CE assets when their utility goes beyond a threshold. Afterwards, the assets are gifted to third-world countries that use older technologies in their networks. When the products are no longer working, they are recycled in businesses that are close to these areas. Finally, a subset of useful materials is exported back to the manufacturers and the loop starts again. Instead of just dropping the equipment, which could end up in landfills or swamps, the working lifetime is to prolong as much as possible and the useful materials are recycled, implementing an advance green computing and e-waste management infrastructure.

3.1.2. The Ledger

The registered assets are represented as a collection of key-value pairs, with state changes recorded as transactions on the ledger. The chain code and the permissions define these assets and the transaction instructions for modifying them. The involved members interact with the network's ledger using this chain code in the form of *smart contracts* (i.e., through new smart contracts that add new business logic or invoking transactions of early contracts). All the members are identified and authorized with specific access rights. Access control lists may also be deployed for additional permission layers.
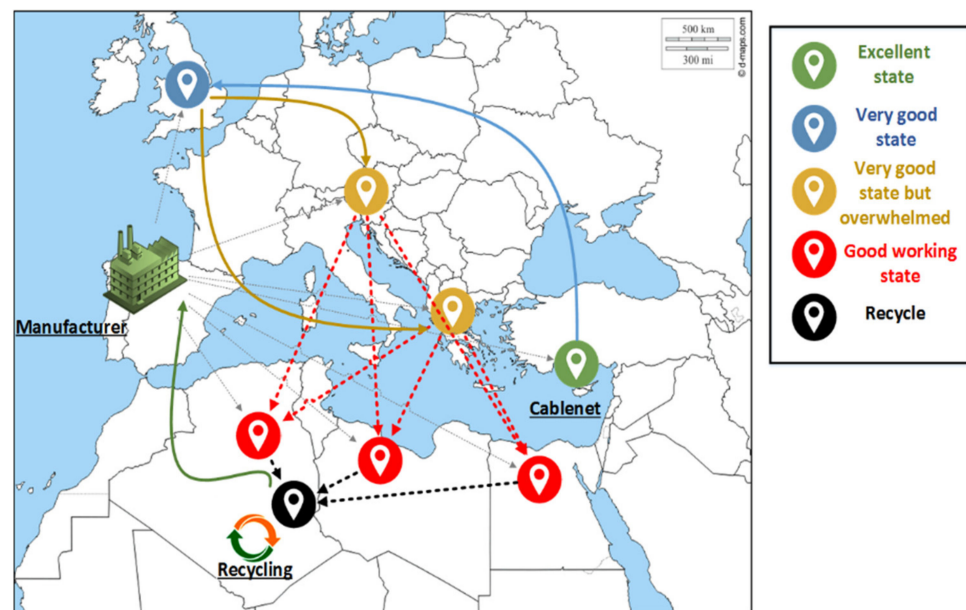
Figure 1. The CE-IoT emulated scenario.

The chain incorporates the following two main components: (i) the *blockchain log* that maintains the immutable sequenced record of transactions in blocks, and (ii) the *state database* that stores the current state of the blockchain. The log helps in tracking each asset's provenance (e.g., when and where it was created, where it was moved to, etc.), while the database assists the participating stakeholders to figure out the current state of an asset.

However, in several business models, the related assets information may be considered confidential for an organization or raise privacy issues. Thus, private channels can be utilized, where restricted messaging paths are enabled that provide privacy for specific attribute subsets and restrict access to unauthorized parties.

Adding a new transaction for a block requires the following three sequential operations: (i) the verification of the current chain, (ii) appending and signing the new data, and (iii) creating the new hash. Therefore, two node types are supported in the network in an attempt to increase efficiency and scalability. The *peer nodes* are liable for the execution and verification of the transactions. They can process many records simultaneously. On the other hand, the *ordering nodes* order and propagate transactions. They are also responsible for the creation of a single true record of transactions.

3.1.3. Actuators Roles

For the CE cooperative business model, we consider the following three main actuator types: asset operators, entrusted auditors, and regulators. "Operators" are the current owners of a CE asset and can update its LCA properties in the ledger. They can exchange these assets, changing the ownership accordingly. "Auditors" are authorized by an asset's operator in order to validate its state. They can also be entitled in order to update the assets' status. Auditors foster trust between the current owner and prospective asset operators and certify that the assets abide to the regulator's CE policies. The "Regulator", on the other hand, represents the authority that is responsible for establishing the governing rules. They can intervene in the operator interactions and enforce specific sustainability goals.

Thereafter, smart contracts can be used to control who is approved to do what. The following four contract types are defined for these purposes:

1. The "Asset Registry Contract" is owned by the regulator and maintains the contract addresses for assets, operators, and auditors.
2. The "Asset State Contract" is owned by the asset's operator and contains the related LCA properties.

3. The "Asset Audit Agreement Contract" is also owned by the operator and specifies the allowed actions for updating the Asset State Contract.
4. The "List of Asset Agreements Contract" can be owned either by operators or auditors and contains the access agreements and their state (i.e., active or expired).

