PAIRING A CIRCULAR ECONOMY AND THE 5G-ENABLED INTERNET OF THINGS: Creating a Class of "Looping Smart Assets"

Andreas Miaoudakis, Konstantinos Fysarakis, Nikolaos Petroulakis, Sofia Alexaki, George Alexandris, Sotiris Ioannidis, George Spanoudakis, Vasilios Katos, and Christos Verikoukis

Abstract— **The increase in the world's population has led to a massive rise in human consumption of the planet's natural resources, well beyond their replacement rate. Traditional recycling concepts and methods are not enough to counter such effects. In this context, a circular economy (CE), that is, a restorative and regenerative by-design economy, can reform today's "take–make–dispose" economic model. On the other hand, the Internet of Things (IoT) continues to gradually transform our everyday lives, allowing for the introduction of novel types of services while enhancing legacy ones. Taking this as our motivation, in this article we analyze the CE/IoT interplay, indicating innovative ways in which this interaction can drastically affect products and services, their underlying business models, and the associated ecosystems. Moreover, we present an IoT architecture that enables smart object integration into the IoT ecosystem. The presented architecture integrates circularity-enabling features by maximizing the exploitation of assets toward a new type of IoT ecosystem that is circular by design (CbD). Finally, we provide a proof-of-concept implementation and an application study of the proposed architecture and results regarding the applicability of the proposed approach for the telecommunications (telecom) sector.**

I. Restorative and Regenerative by Design

Since early times, the use of natural resources has followed the same pattern: acquire materials and then manufacture, use, and dispose of them. Nevertheless, it is now clear that this is not a sustainable model, considering the constantly increasing demand [1] and our planet's finite resources. Although efficiency in the use of resources and rates of recycling have improved, there is still more to be done. In this context, a CE has emerged in recent years, inspiring the transition of modern societies from the "take–make–dispose" model to an economy that is restorative and regenerative by design: a continuous cycle that preserves and enhances existing resources while optimizing their yields.

On the technological front, advances in computing and networking technologies drive the rapid expansion of the IoT, also exploiting the evolution of 5G. Billions of smart objects are already deployed, and more devices are positioned daily, creating an open, global network connecting people, data, and "things" and generating a massive potential for innovative applications and services, thereby leveraging the convergence of a consumer–business–industrial Internet. However, the realization of the IoT's potential still requires overcoming significant business and technical hurdles.

II. Motivation

A CE and the IoT provide a fertile ground for innovation and value creation [2]. CE value drivers include the extension of the useful life of finite resources, the maximization of assets' utilization, and the regeneration of natural capital for more effective and efficient use. In parallel, IoT value drivers create new opportunities for a new breed of circular economics: the IoT becomes an enabler by aggregating knowledge from smart assets (e.g., location, condition, sensed parameters, and performance). Conversely, the feedback-rich nature of a CE facilitates the extraction of value from the vast, aggregated IoT data. Therefore, even more profound opportunities emerge when CE and IoT value drivers are paired, and their congruency must be extensively explored.

This article focuses on the interplay between the CE and the IoT, highlighting the innovative ways in which it drastically affects products, services, business models, and ecosystems. A bidimensional and bidirectional method is presented in our analysis to accomplish the following:

- emphasize the potential of CE business models and service supply chains to unlock the cooperation needed to create increased value for end users and optimize resource usage
- sketch an open IoT architecture, referred to as CE–IoT, that is circular by design, facilitating the integration of smart objects with proven circularity-enabling properties into the IoT ecosystem.

III. Interplay Analysis

A. The IoT as an Enabler for a CE

Our current economy is based on an overwhelmingly lin-ear model, which is stretching the resource limits of our planet. A CE proposes an innovative economic model, restorative and regenerative by design, that necessitates the alignment of government policy, business practices, and consumer preferences. It drives new business models, which use as few resources as possible for as long as possible, reuse resources as much as possible, extract as much value from those resources in the most effective way possible, and then recover as much of those materials and products as possible at the end of their life. The CE is positioned to decrease new materials consumption by 32% within 15 years and by 53% by 2050 [3]. Just moving toward a CE could eliminate 100 million tons of waste globally in the next five years [4]. Besides material savings and increased efficiency, the CE can be a game changer regarding the utilization of productive resources and assets [3].

At the same time, the rapid increase in the number of Internet-connected objects is reshaping the economy, with an estimated 75 billion connected devices by year 2025 [5]. Smart objects already generate real-time readings that are unprecedented in both variety and volume, enabling insights previously inconceivable. Nevertheless, the further intertwining of data, technology, business models, artificial intelligence, and societal trends has created nonlinear complexity that seems unmanageable.

