A Heritage Digital Twin for Serra da Estrela Cheese Production

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Abstract

This paper presents the design of a heritage digital twin of the Serra da Estrela cheesemaking process. The proposed solution integrates traditional knowledge with digital capabilities to ensure the preservation and sustainable practices of this intangible cultural heritage. Design science research is the selected approach to create a digital replica of the cheesemaking process, refined through iterative design and development phases, stakeholder interviews, and field demonstrations. The findings reveal that a heritage digital twin enables (1) memorization of local practices, (2) real-time monitoring and decision support, and (3) audit traces. It upholds traditional methods while enhancing resource efficiency and compliance with health standards. This work pioneers the application of digital twins to the cultural heritage of local food production, adhering to the requirements of protected designation of origin.

Keywords: digital twin, intangible cultural heritage, Serra da Estrela cheese.

1. Introduction

As defined by UNESCO [28], intangible cultural heritage refers to the practices, representations, expressions, knowledge, and skills that communities, groups, and, in some cases, individuals recognize as part of their cultural heritage. It includes traditions and living expressions inherited from ancestors and passed on to descendants. The preservation and digitalization of intangible cultural heritage received a boost with the emergence of Industry 5.0 [22]. However, despite the rapid development of digital technologies, the complexity of capturing, preserving, and transmitting the essence of cultural practices, knowledge, and expressions requires innovative approaches [9], [26]. The digital transformation of the artisanal production of Serra da Estrela cheese, a culturally significant practice proposed for inclusion in UNESCO's Intangible Cultural Heritage of Humanity, exemplifies these challenges. This process not only embodies centuries-old traditions but also encapsulates the socio-economic fabric and ecological wisdom of the region that needs to be preserved and improved [13].

Digital Twins (DTs), defined as digital replicas of physical entities or processes that allow for simulation, analysis, and optimization in a virtual environment [27], have entered the agenda of cultural heritage protection. DTs provide an innovative approach to ensure digital memorization [21], process validation [35], and resource optimization [25]. However, the adoption of DTs to intangible cultural heritage is only now appearing in the literature; most of the studies are conceptual, and none address the case of food products with protected designation of origin.

Design Science Research (DSR) [10] was selected to (RO1) *design and evaluate a* *heritage digital twin for the traditional production of Serra da Estrela cheese*, in collaboration with an artisanal cheese dairy located in the Estrela UNESCO Global Geopark (Estrela Geopark). Their motivation for this research stems from two needs: (1) to preserve the dwindling knowledge and practices of traditional cheesemaking in the Serra da Estrela region [13], and (2) to use digital innovation to ensure the sustainability and resilience of local production [34]. Therefore, our work also aims to (RO2) *validate the production process's compliance with traditional practices* and (RO3) *understand how DTs can be used to optimize resources for the sustainability and resilience of the cheese supply chain*. The integration of DTs in preserving intangible cultural heritage can bridge the gap between artisanal knowledge and digital capabilities [33].

The remainder of this article is structured as follows: Section 2 presents essential concepts on DTs and their potential applications. Section 3 describes the research approach. Next, Section 4 includes the results and discussion, covering design and development, demonstration, evaluation, and design principles. The conclusion is summarized in Section 5, including the limitations and suggestions for future research.

2. Background

2.1. Digital Twins in Smart Manufacturing

The advent of DTs marks a transformative phase in manufacturing, harnessing the power of digital replication and intelligent automation [27]. A DT is a dynamic, digital replica of a physical entity or process [17], [27]. Historically, the concept of DTs emerged from the aerospace and defense industries [8] in the early 2000s and has gradually evolved to become a central part of smart manufacturing strategies [6].

Recent studies underline the significant role of DTs in improving smart manufacturing. For example, Li et al. [15] discuss their usefulness in facilitating green performance assessment in manufacturing. DTs have the potential to revolutionize manufacturing [18] and be integrated with machine learning and 5G networks, focusing on the challenges and opportunities for industrial processes [1].

Different sectors of the economy are adopting DTs, including the food supply chain and Industry 5.0. Gallego-García et al. [7] explore the use of DTs to increase the resilience of smallholder farmers, highlighting the technology's potential to optimize agricultural supply chains and improve sustainability. Melesse et al. [20] demonstrate the use of DTs to monitor fruit quality, reduce waste, and improve the efficiency of the food supply chain. Furthermore, the emergence of Industry 5.0 has led to novel applications of DTs, such as the development of human digital twins by Wang et al. [31] to prioritize human-centric manufacturing systems and the proposal of a blockchain-secured smart contract system for decentralized autonomous manufacturing systems [14].