The actuator roles and the administration of their interaction via smart contracts are detailed in [9]. The relevant contract-based model is depicted in Figure 2.
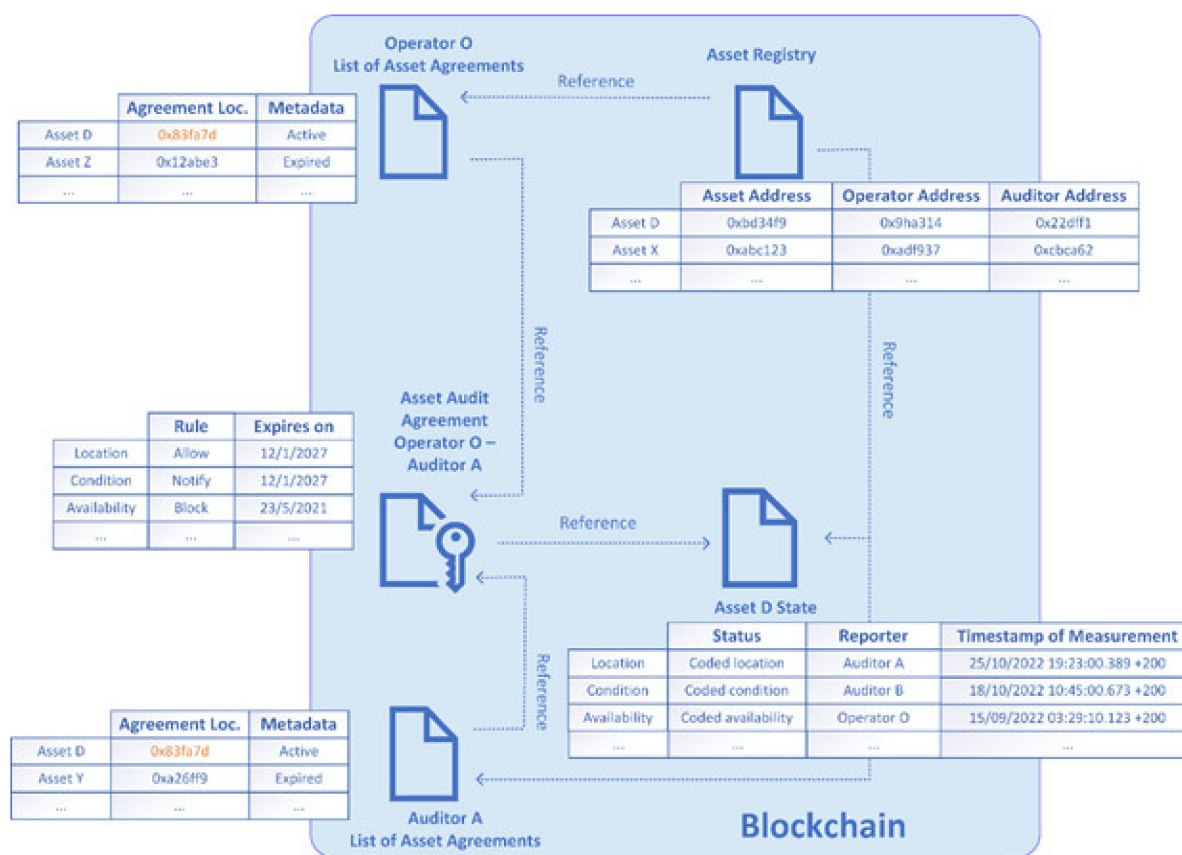
Figure 2. Smart contract-based data model.

3.1.4. Implementation

Every participating organization has its own "wallet" with its blockchain accounts. Normally for the CE-IoT blockchain, each organization will possess a single "account". The account is managed by the organization's master agent, which gathers information from its underlying field agents and adds the performed actions to the chain. These recorded actions have the form of valid blockchain "transactions", which are signed by the master agent using the organization's private key. Normally, the operator registers sequential usage patterns for an asset, which can be then verified by auditors (see Figure 3).

Figure 3. Multiple sequential asset operators.

For the implementation of the blockchain, we utilize a lightweight version of Ethereum in Java [8]. It deploys the AES128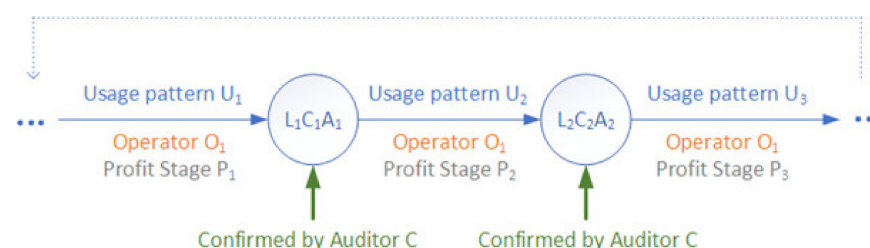 cipher in CTR mode for symmetric cryptography, the ECC cipher for asymmetric cryptography (public/private key), and the hash function SHA256 (block hashing) via the ECDSA signature scheme [8]. The smart contracts are written on Solidity—a Turing-complete programming language that is suitable for modelling the contract's complex logic [58].

The ledger's blocks are modeled in a JavaScript Object Notation (JSON) format [59]. For example, the following piece of code publishes a new transaction that sets/updates the LCA properties for an asset:

publishstream key1 '{"json":{
"component":"C1, switch",
"location":"CABLENET-room1", "condition":"maintenance",
"availability":"working"}}'

The transaction resembles the event for the asset C1 (a switch), which is working in room1 but now it needs maintenance. As mentioned above, the effort for performing these contracts has been kept low. On a typical machine (i.e., i7 CPU at 2.1 GHz and 8 GB RAM) it takes around 10–50 ms to execute 1000 contracts.
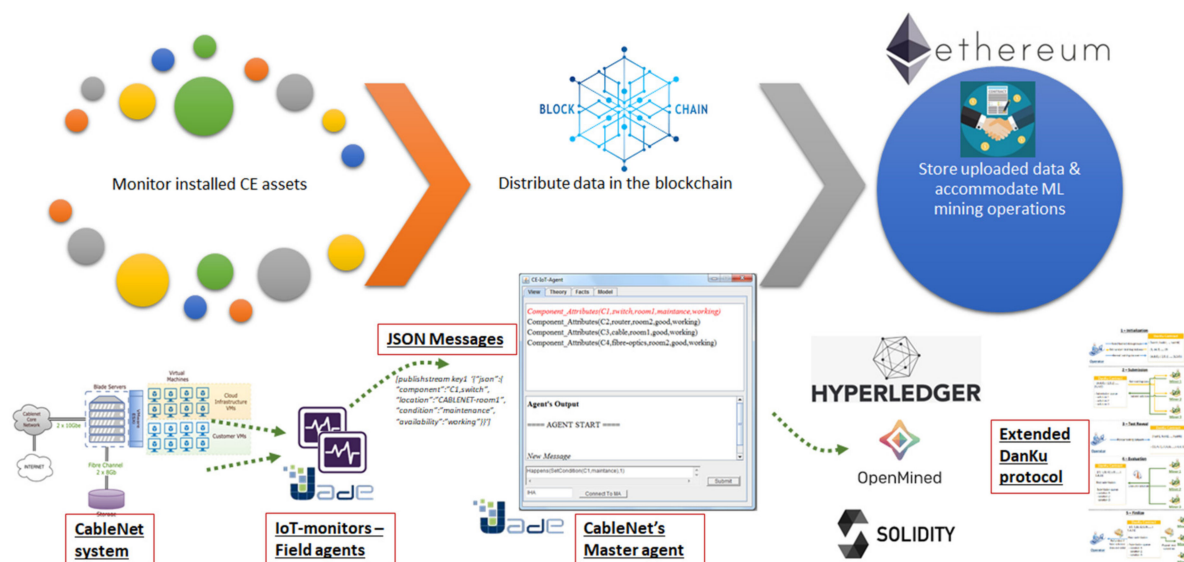
The overall solution is portrayed in Figure 4.