To address these challenges and realize the full potential of the CE–IoT interplay, the following two fundamental research questions arise [6]:

- How can IoT-enabled circular provisioning be exploited to create business value?
- What is the best way to reorganize supply, delivery, and value chains in the interplay of the CE and IoT?

Answering these questions requires advancing the state of the art in two directions: 1) developing new IoT-enabled CE business models and 2) encouraging the IoT-enabled provisioning of CE service supply chains. Al-though a global network of smart assets creates an enormous potential for the generation of new IoT applications and business models, significant business and technical hurdles remain.

First, at present, the IoT landscape is very fragmented. Overcoming this fragmentation is a big challenge, but it is essential to fully leverage the change in business value that the cocreation and continuous innovation of IoT services brings. Additionally, key technical challenges should be taken into account; these include providing scalable connectivity, the seamless interoperability and adaptability of services, and highly trustworthy chains with low cost and complexity. Therefore, efforts should focus on the following key issues [6]:

- scalable IoT connectivity
- semantic interoperability
- high trustworthiness of IoT service chains.

IV. Implementing the CE–IoT Concept

Motivated by the aforementioned challenges, we propose a structured and holistic approach toward the development of the CE–IoT ecosystem. A sketch of the associated architecture is depicted in Figure 1, covering IoT smart assets and other field devices, programmable networks, the cloud, and back-end services. Moreover, the three key technical challenges that must be addressed are shown with arrows at the left side of the figure.

A. Methodological Approach

The implementation of a usable CE–IoT-enabled ecosystem, as shown in Figure 2 (also depicting the complementarity of a CE and the IoT, which provides added value), must be based on a requirements' analysis focusing on the following [6]:

- the circularity-enabling properties of smart assets, namely, location, condition, and availability (LCA)
- key enabling IoT technologies, namely, connectivity,

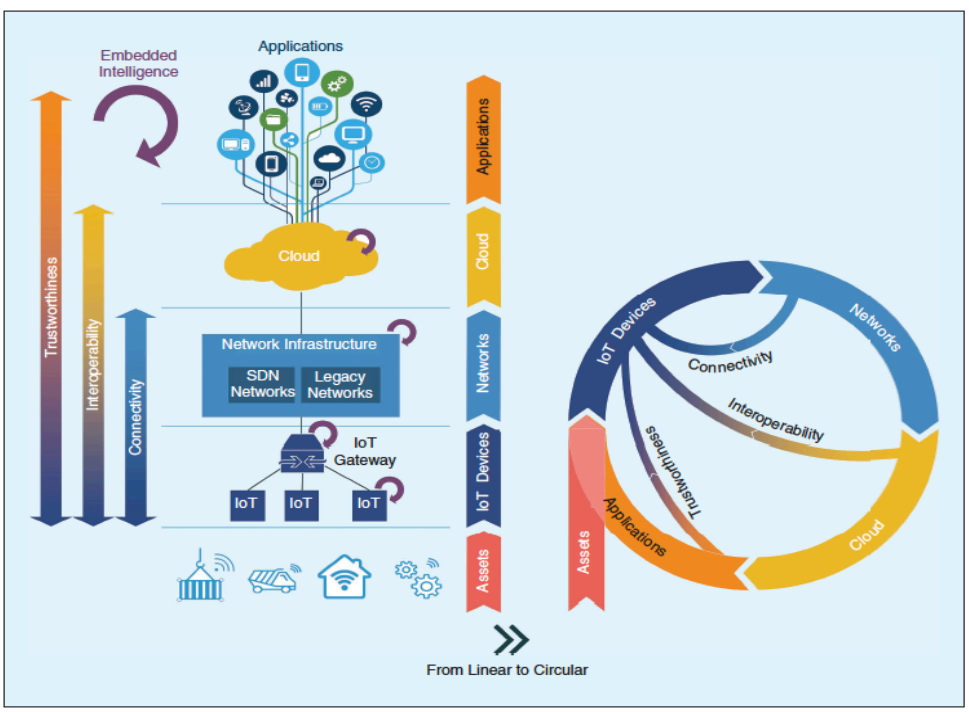

Figure 1. A Sketch of transitioning to a CE–IoT architecture. SDN: software-defined networking.

