The Circular Digital Twin: Climate-Smart Soils as a Use Case

José Monteiro
University of Coimbra, CISUC, DEI
Coimbra, Portugal *jafmonteiro@dei.uc.pt*

João Barata
University of Coimbra, CISUC, DEI
Coimbra, Portugal *barata@dei.uc.pt*

Abstract

This paper presents a circular digital twin for climate-smart soils supported by a community composting network within a UNESCO Geopark site. The research addresses the challenges of water use management and organic matter optimization, with the dual objective of promoting sustainable land management practices and enhancing carbon sequestration. Following the design science research paradigm, we develop a circular digital twin architecture, which is then demonstrated and evaluated in terms of technical risk and efficacy, as well as human risk and effectiveness. This work advances the digital twin body of knowledge by presenting a solution that closes the loop of the food supply chain, improving soil management. For practitioners, our work provides an accessible and detailed demonstration and evaluation framework for digital twins in climate-smart soils, revealing how carbon sequestration can be deployed at a regional scale.

Keywords: digital twin, climate-smart soils, community composting, carbon sequestration, circular food supply chain.

1. Introduction

Soil degradation refers to the reduced capacity to support plant growth due to anthropogenic and natural causes, such as erosion, salinization, compaction, and contamination [20]. Environmental challenges arise because degraded soils lead to the loss of essential ecosystem services such as water filtration, carbon storage, and biodiversity conservation [18], reducing resilience and accelerating climate change. Degraded soils can lead to reduced agricultural yields [7], requiring fertilizers that increase production costs. The resulting decline in productivity threatens food security, potentially increasing prices and reducing access to food. These challenges underscore the need for new soil management practices that maintain soil health and productivity.

Climate-smart soils focus on adapting to and mitigating the negative impacts of climate change while improving soil health [19]. Composting is a way to promote them, using organic matter to increase carbon content, structure, and water-holding capacity [1]. Compost gradually releases nutrients, reducing the need for chemical fertilizers. Therefore, composting is a socio-economically viable practice that increases food security and reduces waste management costs by using local resources and involving community members [33]. Climate-smart soils supported by community composting offer a holistic approach to creating more resilient and circular food supply chains by (1) providing a destination for food waste and (2) enhancing carbon sequestration.

The dynamic nature of the soil ecosystem and the overarching goal of achieving a circular food supply chain require advanced monitoring and management solutions. Defined as a digital replica of physical entities, a digital twin enables real-time tracking, analysis, and optimization of specific objects or systems [26]. Paustian et al. [19] emphasize the importance of *"expanding measurement and monitoring networks"* and taking advantage of *"ongoing advances in information technology."* Using digital twins, stakeholders, from local farmers to policymakers, can access a comprehensive view of soil health and the effectiveness of implemented practices. This integration provides a platform for crowdsourcing local knowledge, improving predictive models to make climate-smart soils a reality.

This paper presents a Design Science Research (DSR) project [11] carried out in the Estrela UNESCO Global Geopark (Estrela Geopark). The GEOfood Manifesto, explicitly created for UNESCO Global Geoparks, aims to address the challenges of food production in protected areas of geological interest [8]. Climate-smart soils and community composting are both integral to these principles. On the one hand, climate-smart soils help to improve soil health based on local conditions, optimizing the natural resources specific to a region's geology and climate. On the other hand, community composting focuses on using organic waste to rejuvenate these soils, reducing waste and transport distances while resonating with local identity and sustainability principles. The need to adopt GEOfood principles in Estrela Geopark is the starting point for our research, focusing on the dynamics of return and source links of the food supply chain. Therefore, two Research Objectives (RO) are formulated:

- ***RO1:*** *Investigate the interdependencies between different segments of the food supply chain (return and source), offering the foundations for a circular digital twin.*
- ***RO2:*** *Design and evaluate a circular digital twin to continuously monitor and track the implementation of the GEOfood in Estrela Geopark, closing the loop of food waste and incorporation into climate-smart soils.*

The rest of this paper is structured as follows: Section 2 presents the theoretical foundations for our work, followed by the research approach in Section 3. Next, Section 4 details the design and development of the circular digital twin. Subsequently, the demonstration (Section 5) and an evaluation (Section 6) are explained. Design principles for circular digital twins are included in Section 7, and the paper closes in Section 8, summarizing the main conclusions and future work opportunities.

2. Theoretical Background

Digital twins are digital replicas of physical objects or systems that enable real-time monitoring, analysis, and optimization. According to Raj and Surianarayanan [26], digital twins use real-world data to generate output that reflects the system's current state, providing a robust basis for informed and predictive decision-making. The application of digital twins has been expanded to several areas, including manufacturing, healthcare, and, more recently, smart agriculture [13].