Figure 4. The CE-IoT framework.

Initially, the deployed field agents are deployed in the system and monitor the status of the installed CE assets. Relevant messages in a JSON format are transmitted in the correlated master agent, which collects all the information for this organization. The master agent also facilitates the communication with the blockchain via the execution of the aforementioned smart contracts. The agents are implemented in the Java Agent Development Framework (JADE) [60], the smart contracts in Solidity, and the blockchain in Ethereum [8]. Then, green-miners can also perform ML computations by executing additional smart contracts that implement an extended version of the original DanKu protocol [61] (see Section 3). The use of machine learning in blockchains is following the principles of the OpenMined initiative (https://www.openmined.org/, accessed on 23 July 2021) and the overall CE-IoT solution is in accordance with the HYPERLEGER guidelines.

3.2. Federated Learning with Green-Miners

As it was mentioned in the introductory section, the multi-participatory environment of CE can include SMEs that cannot perform the computationally intensive ML

algorithms [11]. Thus, we exploit the already deployed CE-IoT mechanisms in order to distribute the ML computations to blockchain miners. A federated learning setting is formed that is inspired by the open-source community for safe AI—OpenMined.

A main issue regarding the federated learning is how one can validate that the requested actions (miner's effort) have been performed and the outcome is valid (proof-of-work). For example, how can we know that a malicious entity does not just send to us bogus data in order to manipulate our ML system or get paid without actually executing the requested contract?

3.2.1. DanKu Protocol

The DanKu protocol [61] resolves this issue and allows the participating entities to solicit ML models for a reward in a trustless manner. We apply this approach in order to support the federated learning functionality of the CE-IoT ecosystem. The protocol is composed of five phases. At first, the asset operator (i.e., the organizations MA) constructs a contract that contains the hashed data groups of the sensed events along with the training dataset. The miners obtain the contract, train the model, and send the computed solution. Then, the operator reveals a testing dataset and the submitted models are evaluated. The best solution is rewarded and the related miner is paid. If there is no best solution, the operator is refunded. Figure 5 depicts the five phases of the DanKu protocol for ensuring that a contract has been performed successfully.

The DanKu protocol is formed as a smart contract in the chain. The core CE-IoT chain is permissioned; thus, participation is restricted and controlled by the regulator. Nevertheless, we could maintain a public CE-IoT chain in parallel with the core one and enable various miners to use the system.

When an organization applies the CE-IoT policies and starts collecting the ML datasets, the data volume is low as well as the resource demands for executing its federated contracts. As the data volume increases, the miners' effort is also increased, and the ML outcomes are becoming more and more accurate and fruitful for the beneficiary. In the Ethereum economic scale [61], it is estimated that performing a transaction with 1 KB–11 MB of ML data with DanKu, it would cost around 6 Mwei–275 Ether, respectively. The amount in euro is around EUR 6500–480,000 (based on 2021 currency), which makes the utilization of the pure protocol inefficient.