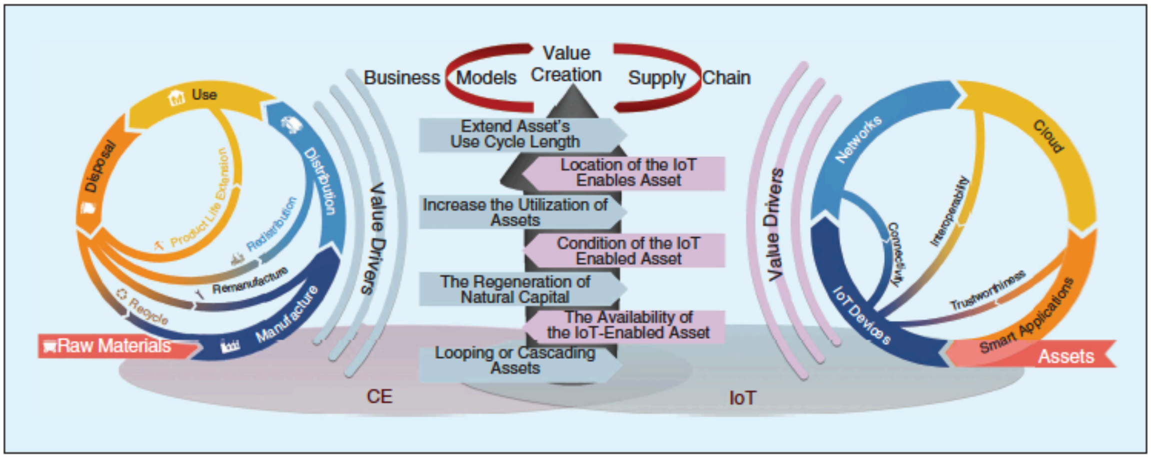

Figure 2. The CE–IoT ecosystem, offering novel business models and supply chains that converge into value creation.

security, privacy, dependability, and interoperability (CSPDI)

- the application-specific business and technical needs of each application domain (e.g., telecom, smart energy, and e-health).

Part of the goal is to design a product–services–systems supply chain framework with effective and secure reverse logistics capabilities. The essential LCA and CSPDI proper-ties of the CE–IoT deployment in each of the application domains will have to be considered. Furthermore, concrete business models and IoT-enhanced supply chains as well as robust networking, interoperability, monitoring, and adaptation capabilities will need to be encompassed to address the needs of each specific domain. This will have to be car-ried out in two phases. In the first phase, an initial set of architectural CSPDI patterns has to be developed, along with CE and IoT value drivers. In the second phase, the outcome of the first phase will be integrated into the overall CE–IoT architecture and adapted to the specific application/vertical domain.

B. Toward a CE–IoT Architecture Definition

The CE–IoT architecture is developed using open standards and reference specifications across all layers, including standardized networking and IoT protocols (such as OpenFlow and MQTT) and security mechanisms (e.g., authentication and authorization schemes). It also takes into account the existing capabilities of the IoT platforms and service interfaces and offers adapters for accessing services as necessary. This is essential to ensure that the architecture will be able to interoperate with existing IoT solutions, networking, security and smart device technologies and evolve to accommodate future technological changes.

A CE–IoT-enabled ecosystem advances the current state of the art by introducing a holistic approach that we refer to as CbD in the IoT. CbD can be considered a core property of the IoT that meets key technical properties in terms of scalable connectivity and end-to-end CSPDI. Under this broader notion of CbD, the CE–IoT improves the state of the art in several technical areas that comprise circularity at the technical level. Such key areas are identified in the following sections.

V. Key Building Blocks and Challenges

To support a CbD approach, several key building blocks are incorporated in the architecture, toward a solution that also features security, privacy, dependability, and interoperability by design. An emerging approach used to secure IT systems, known as security by design, aims to guarantee system-wide security properties. A key, required capability is the ability to verify the desired security properties as part of the design process.

Pino et al. [7] use secure service orchestration pat-terns to support the design of service workflows with required security properties. The adoption of a pattern-based approach for the CE–IoT ensures the circularity of IoT ecosystems through the guarantee of CSPDI proper-ties across compositional structures of IoT applications. CSPDI patterns in the CE–IoT define the overall design goal of CbD and can set necessary and sufficient conditions not only for composing different components within IoT applications in ways that guarantee CSPDI properties but also for ensuring that these properties are guaranteed when IoT applications use the CE–IoT architecture. The CE–IoT's CSPDI patterns extend existing work on patterns [8], covering in an integrated manner not only security but also the connectivity, dependability, privacy, and interoperability properties of the IoT.

In terms of semantic IoT interoperability, the focus is on the definition of semantic annotations for respective IoT architectural patterns and the development of data transformation and validation mechanisms [9]. The semantic annotation process is based on the Web Service Specification Language validation mechanisms used for semantic interoperability, which rely on including interoperability conditions in the patterns and are based on the use of semantic reasoners or rule engines as well as logic programming.