Paustian et al. [19] highlight the importance of strategies that increase the soil's carbon content and improve its water retention capacity. Community composting is a recognized practice that contributes significantly to these goals, providing the return of organic matter to the soil and reducing the need for chemical fertilizers [1]. Studies indicate that it improves soil health, reduces waste management costs, and increases food security [2].

Several authors have explored the application of digital twins in agricultural contexts. For example, Khatraty et al. [14] developed a digital twin for irrigation management in rice plantations, demonstrating significant improvements in water use efficiency. Similarly, Madeira et al. [15] presented a digital twin for monitoring soil health in vineyards, showing crop production and sustainability increases. Moreover, Prieto-Sandoval et al. [25] state that integrating circular economy concepts into agricultural systems can transform how resources are managed, ensuring long-term sustainability. Implementing a circular digital twin is an important step toward operationalizing circular economy principles in agricultural systems.

The scientific literature confirms the importance of digital twins in agriculture and the lack of studies explaining how the technology can support climate-smart soils initiatives at a regional scale.

3. Research Approach

DSR aims to develop and evaluate novel artifacts that address real-world problems [11], generating knowledge through design [10, 16]. The DSR approach adopted in this paper is developed in six phases: (1) problem identification and motivation, (2) setting goals for a solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication [21]. Table 1 summarizes our DSR.

Table 1. DSR grid [3] for the circular digital twin design.

Problem	**Research Process**	**Solution**
Insufficient community-focused IS for optimizing climate-smart soil management	A phased DSR research process [18] that includes problem identification, design and development, demonstration, and thorough socio-technical evaluation [31]	A circular digital twin for climate-smart soil, including support for community composting
Input Knowledge	**Concepts**	**Output Knowledge**
2030 Agenda [2], European Green Deal [6], Farm to Fork [5], GEOfood [8], Smart regions [17]	Digital twin [26], Climate-smart soil [19], Carbon sequestration [18], Community composting [1], Circular economy [25]	Design principles for the development of circular digital twins

Estrela Geopark is one of the 177 UNESCO Global Geoparks. Located in the central region of Portugal, this Geopark covers an area of 221,600 ha through nine municipalities around Serra da Estrela [32]. Agricultural land occupies ~1.93% of the Estrela Geopark territory, consisting of 9,324 farms, of which ~24.47% are business-related [22, 23]. Agriculture significantly impacts the region, representing ~11.13% of the total number of companies. There are 1,909 agricultural enterprises in the region with a total turnover of 60.345 million euros (~1.93%). In addition, agriculture employs ~2,550 people, which is ~5.87% of the total employment in the Geopark region [23, 24].

Estrela Geopark became part of the GEOfood brand in 2020 and currently involves five GEOfood farmers. They cultivate crops such as aromatic herbs, teas, pears, wine, and olive oils and grow them on plots ranging from a few square meters to over 60 ha. The Geopark managers have expressed interest in digital twin solutions, which aim to help monitor compliance with sustainable development policies, promote the region's growth, and support local communities.

The evaluation of our DSR followed the FEDS framework, which consists of four steps: *"(1) explicate the goals of the evaluation, (2) choose the evaluation strategy or strategies, (3) determine the properties to evaluate, and (4) design the individual evaluation episode(s)"* [31]. In this paper, we used the ISO/IEC 25010:2011 standard to assess the technical risk and efficacy. In addition, we examined the environmental impact, economic viability, and social responsibility with a focus on human risk and effectiveness assessment.

4. Design and Development

4.1. Design

The circular digital twin proposed in this DSR aims to explore the relationships between return (food waste) and source (soil compost) links in the food supply chain while providing mechanisms to help the Estrela Geopark experts monitor and follow the development of GEOfood in their territory. Figure 1 models in UML the different devices and actors in the information system development and their relationships.