DTs enable simulations, predictive maintenance, and optimized decision-making. Their applications range from improving the environmental sustainability of manufacturing processes to increasing the resilience of the food supply chain to fostering human-centric manufacturing systems in Industry 5.0. DTs are at the forefront of advancing smart manufacturing practices. However, their application in traditional sectors of the economy, like artisanal production, is still limited.

2.2. Digital Twin in Intangible Cultural Heritage

The study of DTs in intangible cultural heritage is starting [33]. Searches of the most significant scientific databases – Scopus and Web of Science – reveal a modest body of literature, with only five and three results, respectively, when combining DT and intangible cultural heritage. This scarcity underlines the novelty of the topic and the significant potential for groundbreaking research and development in this area.

A literature review on DTs applied to cultural heritage suggests a growing interest in using them for cultural preservation. Dang et al. [5] detail the application of DTs to Chinese cultural world heritage sites, highlighting their data acquisition and visualization affordances. Vuoto et al. [30] show how DTs can be adopted in the architecture, engineering, construction, and operation sectors, particularly for conserving built cultural heritage, and advocate enhanced performance-based management strategies. Niccolucci et al. [23] discuss the development of a heritage DT ontology, which aims to create the knowledge base for the cultural heritage data space and demonstrate the potential of the technology for a holistic approach to cultural heritage conservation.

Focusing on intangible cultural heritage, Li et al. [16] demonstrate DT use for the dynamic transfer of handmade intangible cultural heritage, using the Yangxin Cloth Paste of East Hubei Province (China) as a case study. Banfi et al. [3] investigate the management of Lamalunga Cave (Italy) using DTs, photogrammetry, and laser scanning to preserve the site's microclimate and paleontological remains. Wang and Lau [32] propose a digital strategy to preserve Miao silver jewelry (China), extending the commercial value and lifespan of traditional handicrafts. Shi et al. [25] explore the application of DTs to the preservation and digital dissemination of Mongolian dressing gowns, demonstrating the use of 3D scanning and simulation technologies to protect traditional clothing practices. These examples, although not focusing on food, prove the potential of DTs for intangible heritage preservation and improvement.

The application of DT to intangible cultural heritage is an exciting opportunity for the preservation and dynamic transmission of cultural traditions. By creating digital replicas of cultural practices, skills, and knowledge, DT can facilitate the visualization, understanding, and engagement with intangible cultural heritage and offer innovative solutions for its protection. DTs also increase accessibility, allowing future generations to explore and learn from human heritage. Nevertheless, we could not find studies proposing heritage DT for ancillary food production.

3. Research Approach

DSR is a problem-solving paradigm that involves the creation and evaluation of artifacts designed to address a specific problem [12]. DSR is particularly suited to disciplines where knowledge creation is intrinsically linked to innovative artifacts, offering a framework for developing and evaluating new solutions, processes, or models [10, 19]. This approach enables researchers to address complex problems through iterative design, development, demonstration, and evaluation cycles, ensuring both rigor and relevance in research outcomes [12], [24]. Table 1 summarizes our research.

Table 1. The heritage digital twin DSR according to the DSR grid [4].

Problem The dwindling knowledge and practice of traditional cheesemaking in the Serra da Estrela region require innovation through digital innovation to ensure sustainability and resilience	**Research Process** An iterative process of problem identification, artifact design and development, demonstration, evaluation, and refinement based on feedback	**Solution** A DT of the artisanal production process of Serra da Estrela cheese, acting as a digital memorial, a compliance tool, and a resource optimization mechanism
Input Knowledge Literature on DT in smart manufacturing, preservation of intangible cultural heritage, and artisanal cheesemaking practices	**Concepts** DTs, intangible cultural heritage, sustainability, smart manufacturing	**Output Knowledge** Design principles for heritage DTs. Insights into the integration of digital and traditional knowledge, evaluation of the impact of the DT on sustainability and cultural preservation

The design and development phase involved gathering detailed insights through interviews with local cheesemakers and visits to cheese dairies to capture the essence and evolution of the cheesemaking process. Venable et al. [29]'s framework guided the evaluation of the prototypes, emphasizing human risk and effectiveness as the evaluation strategy, reflecting the project's focus on cultural sensitivity and practical applicability. Feedback from stakeholders, including cheese dairy representatives and experts in cheese certification and intangible cultural heritage, was instrumental to the evaluation process. The establishment of design principles was informed by Gregor et al. [11], ensuring a structured approach to defining the characteristics and functionalities of the heritage DT artifact for cheese production.