Considering the trustworthiness of IoT service chains, the focus of the efforts is on preserving security, privacy, and dependability (SPD) properties in the IoT, a particularly challenging problem despite the current existence of various security and privacy mechanisms. Efforts also focus on analyzing end-to-end SPD vulnerabilities and on making optimal the delegation of SPD issues to the various control mechanisms. Another focus point is preserving SPD properties when the components and compositions of the IoT change, are compromised, or stop behaving normally. More details on the associated building blocks are provided in the following section.

VI. LCA AND CSPDI PATTERNS

The key element enabling the proposed implementation of the CE–IoT approach is the use of architectural pat-terns. The patterns specify abstract and generic smart object interaction and orchestration protocols and, if necessary, define transformations to ensure data semantic interoperability.

Furthermore, smart object interaction and orchestration protocols must have the proven ability to achieve the specific CSPDI or LCA properties that may be required. The compositions defined by patterns are both vertical and horizontal, i.e., they can involve smart objects at the same (horizontal) or at different layers (vertical) of the IoT stack. Specifically, the CE–IoT agents implement a reasoning behavior for pattern evaluation that exhibits the following features:

- composition structures for integrating smart objects and components of the IoT, enabling platforms while guaranteeing CSPDI properties
- the end-to-end CSPDI properties that the compositions expressed by the pattern preserve
- the component-level CSPDI properties that the types of smart objects and/or components orchestrated by the patterns must satisfy
- additional conditions that need to be satisfied for guaranteeing end-to-end CSPDI properties
- monitoring checks performed at runtime to verify that any assumptions about the individual smart objects and pattern-orchestrated components are true
- adaptation actions that may be undertaken to adapt IoT applications and realize the runtime composition structure of the pattern.

The last on the list may include the replacement of individual smart objects within a composition or the modification of the configuration of the network services used. Adaptation actions are specified along with the guard conditions triggering their execution.

Based on these features, a pattern specification language is defined, which identifies and specifies concrete LCA and CSPDI machine-interpretable patterns. The development of this pattern language is based on [7], focusing on extensions that support both the LCA properties of intelligent assets and the CSPDI properties for the different types of smart objects, network and software services, and components.

VII. LOCALIZED, EMBEDDED INTELLIGENCE

Although back-end analytics is a field that has been studied intensively in the past few years, the need for localized analytics at the edge devices has emerged [10]. An International Data Corporation FutureScape report [11] for the IoT reported that, by 2018, 40% of IoT data will be stored, processed, analyzed, and acted upon locally for reducing both the volume of transmit-ted data and the reaction times because decisions are made locally.

To implement an effective and efficient CE–IoT ecosystem as well as the adaptive and autonomic behavior needed to maintain the required LCA and CSPDI properties across all layers, intelligent analysis is required. Local analytics are required for semiautonomous reaction, but, considering smart objects' re-source constraints, it should also be possible to involve local intelligence at higher levels, thereby enhancing the system's smart behavior (see the circular purple arrows depicting embedded intelligence in the architectural sketching presented in Figure 1). Thus, localized analytics will not only enable semiautonomous smart operation but also improve the subsequent global analysis on the cloud. The latter can create knowledge for the whole system and extract global patterns that, again, can be used by local analytics to improve its performance.

VIII. SCALABLE IOT CONNECTIVITY

The vast number of smart objects connected daily to the Internet increases the volume and diversity of net-work traffic, making the development of more scalable and agile networking techniques an absolute necessity. Networks will need to be dynamically reconfigured, maintaining connectivity across all layers. Software-defined networking (SDN) and network function virtualization (NFV) have been used as key networking technologies for 5G [12] to tack le connectivity and availability issues under heterogeneous communication systems [13], [14]. Furthermore, to take full advantage of underlying network programmability, IoT applications will need to be resource- and network-aware.

In this context, developing a CE–IoT ecosystem re-quires the investigation of network challenges concerning the interconnection of heterogeneous smart objects to achieve end-to-end connectivity and adaptive IoT application deployment as well as the development of relevant supporting mechanisms, including

- frequency spectrum and power allocation utilizing the advantages of cognitive radio augmented by distributed, scalable, and load-adaptive protocols based on the developed trusted patterns, avoiding interference and achieving maximum wireless resources utilization
- an SDN architecture for the wired and wireless inter-connectivity of smart objects and efficient mechanisms for their effective internetworking
- SDN orchestration mechanisms for core networks with different quality-of-service (QoS) levels between different IoT domains to provide end-to-end service connectivity and meet different IoT application requirements
- VNFs to remove complexity from local and access sensor networks by moving complex network functionalities (e.g., routing and network security)
- adaptable and dynamic networking services offered to client IoT applications.