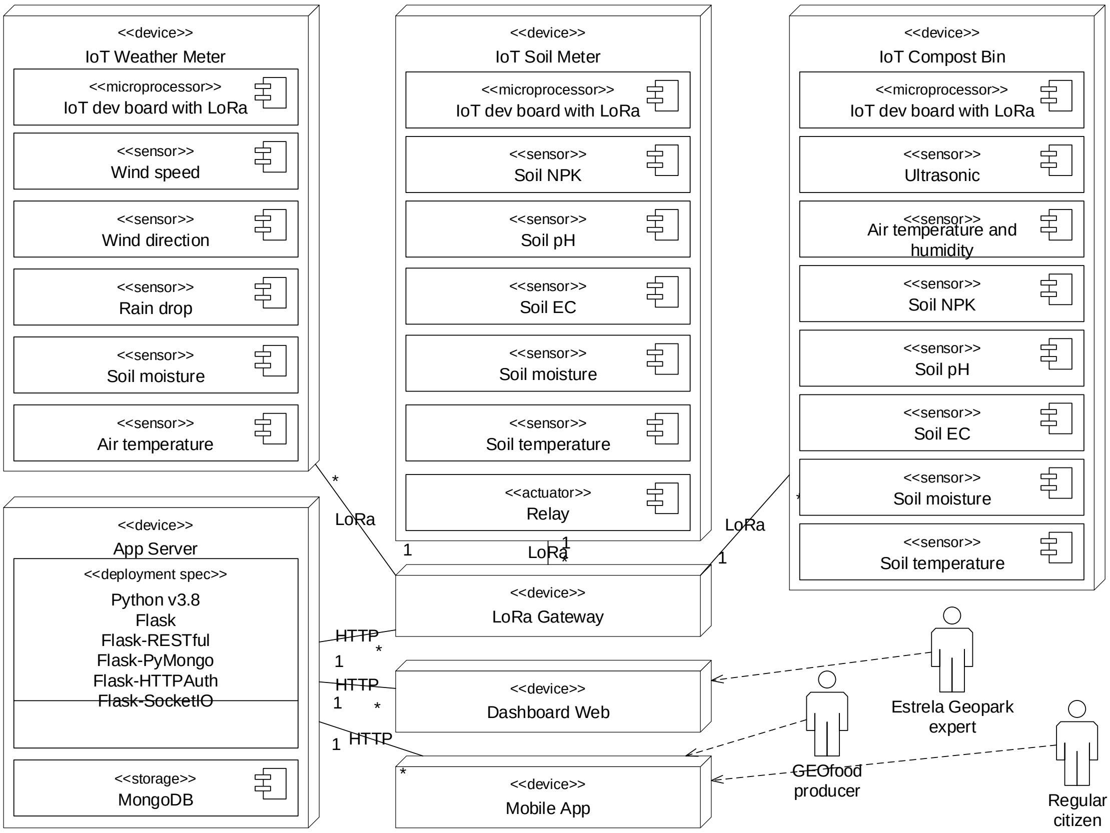

Fig. 1. UML deployment diagram (Source: Authors own work).

The technical layer of the digital twin consists of an IoT infrastructure (IoT Weather Meters, IoT Compost Bins, IoT Soil Meters, and LoRa Gateways), an application server, a web dashboard, and a mobile application. The IoT infrastructure, in turn, integrates two different categories of devices: (1) *community*, consisting of the IoT Weather Meters and IoT Compost Bins deployed and maintained by the Estrela Geopark throughout its territory to produce open data available to all stakeholders in the regional food supply chain; and (2) *proprietary*, consisting of the IoT Soil Meters owned by GEOfood producers to monitor the health of the soil and their farmland.

The system's modular architecture was selected to ensure the digital twin's scalability and adaptability to different regional scenarios. Integration with the LoRaWAN network enables long-distance communication with low power consumption, which is essential for rural areas with limited network coverage.

4.2. Development

The IoT Soil Meters use the JXCT Integrated Sensor to collect various parameters related to the quality and health of the soil, namely the amounts of nitrogen, phosphorus, and potassium (NPK - three primary nutrients for plants), pH, electrical conductivity, temperature, and soil moisture. This sensor communicates its data via RS485, which requires a Modbus module (MAX458) to facilitate the interface with the microcontroller (Arduino MKR WAN 1310). The IoT Weather Meters are community devices that use the Sparkfun Weather Meter Kit to monitor various meteorological parameters, such as wind speed and direction, rainfall, soil moisture, and atmospheric temperature and humidity. Another community device is the IoT Compost Bin, which monitors the community composting network set up in the Estrela Geopark, including the loading level of the compost bin, the state of the compost heap, and the factors that promote composting. The data collected by the IoT devices (IoT Soil Meters, IoT Weather Meters and IoT Compost Bins) is transmitted via LoRa to LoRaWAN Gateways (Dragino

LG308N) and then forwarded to the application server via The Things Network (TTN) cloud, which means that the gateways and end devices must be first registered in this open LoRaWAN network, which will act as an MQTT server.

The application server was developed using Flask, a Python microframework, where we implemented a REST API (Flask-RESTful) to facilitate data exchange in a secure, scalable, and flexible way. The data collected by the IoT infrastructure is retrieved via an MQTT client (Flask-MQTT) connected to the TTN cloud and stored in a non-relational MongoDB database (Flask-PyMongo). In addition, the server communicates the collected data to the web dashboard and mobile application in real-time using Flask-SocketIO. Flask framework was selected for its lightness, flexibility, and scalability, which are crucial for processing large volumes of data in real-time.