Estrela Geopark, located in Portugal, is known for its geological diversity and cultural richness. A standout example of this cultural heritage is the production of Serra da Estrela cheese, a practice that embodies the local communities' memory, identity, and tradition. This cheese is more than just a culinary delight; it represents a crucial component of the social, economic, and environmental sustainability of the region. Additionally, Geopark's affiliation with the GEOfood brand underscores its commitment to sustainable development by reinforcing the connection between local stakeholders and Geopark's identity while promoting the valorization of endogenous products like Serra da Estrela cheese. Figure 1 shows the territory of the Estrela Geopark, where this research occurs.

Fig. 1. Territory of the Estrela Geopark and identity elements.

4. Results and Discussion

4.1. Design and Development

This phase started with the specification and control plan of the Serra da Estrela cheese production process, as well as interviews with four cheesemakers to learn about the process and how it has evolved over the last century. We then proceeded to establish the requirements and design a DT prototype using Microsoft's Azure Digital Twin. We chose this platform because it integrates both the data model and the digital representation of the physical twin, but other platforms could be used for prototyping.

Serra da Estrela cheese is made from specific raw materials: (1) milk from Bordaleira Serra da Estrela or Churra Mondegueira breeds; (2) salt; and (3) cardoon thistle (*Cynara cardunculus, L.*) as a coagulant. Figure 2 systematizes the main tasks that make up the Serra da Estrela cheese manufacturing process.

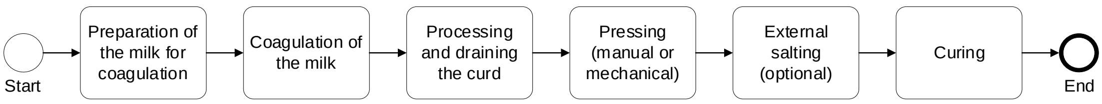

Fig. 2. Simplified flow of the Serra da Estrela cheese manufacturing process.

First, raw sheep's milk is filtered and heated to 28-32ºC to prepare it for coagulation. The milk is mixed with ground thistle flower and salt and left to rest for 45-60 minutes. The curd is then cut, placed in a cloth, squeezed to extract the whey, and placed in open "cinchos" (molds) for molding. The curd is compressed to reduce the diameter of the mold and remove the whey. Once the curd has been worked, the cheese is pressed (either manually or mechanically) by placing a 4-5 kg weight on each cheese for about six hours. After pressing, the cheeses are externally salted by rubbing the surface with salt. The maturing process consists of two phases: drying and curing. The drying phase, which lasts 15-20 days, requires a temperature of 6-12ºC and 85-90% relative humidity, with daily turning and washing of the cheeses. Curing begins on the 20th day and lasts for 25-

30 days at 6-14ºC and 90-95% humidity, with turning and washing depending on the appearance of the rind.

The interviewees included two retirees aged 91 and 92 (Q01 and Q02), a 58-year-old education assistant (Q03), and a 35-year-old food engineer (Q04). Q01 and Q02 were involved in agriculture and cheesemaking, selling their cheese at local fairs. Q03, Q02's daughter, supplements her income with cheese production from her small herd and sells at the municipal market. Q04 operates a small cheese dairy, processing about 100 liters of milk daily, with no prior cheesemaking experience. All participants acknowledge the main steps of the Serra da Estrela cheesemaking process through minor variations in their methods. Q01 and Q04 use a cloth in curd processing for easier whey extraction, whereas Q02 and Q03 directly use molds. While Q01-Q03 employs manual pressing, Q04 utilizes a mechanical system. Practices have naturally evolved: Q01 and Q02 used traditional fire heating, Q03 used a stove, and Q04 opted for a water bath. The maturation process has also adapted, with Q03 using a refrigerator and Q04 employing specialized chambers for curing. Utensils have been updated to meet HACCP standards, transitioning from wood to stainless steel and plastic for health compliance.