Table 1 lists the key technical and nontechnical areas where challenges exist and required advancements to the state of the art are needed, including technical, business, and academia- and industry-focused domains.

TABLE 1. The challenges to and the advancements needed of the current state of the art.

New Knowledge and Advancement Area	Academia	Industry
An IoT-enabled CE	✓	✓
The business modeling used for the interplay of the CE and the IoT	✓	✓
The supply and delivery chains used for the interplay of the CE and the IoT	✗	✓
The CE and IoT value drivers and value creation	✗	✓
Scalable IoT connectivity	✓	✗
Semantic IoT interoperability	✓	✗
The trustworthiness of IoT value Chains	✓	✗
CbD IoT architectures	✓	✗
The business and technical integration of the CE–IoT framework	✗	✓

A. *Application Study—Telecom Sector*

The CE–IoT interplay and the proposed framework can bring benefits to various vertical domains. Herein an application in the telecom domain is presented as a characteristic example, covering both business aspects of a CE and the different IoT-enabling technologies.

In this domain, having already gone through big changes associated with the transition to 5G, it is possible to embed circular economic principles into the fabric of a telecom operator's infrastructure, operations, and culture and to integrate CbD into the information and communications technology infrastructure of the tele-com operator.

1) *Business Pillar of the Telecom Demonstrator*

The application of the CE–IoT concept on this domain can encompass the network infrastructure and its associated network components. For the business pillar, the goal must be to understand the current practices in net-work operations and the supply chain, including the scale and scope of current practices and the further opportunities that can be explored to expand CE practices in the telecom industry.

2) *Technical Pillar of the Telecom Demonstrator*

For the technical pillar, the objective is to develop and apply CbD algorithms for discovering, aggregating, and dynamically (re)assigning physical resources to overlay virtual entities, considering the context of the transferred data and telecom services that run over those entities. A key aspect will be the use of semantic information such as metadata, sensor/actuator information, sender details, and network information as well as the application requirements for describing the network's resources and QoS requirements.

3) *Telecom Supply Chain*

The supply chain consists of Internet Protocol network components, including network controllers, network switches, cables, fiber optics, and other network equipment. The following CE requirements are essential to the telecom supply chain:

- Maintain/prolong: Repairs of the network infrastructure enable a longer life expectancy. As network components fail and fall into disrepair, defective parts are replaced. Network components, devices, and switches are the most commonly repaired (replaced) components. The repairs program replaces failed components using a mix of new and refurbished parts.
- Refurbish/remanufacture: Once network devices are decommissioned, they are sent back to the central hub. At the hub, network devices are dismantled and de-kitted to their usable components (CPU, mother-board, flash devices, hard disks, memory modules, and other components). After quality inspection, components are stored to be reused.
- Reuse/redistribute: Any excess component should be redistributed as determined by a periodic internal process. After utilizing all internal avenues, a procedure should be implemented to ensure that no proprietary technology resides on the components before selling on the secondary market.
- Recycle: The aim is to maximize the recycling of net-working material, including the electronic equipment, that leaves the data centers. Equipment that cannot be repaired/reused is sent to a recycling partner for secure processing and recycling into reusable materials.

4) *Technical Requirements*

The main technical requirements for applying the CE–IoT concept on the telecom domain are

- preservation of the scalability of network infrastructure and its interoperability with IoT platforms
- preservation of the privacy, confidentiality, and integrity of data in transit
- preservation of a high degree of network infrastructure and services availability.

B. *Proof of Concept*

As a proof of concept, the deployment of a 5G network infrastructure in the telecom domain is presented, using which we seek to investigate and evaluate the applicability and performance of the proposed CE–IoT framework. The defined LCA and CSPDI pattern-based approach is deployed to satisfy the CE requirements on different IoT-enabling technologies. More specifically, as presented in Figure 3, a 5G infrastructure includes a multidomain distribution of 5G-enabled network components aiming to offer fast, reliable, and trustworthy communication. The proof-of-concept evaluation of the proposed CE–IoT framework includes

- measuring the scalability and performance capabilities of the agent
- multidomain LCA monitoring to enable predictive circularity, that is, preserving CSPDI properties.