The mobile application serves two main actors: citizens and GEOfood producers. Through this application, citizens can access the community composting network, where the user can locate the nearest compost bin to their location and see the route to get there. In addition, the mobile application allows citizens to monitor the amount of biowaste they have "recycled," as well as estimate their carbon footprint reduction and contribution to adopting sustainable practices in the region. The mobile application also provides mechanisms to help GEOfood producers manage their farms, from land and production management to planning and advice on irrigation and fertilization. The farm management module allows for managing farmland and IoT devices, which can be registered by scanning a QR code inside the device's housing. GEOfood producers can associate one or more crops with a plot of land and indicate which IoT devices are used to monitor soil quality and health in real-time. In addition, the mobile application provides decision support mechanisms that allow GEOfood producers to plan crop irrigation and advise when to fertilize their land. These informed decision support mechanisms use data collected by the IoT infrastructure and external data (e.g., weather forecasts via AccuWeather API). The web dashboard is the main mechanism available to Estrela Geopark's experts (local policymakers and research institutions) to monitor and follow up on the implementation of the GEOfood brand in their territory and the compliance of certified producers with the standards.

The fertilizer advice mechanism is based on the digitalization of the soil fertility assessment process commonly used in agricultural science. The main indicators of soil fertility (pH, concentrations of macro-, micro-nutrients, and potentially toxic elements) are collected by the IoT Soil Meters, and knowing the specific nutrient needs of the crop to be produced, the system calculates the units of fertilizer required. This determination can be expressed mathematically by Equation 1 [27]:

$$\text{Compost Quantity} = \frac{(\text{Required Nutrients} - \text{Land Nutrients}) \times \text{Land Area}}{\text{Compost Nutrients}} \qquad (1)$$

For example, if a farmer wants to produce a crop with a N requirement of 150 kg/ha, the current soil N level is 50 kg/ha, and the fertilizer contains 20% N, the farmer must apply 500 kg/ha of fertilizer to supply the remaining 100 kg of N (100 ÷ 0.2 = 500). In addition, the recommendations for the fertilizer to be applied are also based on the production stage of a given crop, i.e. during the sowing stage, we will preferably recommend the use of natural fertilizers (such as composts that can be obtained from the community composting network, specifically indicating which composter has the best compost for the soil and crop to be produced) or after, sowing the use of mineral fertilizers as a reinforcement. It is important to remember that natural fertilizers take 120-130 days to be "digested" by the soil, whereas mineral fertilizers take 7-14 days.

The amount of carbon sequestered in the soil is also estimated using the data collected by the IoT Soil Meters and multiplying the organic matter by a conservation factor (Equation 2), typically around 0.58, which assumes that 58% of the organic matter is carbon. In a scenario where the organic matter content of the soil is 4%, the organic matter content would be 4 × 0.58 = 2.32%. The amount of carbon sequestered is the product of organic carbon content, soil density, and field area (Equation 3) [4].

$$\text{Organic Carbon Content} = \text{Organic Matter} \times \text{Conversion Factor} \quad (2)$$
$$\text{Soil Carbon} = \text{Organic Carbon Content} \times \text{Soil Bunk Density} \times \text{Field Area} \quad (3)$$

This section presented the design and development of the circular digital twin for climate-smart soils. The following section instantiates the solution with field examples.

5. Demonstration

The mobile application provides the main mechanism for GEOfood producers and regular citizens to interact with the regional community composting network (for both users) and climate-smart (for GEOfood producers only). Figure 2 shows the main screens of the mobile application.