3.2.2. CE-IoT Extensions of the Pure DanKu Protocol

Although the DanKu protocol defines the main function of performing ML operations in the blockchain, there are several obstacles that have to be resolved before its adoption on a wide scale [61]. First of all, it has a very high cost to upload even a small to medium dataset. To overcome this, we propose a method, called "time-wise ML data offloading contracts". Therefore, the issuer (operator) will have to deploy a pair of contracts when he/she wants to disclose a dataset (either the training or the evaluation ones). The first contract includes information on how to access the dataset externally and the second one denotes how the miner or the evaluator can submit your contribution (run the relevant functionality of the DanKu protocol). Thus, in the first contract, the operator includes a unique identifier— dataset ID (DID), an external link to the dataset (and not the data itself), its hash value, and the data size. The miner or the evaluator downloads the dataset and performs the related tasks. The results would be communicated to the second contract, which shares the same DID. The overall process could be performed either manually by the miner or automatically by a relevant agent. Additionally, the issuer has the obligation to maintain the dataset active for a specified period (e.g., one year). Thus, apart from the verifying nodes that will validate the contracts in a timely manner, an auditor would have the possibility to validate the legitimacy of the recorded transaction, while the blockchain size and the ML costs are kept low. Moreover, the issuer is in control of his/her data, can know who has accessed it, and can revoke it wherever it is needed (after this defined period).
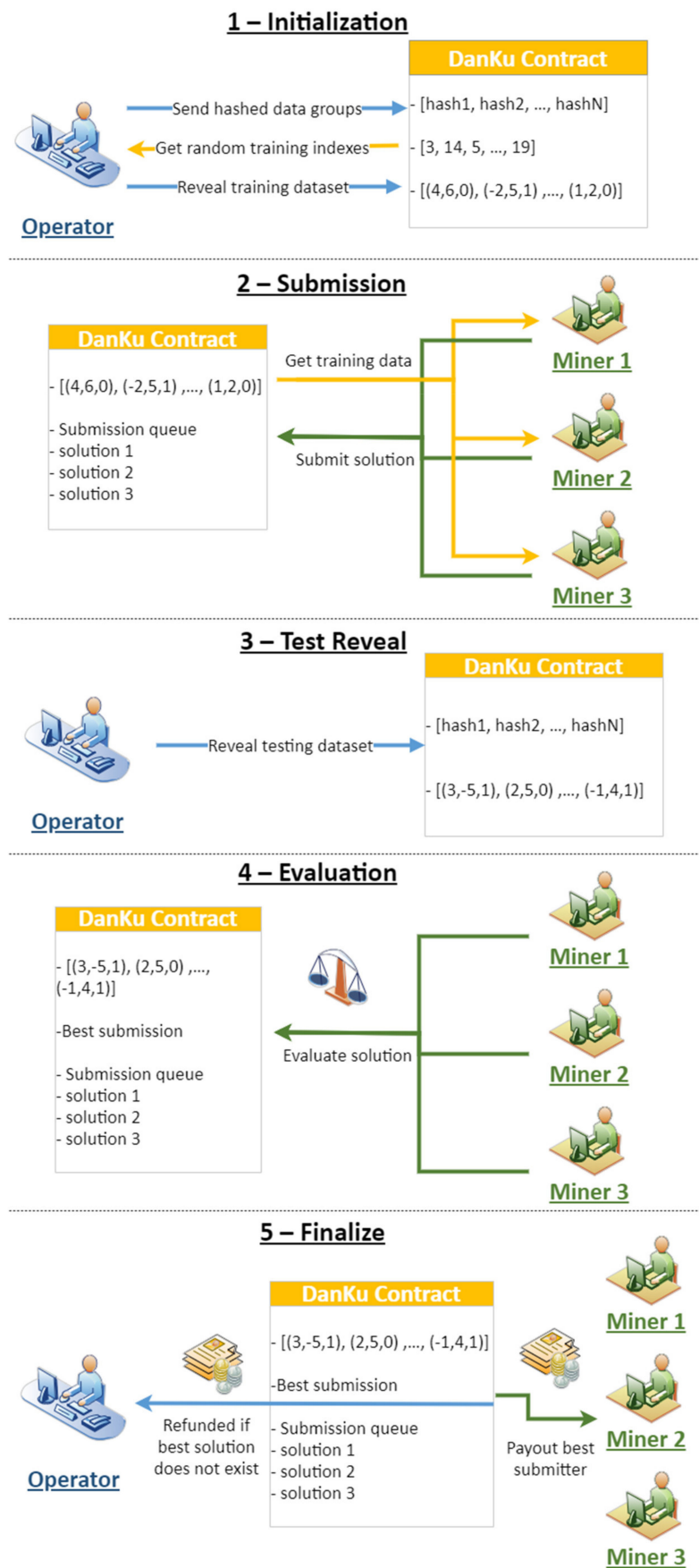
Figure 5. The DanKu protocol.

In the pure protocol, the data are recorded in the blockchain, making it impossible to erase it. Our strategy deviates from the ordinary public blockchains' functionality, where every piece of information must be maintained. On the other hand, the private CE-IoT blockchain would keep only the result of the ML-related contracts along with some information concerning the external link to the dataset and its hash value. Nevertheless, this strategy is sufficient for the examined domain, providing all the above-mentioned benefits. Concerning the overall economic cost, SMEs can further receive donations by the CE-IoT users and green-computing initiatives to continue optimizing their operation.

Data privacy and confidentiality constitute other significant drawbacks of DanKu. Except from our strategy to not include the raw data in the blockchain, under the CE-IoT methodology, we are considering that the data owner would have performed anonymization/pseudo-anonymization techniques [62] prior to the inclusion of the data in our ecosystem.

As mentioned before, the CE-IoT blockchain is permissioned. Therefore, the identities of the involved entities are verified and authorized. To surmount some flaws of DanKu regarding malicious issuers or miners [61], we give the opportunity to auditors to assess the legitimacy of these two groups and report the results back to the regulator, who can then take relevant actions (i.e., exclude participants that misbehave).

3.3. Evaluation of the Email Service and the Involved Equipment

As a case study, we evaluate the email service of the cloud services platform and the involved infrastructure components. We apply ML algorithms for feature selection on the edge monitoring devices and diagnosis at the backend. More specifically, we apply a *reinforcement learning* method based on the Fido ML lightweight library.

At runtime, sensory equipment monitors the ambient temperature of the room where a specific component is installed, as well as the component's temperature, CPU utilization, RAM consumption, and the recorded system failures. Analysis can reveal the operating patterns that cause failures, and thus enhance the predicting capabilities of the tool.

As training data, we also utilize the Enron email dataset that contains around 1.32 GB data of 500,000 emails generated by 150 employees of the Enron Corporation in a period of four years [63]. The ground truth captures main and general events for email hosting businesses [12], such as the daily service usage, peak working or holiday periods, etc. These results give insights regarding the ordinary operation of the potential customer and affect the decision-making process regarding the components' maintenance activities. Moreover, the organization can promote green computing policies and favor the service usage during less active periods (i.e., transmit public announcements or perform e-mail advertising and transmitting high volumes of messages).

3.4. Validation

To assess the overall results of our proposal, we have to validate (i) the effectiveness of the provided CE-related functionality, and (ii) the results of federated learning.