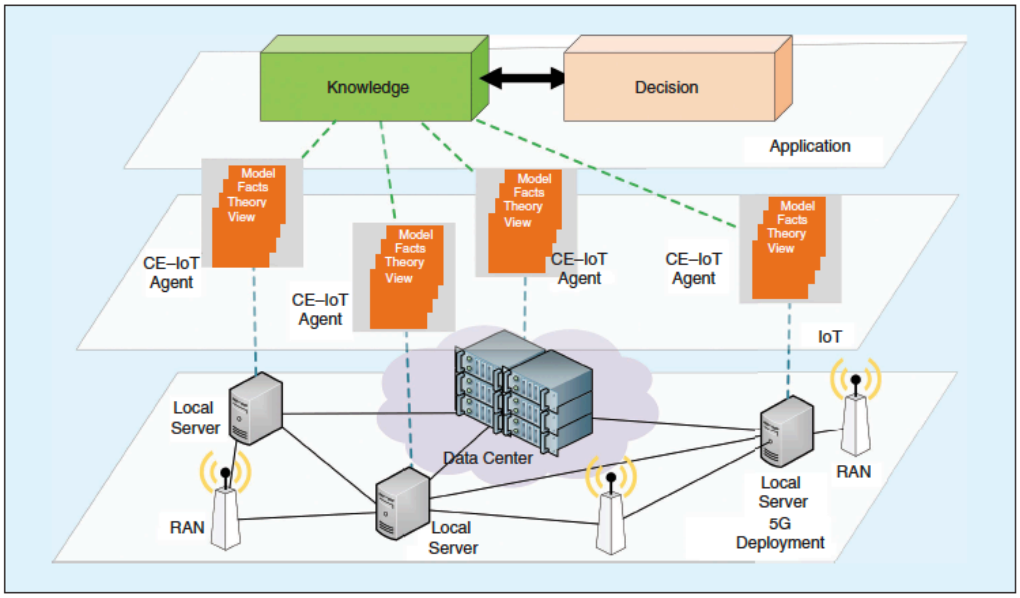

Figure 3. The proof-of-concept, deployed 5G scenario, including the CE–IoT agent. RAN: radio access network.

1) Scalability and Performance of the Agent

The core embedded intelligence agent was implemented and tested on LCA properties, adopting intelligent agent technologies. We utilized the Java Agent DEvelopment multiagent platform to implement the proposed function-ality on the various architectural layers. The platform supports all of the Foundation for Intelligent Physical Agents standards regarding agent development and the relevant technologies.

The agents are deployed at

- the more powerful IoT devices or gateways used for embedded intelligence
- the network controllers used for local analysis and enhanced connectivity over heterogeneous settings,
- the cloud, which is used for global management, big data analysis, and machine learning.

The agents collect data from the underlying system components, integrate them based on semantic technologies, exchange knowledge, and administrate their sub-systems based on the artificial intelligence processes derived from the LCA and CSPDI patterns. For this proof-of-concept setup, the smart agents model the LCA parameters of the system. The agents are aware of each component's physical location, operative condition, and availability (i.e., working, ready for reuse, or unusable). Figure 4 shows the agent's graphical user interface, four emulated components, and the triggering event (component C1 needs maintenance).

Concerning the scalability and performance of the agent, the computational complexity is linear to the working memory size and affected by the number of facts required in the modeling. In the examined scenario, each component requires roughly 10–20 facts to be modeled; therefore, in the initial proof-of-concept setup featuring four embedded devices (specifically, credit-card sized Beaglebone embedded systems) that communicate information to the master agent (running on a local computer), it takes, on average, 57 ms to perform a reasoning operation, while requiring 40 MB of random-access memory.

The performance evaluation can define the maximum number of network components and the number of processed facts that each agent can support. Moreover, when the number of network components is increased, more than one agent is required to support the LCA-monitoring network components. Thus, the number and the placement of agents is related to the number of monitored network components.

2) Multidomain LCA Monitoring That Enables Predictive Circularity

One of the most important aspects of the proof-of-con-cept CE–IoT framework evaluation is the multidomain and multiagent support of LCA monitoring and CSPDI guarantees that satisfy CE requirements. To achieve this goal, the CE–IoT LCA patterns are used as an enabler to establish these requirements. The LCA properties of the network components collected by the agents are transferred and stored as facts in the knowledge base of the pattern engine on the master agent. The enforcement of the LCA patterns can be used to enable CE principles (maintain, refurbish, reuse, recycle, and so on) in the described 5G network infrastructure.