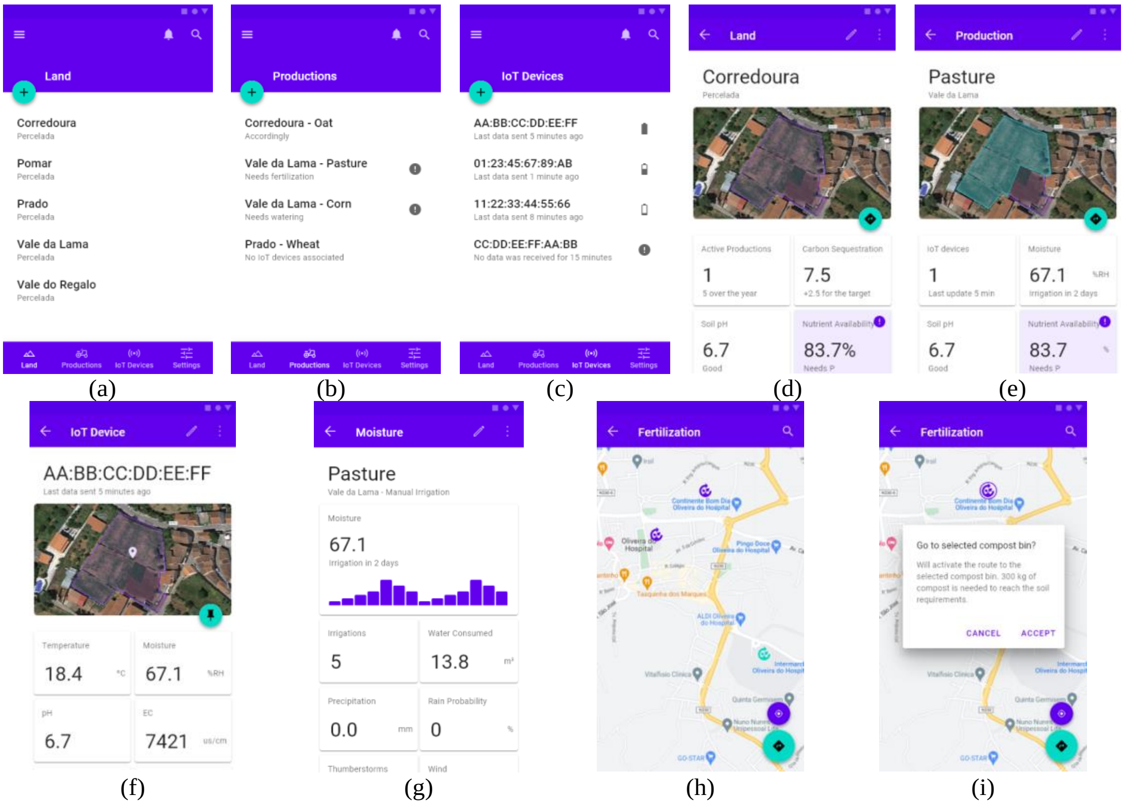

Fig. 2. Mobile application prototype (Source: Authors own work).

The first three screens (Figure 2a-c) list land, production, and IoT devices, with contextual information, such as the location of land and production needs, the battery charge, and the latest data sent by the IoT devices. Each screen has a float action button (FAB) for creating a resource (land, production, or IoT device). Clicking on an item in the list displays the details of the selected resources (Figure 2d-f), allowing the data to be viewed and manipulated. Each card displays a relevant attribute and potential alerts. Clicking on a card displays more detailed information (Figure 3g). The final two screens (Figure 2h-i) allow GEOfood producers to locate the compost bins with the most appropriate compost for their soil needs (Figure 2d-e). These screens have two FABs: the blue one points to the current location, while the green one shows directions to the selected compost bin according to the GPS location of the mobile device. Figures 4 and 5 show the web dashboard.

Figure 3 shows a region map, combining information from the regional community composting network and weather stations (community IoT devices). On the right is a three-dimensional representation of the selected compost bin, with a map showing contextual information (location, state of the compost pile, temperature, pH, and composition). On the map, a cloud represents the IoT Weather Meters, and a plant surrounded by a circular arrow represents the IoT Compost Bins. The color of the IoT Compost Bins icons also provides contextual information, with blue indicating fully functional compost bins and yellow indicating those with problems. The second screen of the web dashboard (Figure 4) focuses on a selected IoT Compost Bin and integrates information about community composting, carbon sequestration and farms (climate-smart soils). The map shows the agricultural land that uses the compost generated by the selected IoT Compost Bin. The thickness of the line connecting the IoT Compost Bin to the climate-smart soil indicates its use, while the color of the land indicates the amount of carbon sequestered. Red, yellow and green represent plots with low, medium and high levels of carbon sequestered by the climate-smart soil respectively.