Concerning the effectiveness of our approach and the benefits for the CE ecosystem, a radar graph is produced on a spider map for CE applications [64]. The spider map evaluates the following five CE properties of: (i) disassembly, (ii) maintenance, (iii) remake, (iv) recycle, and (v) future proof. Four levels are defined for each property based on the effectiveness of the overall solution—the outer the map center, the better. The suggested CE-IoT system can greatly prolong the working life of CE assets, improving the maintenance aspects. The federated learning aspects are foreseeing potential breakdowns of the equipment and enable adaptable operations and policies. In general, the CE assets that are examined in the ICT domain use modular components that support forward/backward compatibility and can be easily disassembled, and their materials can be separated during recycling. The CE-IoT system supports the monitoring of these components throughout the CE cycle. The radar analysis is depicted in the following Figure 6.
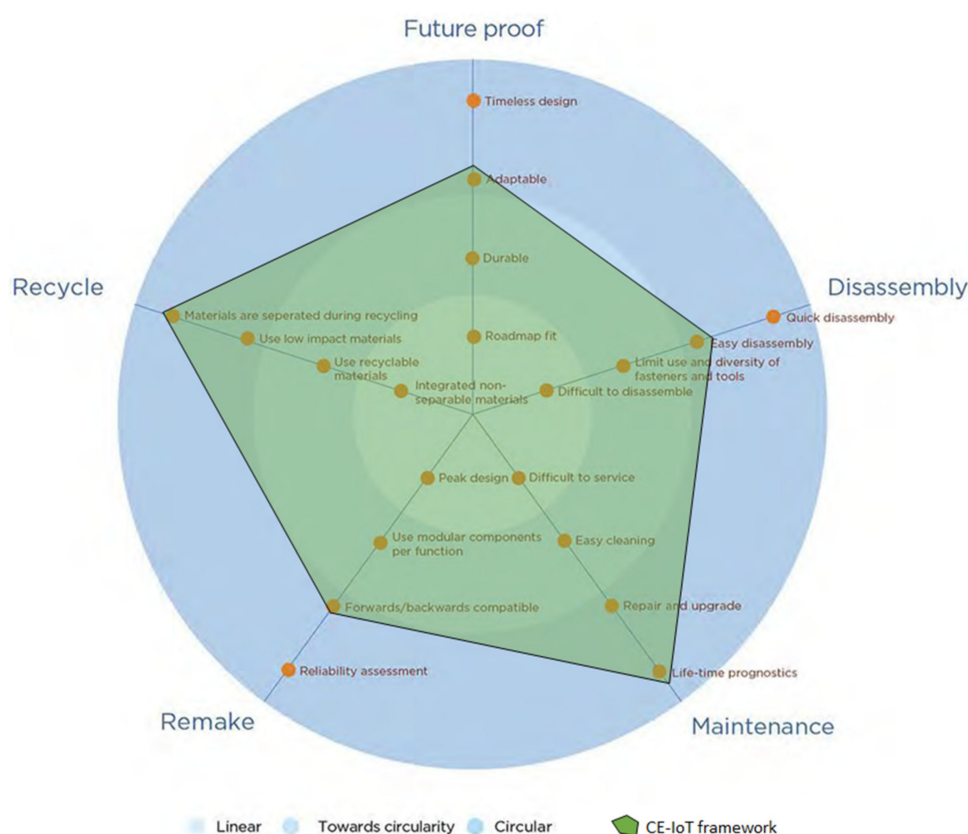
Figure 6. The CE-IoT spider map.

Concerning the ML part, we are corelating the results with similar studies that are processing the same data. The Enron email dataset, which was used in the evaluation Section 3.3, has been analyzed in [63]. There, the researchers process the data with anomaly detection algorithms in order to detect anomalies in the ordinary operation, such as peak working times. When such algorithms are used with the same parameters, the proposed federated learning process outputs similar outcomes.

4. Discussion and Future Work

4.1. Federated ML for CE

A main criticism on cryptocurrencies is the fact that the various users around the globe install specialized equipment for optimizing the mining operations, with a cost of huge energy usage. Just recently, Elon Musk, the CEO of Tesla and a mover of the cryptocurrencies, was provoked by the Anonymous hacking group for his actions, including, among others, the ecological footprint of the promoted technology [65]. Therefore, the integration of green computing with blockchaining establishes a new economic perspective. The miners utilize their computational resources and contribute to the CE organizations' efficiency, enhancing their green computing/networking capabilities.

As in similar studies [66], in this paper, we simulated the interactions of the motivating CE scenario of Section 3.1.1 and applied the federated learning aspects in optimizing the Cablenet's email service, as detailed in Section 3.3. In general, several studies are identifying the feasibility of integrating ML operations in a blockchain, but the result is inefficient for most applications due to the high costs [61]. One of our main contributions are the extensions of the DanKu protocol and the feasibility of deploying the time-wise offloading strategy. According to our knowledge, this is the first system that efficiently uses federated learning in blockchain for the CE domain.

With our approach, we store the main information for a transaction along with links to the raw data. Validation is performed within a specified time-window, both from

validation nodes and auditors, and after that period, only the evidence concerning the history of the performed transactions is remained. Of course, our solution deviates from the pure blockchain concept, where every piece of information must be recorded in the chain. Nevertheless, this is still adequate for the examined application and enables the green-mining features.

4.2. Future Work

Security and privacy are always significant properties that must be continuously audited and revisited in digitalized systems. Concrete policies must be established from the regulator perspective in an attempt to protect legitimate activity and constrain potential misbehaviors or malicious participants.

Another novel perspective that could emerge on future applications is cyber insurance [67,68]. Insuring information systems is a risk-controlling procedure for organizations. The insurance company collects information about an organization's system and calculates risk-related parameters, such as the time to failure or the possibility to violate a service-level agreement (SLA). Based on these data, the contract price is defined. In our previous work, we had implemented a relevant framework for the continuous insurance of information systems [68]. The recorded LCA properties of the core CE-IoT blockchain could feed relevant solutions with fruitful data for every currently deployed digital asset in the organization's setting.

Finally, one of the federated learning visions constitutes the implementation of self-improving AI systems [61]. Therefore, the smart agents of the CE-IoT could upload the ML data in the blockchain, receive the best model, and configure some system operations accordingly. This functionality could be performed seamlessly and automatically by the deployed multi-agent system, which would continuously improve its green-computing characteristics.