Fig. 3. Goal model of the heritage DT for the Serra da Estrela artisanal cheesemaking process.

Figure 3 presents the requirements of the heritage DT using a Goal-oriented Requirement Language (GRL) diagram. This language aims to support modeling and reasoning of goal-oriented requirements, which are supported by scenarios, and provide constructs to express various types of concepts that arise during the requirements process, namely intentional elements, links, and actors [2]. The main international elements are: (1) goals ( ); (2) softgoals ( ), which can be seen as intangible goals; (3) tasks ( ), which operationalize the goals and softgoals; and (4) resources ( ).

The DT seeks to meet the motivations and objectives of four main actors: (1) cheesemakers; (2) certification body; (3) intangible cultural heritage experts; and (4) Estrela Geopark. In the case of the cheesemakers, the DT serves as a task and process management tool to ensure compliance with Serra da Estrela cheese production guidelines and health standards (HACCP), as well as a decision support system for optimizing production. The cheese dairy's perspective is the central one for this actor; the DT suggests tasks to be carried out (e.g., turning and washing cheeses), recommendations during the production (e.g., amount the thistle and salt to be used to prepare the thistle macerate) and their registration makes it possible to guarantee compliance with the manufacturing guidelines, as well as traceability and food health, along with the monitoring of various conditions via the IoT system. For other users, we will no longer have an individual view of the cheese dairy but a regional one. However, for each type of user, there are specific functionalities, for example, monitoring compliance with health standards for certification bodies or capturing the artisanal cheesemaking process for specialists in intangible cultural heritage.

Microsoft's Azure Digital Twin platform employs the Digital Twin Definition Language to create and interact with digital representations of real-world entities and processes. The platform allows the DT to be represented using the model and the twin graphs, the latter shown in Figure 4.

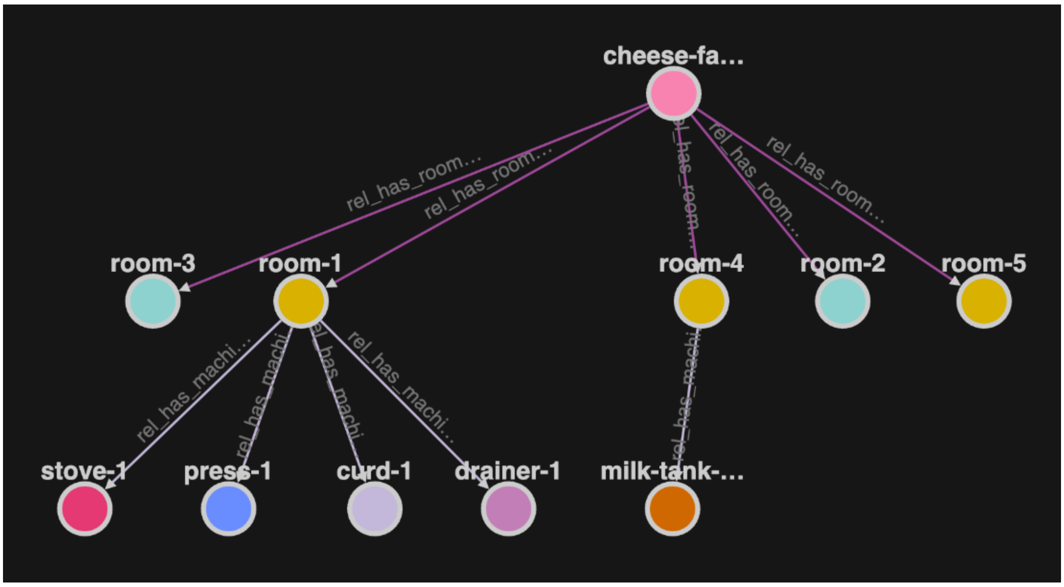

Fig. 4. Digital twin model on the Azure Digital Twin platform: twin graph.

The twin graph integrates all relevant components, connecting the digital and physical realms for real-time monitoring and decision-making, while the model graph has purposes similar to those of an entity-relationship diagram. The model of the cheese dairy that will be used as a use case is made up of five rooms/components: (1) production room (room-1); (2) drying chamber (room-2); (3) curing chamber (room-3); (4) milk reception room (room-4); and (5) packaging room (room-5). There are other components associated with each room, in this case the equipment needed to make the cheese. For example, the production room has the following equipment: milk heating system (stove-1), mechanical press (press-1), curd (curd-1), and drainer (drainer-1). As well as representing the relationships between the various entities, the model graph also shows the various sensors and actuators that will be used. In addition, this graph stores information specific to the model. For example, the 'room-2' elements has the following properties: 'room_id', 'name', 'capacity', 'temp', 'humd', 'rec_temp', 'rec_humd', 'hvac', and 'fogging'.