As a proof of concept, the described scenario is implemented in the Eclipse Modeling Tool using the JBoss Drools (https://www.drools.org). The proposed patterns can be

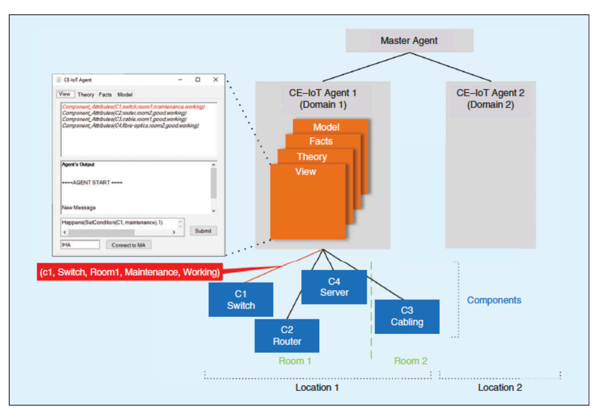

Figure 4. The proof-of-concept implementation of the core intelligent agent operating over LCA patterns.

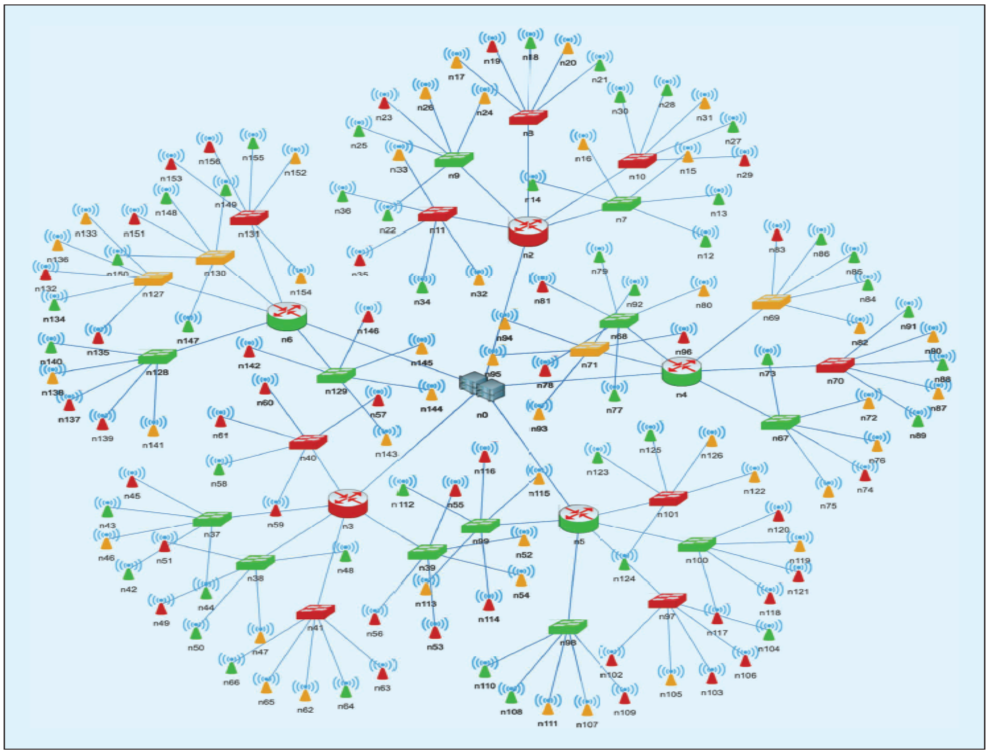

Figure 5. The deployment of a tree-network topology as an output of the LCA patterns.

expressed as Drools business-production rules and inserted in the rule engine. A Drools rule engine applies and extends the Rete algorithm, an efficient pattern-matching algorithm known to scale well for large numbers of rules and data sets of facts, thus allowing for an efficient implementation of the pattern-based reasoning process. Each network component is defined as a Java class corresponding to the components of the system.

A number of network components are deployed in 5G-enabled infrastructure where the LCA can be collected based on the multiagent approach proposed previously. To evaluate this approach, suitable, tree-based network topologies are created by the enforcement of additional architectural pattern rules [15]. The topology consists of a master node interconnected with a number of routers. Each router expresses a different domain, i.e., industrial, smart city, or home environment. In the tree topology, a number of SDN-enabled switches are connected to each router, and a number of access points are connected to each switch. Finally, apart from the lo-cation of the network components correlated with the domain, the condition and availability factors are added randomly.

To present the status of the network topology, a simulation based on Vis.js (https://visjs.org) was run. The output of the network simulator is presented in Figure 5. The different colors of the components (green, orange, and red) express the condition of the components (good, requiring repair/refurbishment, or recycle), and its availability factor (operating or usable) is added in the node properties and inserted in the knowledge base of the pattern engine.