5. Conclusions

The integration of the IoT to CE business models impel eco-friendly initiatives and brings new opportunities for economic development into the foreground. In this article, we present the potential toward the green operation of blockchains in an actual data-driven CE-IoT setting. Blockchains monitor and verify the status of each evaluated asset (e.g., computers, smart devices, etc.). The core CE-IoT blockchain acts as a distributed ledger of these assets, facilitating the asset owners to exchange these elements along the CE loop. Apart from recycling, the proposed solution prolongs the working lifetime of the electronic assets, improves e-waste management, and enhances the economic function of the involved organizations. Upon our advancement in federated learning with blockchain, the ML improves the performance of the green computing operations on the monitoring devices. Moreover, the computationally intensive ML functionality for the enhanced green computing services can be distributed in a federated learning environment. Thus, green-miners earn money while the involved businesses reduce their investment costs and meliorate their operation. Nonetheless, security and privacy issues should be further examined, as the ML data could contain confidential or personal data. Thus, related protection mechanisms and strategies could be considered in future extensions of this work. Additionally, the enhancement of cyber insurance solutions and the implementation of self-improving AI systems are two other interesting perspectives that should be further examined.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Kalmykova, Y.; Sadagopan, M.; Rosado, L. Circular economy—From review of theories and practices to development of implementation tools. *Resour. Conserv. Recycl. Sustain. Resour. Manag. Circ. Econ.* **2018**, *135*, 190–201. [CrossRef]
2. Heshmati, A. A review of the circular economy and its implementation. *Int. J. Green Econ.* **2018**, *11*, 251–288. [CrossRef]
3. Urbinati, A.; Chiaroni, D.; Chiesa, V. Towards a new taxonomy of circular economy business models. *J. Clean. Prod.* **2017**, *168*, 487–498. [CrossRef]
4. Issa, T.; Issa, T.; Issa, T. Awareness, Opportunities and Challenges of Green IT: An Australian Perspective. In *Sustainability Awareness and Green Information Technologies, Green Energy and Technology*; Springer: Cham, Switzerland, 2020; pp. 443–462.
5. Bigliardi, B.; Filippelli, S. Investigating Circular Business Model Innovation through Keywords Analysis. *Sustainability* **2021**, *13*, 5036. [CrossRef]
6. Askoxylakis, I. A framework for pairing circular economy and the Internet of Things. In Proceedings of the IEEE International Conference on Communications (ICC), Kansas City, MO, USA, 20–24 May 2018.
7. Galati, F.; Bigliardi, B. Industry 4.0: Emerging themes and future research avenues using a text mining approach. *Comput. Ind.* **2019**, *109*, 100–113. [CrossRef]
8. Buterin, V. A Next-Generation Smart Contract and Decentralized Application Platform. GitHub White Paper. 2014. Available online: https://github.com/ethereum/wiki/wiki/White-Paper (accessed on 23 July 2021).
9. Hamdaoui, B.; Zorba, N.; Rayes, A. Participatory IoT Networks-on-Demand for Safe, Reliable and Responsive Urban Cities. IEEE Blockchain Technical Briefs. January 2019. Available online: https://blockchain.ieee.org/technicalbriefs/january-2019/participatory-iot-networks-on-demand-for-safe-reliable-and-responsive-urban-cities?highlight=WyJidXNpbmVzcyIsImxhdyJd (accessed on 23 July 2021).
10. Xu, X. A taxonomy of blockchain-based systems for architecture design. In Proceedings of the 2017 IEEE International Conference on Software Architecture (ICSA), Gothenburg, Sweden, 3–7 April 2017; pp. 243–252.
11. Larrucea, X.; O'Connor, R.V.; Colomo-Palacios, R.; Laporte, C.Y. Software process improvement in very small organizations. *IEEE Softw.* **2016**, *33*, 85–89. [CrossRef]
12. Alanazi, S.; Dabbagh, M.; Hamdaoui, B.; Guizani, M.; Zorba, N. Reducing data center energy consumption through peak shaving and locked-in energy avoidance. *IEEE Trans. Green Commun. Netw.* **2017**, *1*, 551–562. [CrossRef]
13. Yang, Y.; Zheng, Z.; Bian, K.; Song, L.; Han, Z. *Sensor Deployment Recommendation for 3D Fine-Grained Air Quality Monitoring Using Semi-Supervised Learning*; IEEE ICC: Kansas City, MO, USA, 2018; pp. 1–6.
14. Datsika, E.; Antonopoulos, A.; Passas, N.; Kormentzas, G.; Verikoukis, C. *Green Resource Management for Over-the-Top Services in 5G Networks Using Matching Theory*; IEEE ICC: Kansas City, MO, USA, 2018; pp. 1–6.
15. Issa, T.; Issa, T.; Issa, T.B.; Isaias, P. *Sustainability Awareness and Green Information Technologies*; Green Energy and Technology; Springer: Berlin/Heidelberg, Germany, 2020; pp. 1–554.
16. Hatzivasilis, G.; Papaefstathiou, I.; Plexousakis, D.; Manifavas, C.; Papadakis, N. AmbISPDM: Managing embedded systems in ambient environment and disaster mitigation planning. *Appl. Intell.* **2017**, *48*, 1623–1643. [CrossRef]
17. Alexandris, G.; Katos, V.; Alexaki, S.; Hatzivasilis, G. Blockchains as enablers for auditing cooperative circular economy networks. In Proceedings of the 2018 IEEE 23rd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), Barcelona, Spain, 17 September 2018; pp. 1–7.
18. Camacho-Otero, J.; Boks, C.; Pattersen, I.N. Consumption in the circular economy: A literature review. *Sustainability* **2018**, *10*, 2758. [CrossRef]
19. Moraga, G.; Huysveld, S.; Mathieux, F.; Blengini, G.A.; Alaerts, L.; Van Acker, K.; de Meester, S.; Dewulf, J. Circular economy indicators: What do they measure? *Resour. Conserv. Recycl.* **2019**, *146*, 452–461. [CrossRef] [PubMed]
20. Pagoropoulos, A.; Pigosso, D.C.; McAloone, T.C. The emergent role of digital technologies in the Circular Economy: A review. *Proc. CIRP* **2017**, *64*, 19–24. [CrossRef]
21. Khalamayzer, A. 7 Companies Advancing the Circular Economy by Selling Products as a Service. GreenBiz, February 2018. Available online: https://www.greenbiz.com/article/7-companies-advancing-circular-economy-selling-products-service (accessed on 23 July 2021).
22. Okorie, O.; Salonitis, K.; Charnley, F.; Moreno, M.; Turner, C.; Tiwari, A. Data-driven approaches for circular economy in manufacturing for digital technologies: A review of current research and proposed framework. *Preprints* **2018**, 2018080159. [CrossRef]
23. Lin, K.-Y. User experience-based product design for smart production to empower industry 4.0 in the glass recycling circular economy. *Comput. Ind. Eng.* **2018**, *125*, 729–738. [CrossRef]
24. Lieder, M.; Asif, F.M.A.; Rashid, A. Towards circular economy implementation: An agent-based simulation approach for business model changes. *Auton. Agents Multi-Agent Syst.* **2017**, *31*, 1377–1402. [CrossRef]