We then proceeded to create the three-dimensional representation of the model using Azure Digital Twin 3D Scenes Studio, where we created the various elements and associated behaviors. Each element can be made up of one or more 3D objects and can have various behaviors assigned to it. A behavior is a business logic rule that uses the DT's data to generate images in the scene. In addition, each behavior can be reused in several elements, and its status information can be displayed by the behaviors of visual rules and widgets, as in our case, it is done by monitoring the temperature and relative humidity conditions that are transversal to all the rooms.

We use temperature and relative humidity sensors to monitor the conditions in all the cheese dairy rooms and various conditions in the existing equipment. For example, in the milk storage tank, as well as monitoring the tank's storage capacity, we monitor the temperature, density, pH, and electrical conductivity of the milk to guarantee the health conditions imposed by HACCP and infer productivity conditions (e.g., density allows us to infer fat content). When we start producing a new batch, we tell the system how much milk we will use to make cheese, and it will indicate how much salt and thistle will be needed. Although there are reference values for the preparation of the thistle macerate (0.2-0.3g of flower of each per liter of milk), the DT optimizes the quantities based on the feedback provided by the panel of experts who annually indicates that the cheese may or may not be certified, as well as feedback from consumers. In the milk heating system, the DT informs when the milk is at the ideal temperature (28-32ºC) for coagulation. The DT will also monitor the time and force applied by the presses during the pressing process and monitor and control the temperature and humidity inside the drying and curing chambers. In addition, the system will have image acquisition systems to record the cheesemaking process to preserve the cultural practice. This IoT monitoring and control system will use MQTT to communicate with the Azure IoT Hub, which will serve as an interface for the data to be received by the Azure Digital Twin. In addition, we need a web application in Flask for users to interact with the system via a dashboard. This web dashboard will have different views for each type of user and different functionalities.

4.2. Demonstration

This platform aims to meet a wide range of needs specific to each actor. Figures 5 and 6 illustrate some of the high-fidelity prototypes developed and presented by different actors to validate that the functionalities meet their real needs.

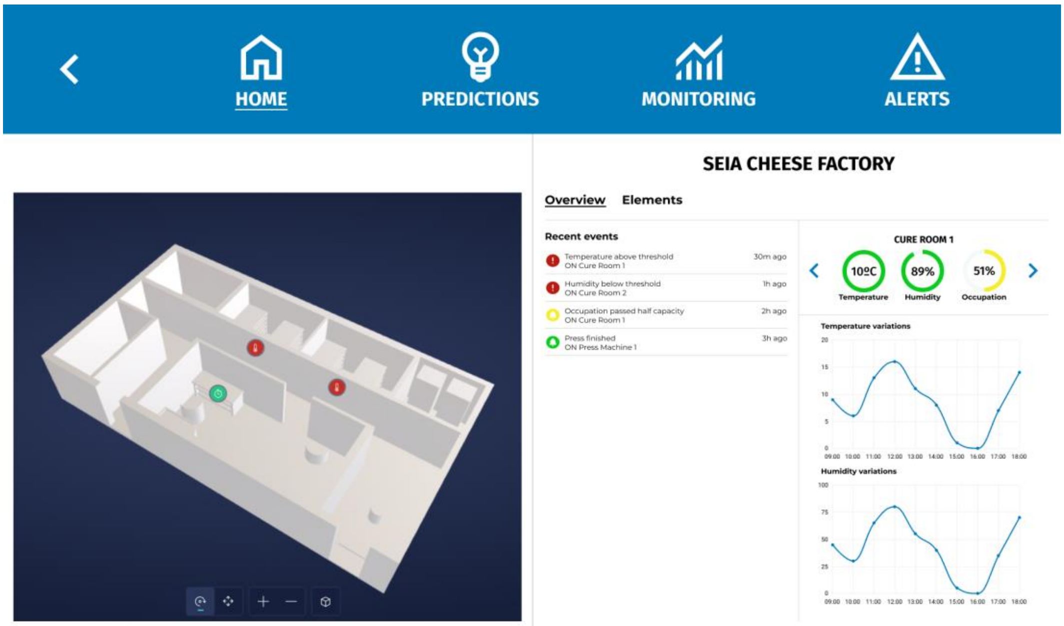

Fig. 5. High-fidelity prototypes of the user interaction system: cheesemaker dashboard.