The role of the LCA pattern is to identify the components that are not in good condition so that they can be replaced, moved, or fixed. More precisely, a CE approach for the network components is supported based on the following components' condition:

- The good condition component with operating-availability status will remain in its location.
- The repaired/refurbished condition component with operating-availability status will be replaced by a condition component in a usable-availability status placement in the network.
- Finally, the recycled-condition component will be replaced by a new component in good condition in the case of an operating-availability requirement or by a repaired/refurbished condition in the case of a usable-availability requirement.

To evaluate the performance of the LCA pattern, the topology presented in Figure 5 is used. The pat-tern monitors the location condition and the avail-ability of the components based on the agent data and identifies the required action to comply with a CE approach. When weak components are identified, the applied pattern proposes the relocation of unused or partially used components from other locations. In the event that existing components (after the relocation) are not able to cover the needs, the pattern application proposes the purchasing of new, necessary equipment.

The results of these steps are presented in Figure 6. The left-hand side of the chart shows the status of the network as produced by the monitoring pattern. The status of network after component relocation is presented in the center of the graph. Finally, the right-hand side of the graph shows, the purchase proposal used to cope with the network needs. Thus the use of the proposed LCA pattern-driven approach, its cost savings, and the reusability of existing components will enable the telecom operator to adopt a CE business model.

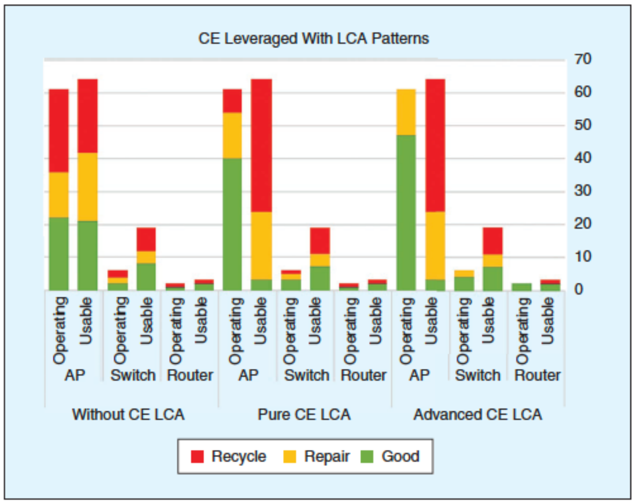

Figure 6. An evaluation of the developed LCA patterns enabling the CE–IoT concept. AP:access point.

IX. Conclusions

As highlighted by the CE, the extension of the useful life of finite resources and the maximization of asset utilization, creating a class of "looping assets," can reform and revitalize modern economies by focusing on the target of sustain-able change and growth. Impactful te chnolog ica l adva ncement s enabling the realization of the IoT, when coupled with the CE concept, can unleash their full potential at a faster pace. Many companies have already integrated IoT technologies into their operations, and IoT value drivers open a new window of opportunity on the economic cycle via a new class of circular business models. The interplay between a CE and the IoT stands out as a critical coupling in this evolutionary phase, and the congruency of the two sectors can provide a fertile ground for innovation and value creation, leading to the realization of the CE–IoT vision. Nevertheless, enabling this interplay will require the alignment of the business and techni-cal communities, policy makers, and citizens them-selves, ensuring that this IoT-driven transformation will remain focused on the urgent sustainability prob-lems to be solved.

The CE–IoT brings to the forefront another impor-tant challenge that needs to be addressed. The red tape associated with innovation-based investments and new technological advancements has always been a chal-lenge; therefore, the value drivers resulting from the merging of technologies with new concepts need to be facilitated using the necessary policy and legislative frameworks as well as targeted financing tools and mechanisms. A rapid deployment of the capabilities used to harvest the benefits and full potential of a data-driven economy is needed; this will create CE models that can enable a sustainable, restorative, and regenerative economy.

Concerning the implementation of the CE–IoT vi-sion, a proof of concept was explored using the CE–IoT

approach applied in the telecom operator sector. Moreover, work is underway that specifies the detailed architecture and implements the individual building blocks based on a clear set of requirements. When complete, the practicality of the developed solution will be validated using three diverse usage scenarios in the areas of renewable energy, health care, and a horizontal smart-sensing scenario. Finally, a future extension of the framework is also planned, using the integration of blockchain-based mechanisms to enable the transfer of asset ownership directly among participating CE par-ties by introducing trust, efficiency, and automation in asset-exchange contracts.

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