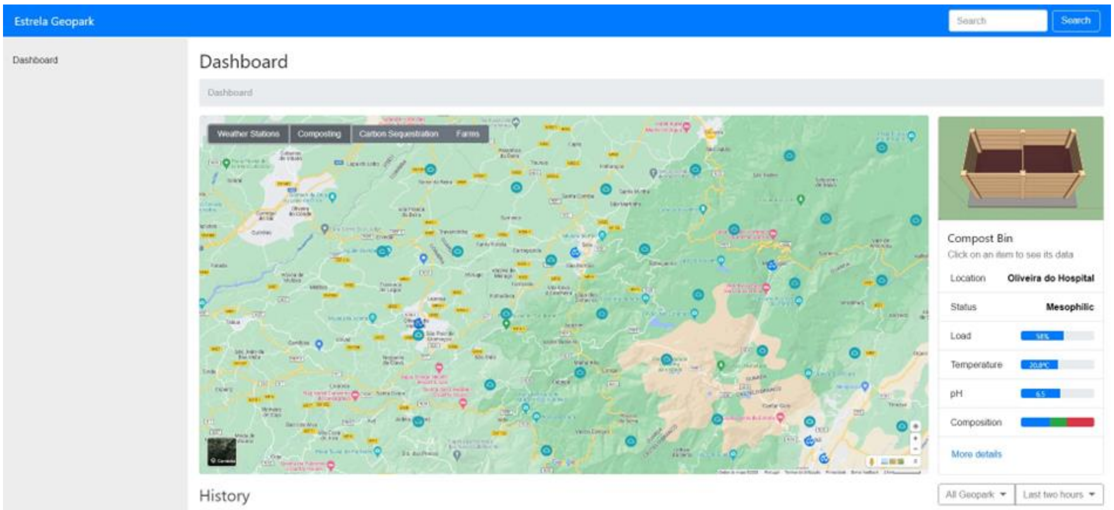

Fig. 3. Web dashboard: region's IoT Weather Meters and IoT Compost Bins (Source: Authors own work).

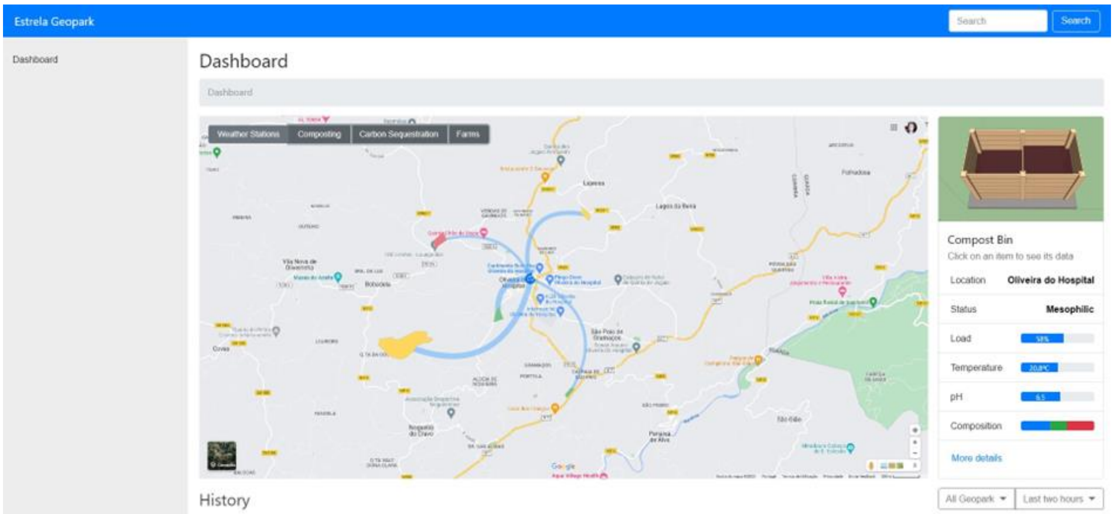

Fig. 4. Web dashboard: municipality's compost bin, farms, and carbon footprint (Source: Authors own work).

Figure 5 details the deployment of IoT infrastructure: (a) IoT Compost Bin; (b) IoT Weather Meter; (c) IoT Soil Meter; and (d) autonomous irrigation system.

(a) (b) (c) (d)

Fig. 5. Circular digital twin IoT infrastructure (Source: Authors own work).

6. Evaluation

Our evaluation is formative (ex-ante) and naturalistic based on the two-dimensional characterization proposed by Venable et al. [31]. It aims to assess three primary aspects: (1) the efficacy and effectiveness of the artifact; (2) the impact of the artifact's instantiation; and (3) the resources required to instantiate the artifact. Technical Risk and Efficacy and Human Risk and Effectiveness [31] were considered critical by the research team. Our selection is motivated by the novelty of the circular digital twin. Table 2 shows the criteria and sub-criteria used in the DSR evaluation process.

Table 2. Evaluation criteria.

Evaluation	Criteria
Technical Risk and Efficacy [12]	*Functional sustainability:* functional completeness; functional correctness; functional appropriateness. *Performance efficiency:* time behavior; resource utilization; capacity. *Usability:* appropriateness recognizability; learnability; operability; user error protection; user interface aesthetics; accessibility. *Reliability:* maturity; availability; fault tolerance; recoverability. *Security:* confidentiality; integrity; non-repudiation; authenticity; accountability. *Maintainability:* modularity; reusability; analyzability; modifiability; testability. *Portability:* adaptability; installability; replaceability.
Human Risk and Effectiveness [28]	*Human sustainability:* nutrition, shelter, clothes; education, health, means of transportation and communication, safety; belongingness, creativity, identity, autonomy, spirituality; togetherness, participation; self-fulfillment; realization of potential. *Social sustainability:* social norms, community cohesion for mutual benefit; connectedness between groups of people; cultural plurality; solidarity; tolerance, respect, compassion, patience, and honesty; discipline; commonly shared rules, laws, and information; equity across gender, age, religions; human rights; peace; participation in decision-making about planned interventions that affect people's lives; justice, accountability, politics; self-reliance/dependency (specifically mobilization of communities, local ownership in decision making, commitment of local resources). *Economic sustainability:* economic benefits to impactees and stakeholders; reduced need for external assistance; allocation of financial resources; efficiency; scale of consumption; preventive anticipation; cost-effectiveness under considerations of unduly costs; paying for past ecological debt; optimizing productivity; use of human, natural and financial capital. *Environmental sustainability:* water, land, air, minerals, ecosystem services; environmental soundness of the intervention, its intended and unintended outcomes and impacts; waste emissions within the assimilative capability of the environment without damaging it; ecological balance and biodiversity; balance in consumption/recycling of resources; disaster risk reduction; irreversible loss of biodiversity, habitat, ecosystem.