25. Despeisse, M.; Baumers, M.; Brown, P.; Charnley, F.; Ford, S.; Garmulewicz, A.; Knowles, S.; Minshall, T.; Mortara, L.; Reed-Tsochas, F.; et al. Unlocking value for a circular economy through 3D printing: A research agenda. *Technol. Forecast. Soc. Change* **2017**, *115*, 75–84. [CrossRef]

26. Williams, E.; Hatanaka, T. Residential computer usage patterns in Japan and associated life cycle energy use. In Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment, New Orleans, LA, USA, 16–19 May 2005; pp. 177–182.

27. Bag, S.; Yadav, G.; Wood, L.C.; Dhamija, P.; Joshi, S. Industry 4.0 and the circular economy: Resource melioration in logistics. *Resour. Policy* **2020**, *68*, 1–16. [CrossRef]

28. Bag, S.; Gupta, S.; Foropon, C. Examining the role of dynamic remanufacturing capability on supply chain resilience in circular economy. *Manag. Decis.* **2019**, *57*, 863–885. [CrossRef]

29. Giudice, M.D. Supply chain management in the era of circular economy: The moderating effect of big data. *Int. J. Logist. Manag.* **2021**, *32*, 337–356. [CrossRef]

30. Bag, S.; Wood, L.C.; Xu, L.; Dhamija, P.; Kayikci, Y. Big data analytics as an operational excellence approach to enhance sustainable supply chain performance. *Resour. Conserv. Recycl.* **2020**, *153*, 1–10. [CrossRef]

31. Dubey, R.; Gunasekaran, A.; Childe, S.J.; Blome, C.; Papadopoulos, T. Big data and predictive analytics and manufacturing performance: Integrating institutional theory, resource-based view and big data culture. *Br. J. Manag.* **2019**, *30*, 341–361. [CrossRef]

32. Upadhyay, A.; Mukhuty, S.; Kumar, V.; Kazancoglu, Y. Blockchain technology and the circular economy: Implications for sustainability and social responsibility. *J. Clean. Prod.* **2021**, *293*, 1–7. [CrossRef]

33. Yildizbasi, A. Blockchain and renewable energy: Integration challenges in circular economy era. *Renew. Energy* **2021**, *176*, 183–197. [CrossRef]

34. Stankovic, M.; Gupta, R.F.J.I. Industry 4.0—Opportunities behind the challenge. United Nations Industrial Development Organization (UNIDO). In Proceedings of the Background Paper for UNIDO General Conference, Abu Dhabi, United Arab Emirates, 17 November–1 December 2017; pp. 1–32.

35. Geng, Y.; Sarkis, J.; Bleischwitz, R. How to globalize the circular economy. *Nat. Comment* **2019**, *565*, 153–155. [CrossRef] [PubMed]

36. State of Green. Circular Consumption through Innovative Business Models. November 2017. Available online: https://stateofgreen.com/en/partners/state-of-green/news/circular-consumption-through-innovative-business-models/ (accessed on 23 July 2021).

37. Lyndegaard, K. Combining spatial and network analysis: A case study of the GoMore network. In Proceedings of the ESRI European User Conference (EUC), Split, Croatia, 13–15 October 2014; pp. 1–11.

38. Slimane, K.B.; Chaney, D. Towards marketing of functionality: Insights from Michelin and Hilti. *J. Strateg. Mark.* **2015**, *23*, 224–237. [CrossRef]

39. Worth, A.T.S.; Escartin-Claveria, B. Alstom's approach to railway condition monitoring. In Proceedings of the 6th IET Conference on Railway Condition Monitoring (RCM), Birmingham, UK, 17–18 September 2014; pp. 1–6.

40. Orehek, M.; Robl, C. Model-based design of an ECU with data- and event-driven parts using auto code generation. In Proceedings of the IEEE ICRA, Seoul, Korea, 21–26 May 2001; pp. 1346–1351.

41. Persis, D.J.; Venkatesh, V.G.; Sreedharan, V.R.; Shi, Y.; Sankaranarayanan, B. Modelling and analysis the impact of circular economy; Internet of Things and ethical business practices in the VUCA world: Evidence from the food processing industry. *J. Clean. Prod.* **2021**, *301*, 1–13.

42. Maksimovic, M.; Vujovic, V.; Omanovic-Miklicanin, E. Application of Internet of Things in food packaging and transportation. *Int. J. Sustain. Agric. Manag. Inform. IJSAMI* **2015**, *1*, 333–350. [CrossRef]

43. Bouzembrak, Y.; Kluche, M.; Gavai, A.; Marvin, H.J.P. Internet of Things in food safety: Literature review and a bibliometric analysis. *Trends Food Sci. Technol.* **2019**, *94*, 54–64. [CrossRef]

44. Kodan, R.; Parmar, P.; Pathania, S. Internet of Things for food sector: Status quo and projected potential. *Food Rev. Int.* **2020**, *36*, 584–600. [CrossRef]

45. Kazancoglu, Y.; Ekinci, E.; Mangla, S.K.; Sezer, M.D.; Kayikci, Y. Performance evaluation of reverse logistics in food supply chains in a circular economy using system dynamics. *Bus. Strategy Environ.* **2021**, *30*, 71–91. [CrossRef]

46. Heitlinger, S.; Bryan-Kinns, N.; Comber, R. Connected seeds and sensors: Co-designing Internet of Things for sustainable smart cities with urban food-growing communities. In Proceedings of the 15th Participatory Design Conference, Hasselt, Belgium, 20–24 August 2018; pp. 1–8.