6.1. Technical Risk and Efficacy Evaluation

The ISO/IEC 25010:2011 standard provides an adaptable framework for digital twin quality, outlining eight primary characteristics subsequently evaluated:

- *Functional suitability:* Consultations with Geopark experts and local food producers confirm the adequacy of the implemented features. The prototype has achieved functional completeness and correctness but is not yet implemented in the region.
- *Performance efficiency:* Three attributes define this criterion: time behavior, resource utilization, and capacity. Data is collected and transmitted every 15 minutes. Arduino microcontrollers, adapted to the task requirements, measure resource usage. Each device produces less than 2 MB of data per year, and energy efficiency strategies extend battery life between 109 and 180 days.
- *Compatibility:* The integrated solution includes IoT devices, a web dashboard, and a mobile application. Interoperability is achieved through the AccuWeather API. Although promising for the Estrela Geopark region, careful analysis is essential for deployment in different Geopark areas due to unique regional characteristics.
- *Usability:* Material Design and Bootstrap guidelines were used for the mobile and web interfaces, respectively. The user feedback verifies the attractiveness, error tolerance, and user support. Usability extends to the hardware, where the user's primary interaction is with the IoT device's protective enclosure
- *Reliability:* The digital twin is at the Technological Readiness Level (TRL) 5

(prototype validation in a relevant environment) and incorporates fault-tolerant mechanisms. Anomalies are detected using data triangulation, and the system prevents unauthorized data deletion, allowing data recovery. Business continuity is ensured despite occasional restarts of IoT devices.
- *Security:* Security measures include confidentiality, integrity, authenticity, and accountability (Flask-Security). However, physical security remains a challenge and is addressed by potential solutions such as device locks and location sensors.
- *Maintainability:* Based on ISO 25010:2011, the modular design of the system adapts to different regional scenarios. The system can self-diagnose and optimize performance, and administrators receive alerts for maintenance needs.
- *Portability:* Our solution has been developed primarily for the Estrela Geopark. The demonstration can help other GEOfood members evaluate how digital twins support the incorporation of food waste into their soils.

6.2. Human Risk and Effectiveness Evaluation

We used Schroeter [28]'s Sustainable Evaluation Checklist, focusing on:

- *Human sustainability:* The transition to a sustainable food system can be facilitated with digital twins, ensuring food security (traceability), health (minimizing the use of chemical fertilizers), and regional resilience by increasing the use of local resources and the control over food production in GEOfood. The community composting network also strengthens the link between urban (food waste producers) and rural areas (carbon sequestration), further reinforcing regional identity.
- *Social sustainability:* Our research can help Estrela Geopark professionals monitor compliance with GEOfood. It provides accurate information to decision makers.
- *Economic sustainability:* An investment of ~84,436.89€ is required for hardware and the initial regional deployment. The detailed cost breakdown includes 72,628.89€ for IoT infrastructure (21 IoT Compost Bins, 29 IoT Weather Meters, 61 IoT Soil Meters, and 29 LoRaWAN Gateways) and 11,808€ for additional costs for equipment installation and other services. The total does not include specific development, training, and maintenance costs, which are estimated at ~45% of the total. Revenues are primarily from savings in fertilizer purchases.
- *Environmental sustainability:* The IoT devices have different energy consumption and carbon footprints (e.g., each IoT Soil Meters consumes 500-550 mWh and generates 1.296 kg CO_2). However, IoT Weather Meters and LoRa Gateways are solar-powered, making them environmentally friendly. The research team estimates an annual sequestration of 419 tons of CO_2. IoT applications in agriculture have already shown positive water savings [29]. Although most of the region's biowaste is recycled, 10,000 tons end up in landfills, causing environmental impact. The composting system can convert some of this value into reusable compost, potentially reducing CO_2 emissions by 461 to 922 tons per year.

The evaluation, carried out in cooperation with experts from the Estrela Geopark association, did not identify relevant human risks. However, the effectiveness results must be interpreted cautiously as they are based on estimates from a prototype that has not yet been deployed across the entire region.

7. Theory Building

According to Gregor and Hevner [10], *"when the design is complex in terms of the size of the artifact and the number of components (social and technical), then explicit extraction of design principles may be needed"*. Five design principles were derived for the creation of circular digital twins, following the guidelines of Gregor et al. [9] (*"DP Name: For Implementer I to achieve or allow for Aim A for Use U in Context C, employ Mechanisms M1, M2, …, Mn involving Enactors E1, E2, …, En because of Rationale R."*):

- ***DP1: Comprehensive data integration.*** For *developers* to achieve *real-time monitoring and prediction* for *stakeholders* in *Estrela Geopark and similar protected regions*, employ *real-time data collection tools and advanced analytics* involving *sensors, satellite data, and community-generated data sources* because of *the need to provide a holistic view of the current state of climate-smart soils, community composting, and food supply chain dynamics*.
- ***DP2: Circular supply chain visualization.*** For *interface designers* to achieve *visual mapping of return and source links* for *supply chain managers* in *protected regions with unique brands*, employ *graphical representations, flow diagrams, and intuitive dashboards* involving *GIS tools, interactive charts, and 3D models* because of *the importance of understanding the circular nature of resource flows and material loops*.
- ***DP3: GEOfood implementation monitoring.*** For *brand managers* to allow for *consistent adherence to GEOfood principles* for *consumers and producers* in *Estrela Geopark*, employ *brand tracking, audit systems, and feedback loops* involving *QR codes, user reviews, and supply chain metadata* because of *the necessity to ensure brand integrity and authenticity in a protected region*.
- ***DP4: Adaptive learning and simulation.*** For *software engineers* to allow for *predictive insights and scenario planning* for *policymakers and farm managers* in *regions like Geoparks*, employ *simulation tools, and historical data analyzes* involving *climate data, soil health metrics, and community composting outputs* because of *the need anticipate challenges, optimize resource use, and promote sustainable practices*.
- ***DP5: Community and stakeholder engagement.*** For *community managers* to allow for *inclusive decision-making* for *local residents and businesses* in *Estrela Geopark and similar regions*, employ *feedback platforms, interactive workshops, and collaborative tools* involving *mobile apps, web portals, and local community centers* because of *the importance of harnessing local knowledge, ensuring transparency, and fostering community ownership of sustainable initiatives*.

These design principles have led us to explore the connection between the circular economy and digital twins. Prieto-Sandoval et al. [25] argue that this connection represents a fundamental shift "*in the way human society is interrelated with nature*". Following these findings from our research and expanding the definition of circular economy [25] and digital twin [26], we define a circular digital twin as: *a computational model that incorporates real-world data from physical systems or objects focusing on their relationship with nature and resource dynamics, simulating and predicting how these systems or objects interact within a cyclical and regenerative lifecycle. The main aim is to prevent resource depletion, close energy and material loops, and promote sustainable development at micro, meso, and macro levels*.

8. Conclusions

This paper presented a DSR cycle aiming to design a circular digital twin for a UNESCO Geopark. Climate-smart soils provided the setting to demonstrate how circular digital twins can be deployed. Moreover, a definition of circular digital twins is proposed, and five design principles are suggested for regional-scale circular digital twins.

Future sustainable agriculture schemes, such as GEOfood, must be transparent in their impact to policymakers and provide tangible economic incentives to local producers. In addition, it is essential to create synergies in different segments of food supply chains to enable circular practices. Our work identifies these synergies at two critical points: (1) the final segment of food waste management and (2) the early stage of precision soil feeding. Their integration would not be possible without the use of circular digital twin capabilities.

8.1. Study Limitations

Several limitations must be acknowledged. First, the regional specificities of a UNESCO Geopark and the priorities of the GEOfood Manifesto. In the selected case, the typology of regional food and the coexistence of urban and rural areas allow the inclusion of compost in the supply chain. Second, the success of our proposal relies on the collaboration between local authorities (e.g., maintenance of compost bins and IoT infrastructure) and local associations (e.g., creation of a sustainable ecosystem for local farmers), which may be difficult to replicate in other regions. Third, although we have provided a detailed presentation of the physical and digital layers of the circular digital twin and conducted an in-depth evaluation, it has not been deployed across the region. The results were obtained in a more controlled environment (selected farmers and specific compost bin locations), limiting the findings' generalizability. Longitudinal studies are needed to confirm system adherence and the long-term impact of the sustainability indicators. Despite these limitations, the strengths of our research lie in the scalability, adaptability, and effectiveness of the circular digital twin for zero km food and circular economy goals (part of the GEOfood strategy).

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