47. Arora, N.; Kaur, P.D. Augmenting banking and FinTech with intelligent Internet of Things Technology. In Proceedings of the 8th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO), Noida, India, 4–5 June 2020; pp. 648–653.

48. Ramalingam, H.; Venkatesan, V.P. Conceptual analysis of Internet of Things use cases in banking domain. In Proceedings of the 2019 IEEE Region 10 Conference (TENCON), Kochi, India, 17–20 October 2019; pp. 2034–2039.

49. Dewick, P.; Bengtsson, M.; Cohen, M.J.; Sarkis, J.; Schroder, P. Circular economy finance. *J. Ind. Ecol.* **2020**, *24*, 1192–1200. [CrossRef]

50. Ozili, P.K.; Opene, F. The role of banks in the circular economy. *World J. Sci. Technol. Sustain. Dev.* **2021**, 1–9. [CrossRef]

51. Ozili, P.K. Circular economy, banks and other financial institutions: What's in it for them? *Circ. Econ. Sustain. J.* **2021**, *1*, 1–18.

52. Ellen MacArthur Foundation. Achieving "Growth Within": A €320-Billion Circular Economy Investment Opportunity Available to Europe up to 2025. London, UK. 2017. Available online: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Achieving-Growth-Within-20-01-17.pdf (accessed on 2 August 2021).

53. FinanCE Working Group. Circular Economy Finance Guidelines. Amsterdam, The Netherlands. 2018. Available online: https://www.ing.com/Newsroom/News/ABN-AMRO-ING-and-Rabobank-launch-finance-guidelines-for-circular-economy.htm (accessed on 2 August 2021).

54. Geissdoerfer, M.; Savaget, P.; Bocken, N.; Hultink, E. The circular economy: A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]

55. Dapp, M.M. Towards a sustainable circular economy powered by community-based incentive systems. In *Business Transformation through Blockchain*, 1st ed.; Palgrave Macmillan, H., Beck, R., Eds.; Palgrave Macmillan: Cham, Switzerland, 2019; pp. 153–181.

56. Wang, B.; Farooque, M.; Zhong, R.Y.; Zhang, A.; Liu, Y. Internet of Things (IoT)-Enabled accountability in source separation of household waste for a circular economy in China. *J. Clean. Prod.* **2021**, *300*, 1–47. [CrossRef]

57. Gligoric, N. Smarttags: IoT product passport for circular economy based on printed sensors and unique item-level identifiers. *Sensors* **2019**, *19*, 586. [CrossRef] [PubMed]

58. Dannen, C. *Introducing Ethereum and Solidity: Foundation of Cryptocurrency and Blockchain Progamming for Beginners*; Apress: New York, NY, USA, 2017; pp. 1–185.

59. Pezoa, F.; Reutter, J.L.; Suarez, F.; Ugarte, M.; Vrgoč, D. Foundations of JSON schema. In Proceedings of the International World Wide Web Conference Committee (IWeC2), ACM, Montreal, QC, Canada, 11–15 April 2016; pp. 263–273.

60. Bellifemine, F. JADE: A software framework for developing multi-agent applications. Lessons learned. *Inf. Softw. Technol.* **2008**, *50*, 10–21. [CrossRef]

61. Kurtulmus, A.B.; Daniel, K. Trustless machine learning contracts; Evaluating and exchanging machine learning models on the Ethereum blockchain. In Proceedings of the Artificial Intelligence Conference, San Francisco, CA, USA, 5–7 September 2018; pp. 1–11.

62. Murthy, S.; Bakar, A.A.; Rahim, F.A.; Ramli, R. A comparative study of data anonymization techniques. In Proceedings of the 2019 IEEE 5th International Conference on Big Data Security on Cloud (BigDataSecurity), IEEE International Conference on High Performance and Smart Computing (HPSC) and IEEE International Conference on Intelligent Data and Security (IDS), Washington, DC, USA, 27–29 May 2019; pp. 306–309.

63. Rayana, S.; Akoglu, L. Less Is More: Building Selective Anomaly Ensemble. *ACM TKDD* **2016**, *10*, 1–33. [CrossRef]

64. Berg, M.R.; Bakker, C.A. A product design framework for a circular economy. In Proceedings of the Product Lifetime and the Environment (PLATE) Conference, Nottingham, UK, 17–19 June 2015; pp. 365–379.

65. News 18. Elon Musk Mocks Anonymous' Cryptocurrency Threat with a 'Hannah Montana' Meme. 14 June 2021. Available online: https://www.news18.com/news/buzz/elon-musk-mocks-anonymous-cryptocurrency-threat-with-a-hannah-montana-meme-3844637.html (accessed on 23 July 2021).

66. Charnley, F.; Tiwari, D.; Hutabarat, W.; Moreno, M.; Okorie, O.; Tiwari, A. Simulation to Enable a Data-Driven Circular Economy. *Sustainability* **2019**, *11*, 3379. [CrossRef]

67. Godsiff, P.; Wood, Z. Circular insurance: Customer-centric, data-driven services for the circular economy. In Proceedings of the 54th Hawaii International Conference on System Sciences (HICSS), Waikoloa Village, HI, USA, 5 January 2021; pp. 1686–1695.

68. Hatzivasilis, G.; Chatziadam, P.; Petroulakis, N.; Ioannidis, S.; Mangini, M.; Kloukinas, C.; Yautsiukhin, A.; Antoniou, M.; Katehakis, D.G.; Panayiotou, M. Cyber insurance of information systems. In Proceedings of the 24th IEEE International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD 2019), Limassol, Cyprus, 11–13 September 2019; pp. 1–7.