Figure 5 provides an overview of the dashboard. On the left is a 3D representation of the dairy, which allows the status of the various rooms and equipment to be monitored in real time. On the right, the user can consult the historical records and use the alarm system to check for anomalies. This view of the cheese dairy also provides mechanisms for consulting information on the batches produced, ranging from the status and fulfillment of the control plan to pending tasks (e.g., washing and turning the cheeses).

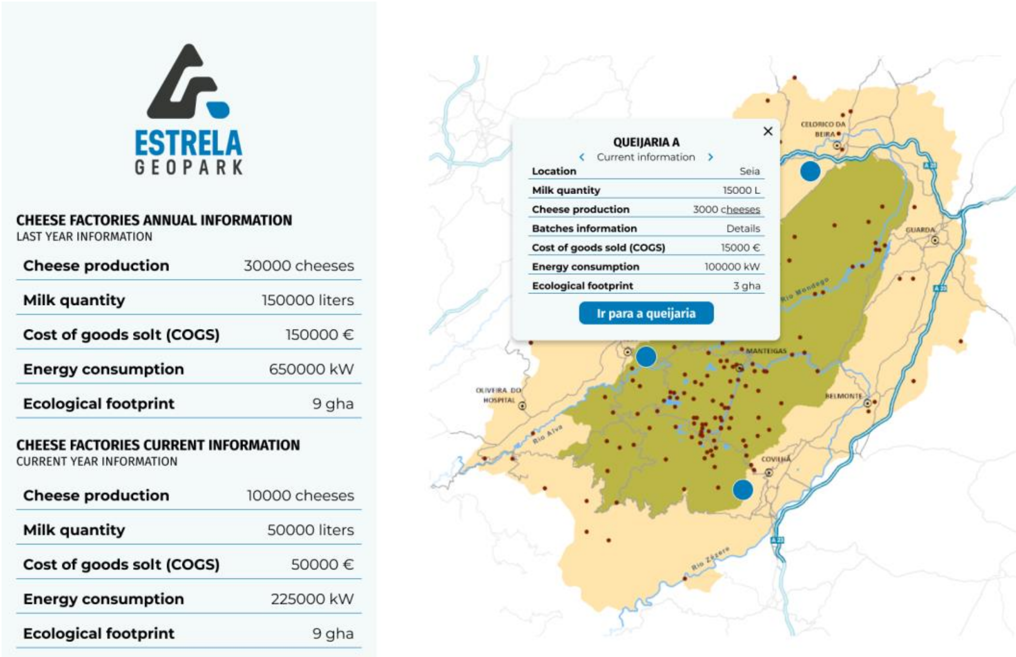

Fig. 6. High-fidelity prototypes of the user interaction system: Estrela Geopark dashboard.

Figure 6 illustrates a regional view of the Serra da Estrela cheesemaking process, presenting the Estrela Geopark with metrics related to economic sustainability (e.g., production, revenue, economic impact), social sustainability (e.g., jobs created, gender equality), and environmental sustainability (e.g., carbon footprint, energy and water consumed, waste generated). In addition, it is also possible to have an individualized view by municipality and cheese dairy, which will help decision-makers to have a multi-level perspective that will contribute to informed and conscious decision-making.

4.3. Evaluation

In this DSR design cycle, we carried out an ex-ante evaluation, prioritizing user insights in order to anticipate complications from human and social difficulties of adopting and using the system. Therefore, we opted to adopt a human risk and effectiveness strategy [29], where through individualized open interviews, we presented the requirements and user interface prototypes to the system's actors in order to obtain their feedback.

The cheesemaker recognized the importance of the system, pointing out that various benefits it could bring: *"A system like this could reduce the amount of paperwork we have to kill in on a daily basis, as well as warning us to important tasks that we sometimes forget."* However, they also counseled about the practicality and user-friendliness of the system: *"However, if the system is to complex, it could become a hindrance and instead of helping, it could get in the way."* Equipment monitoring was useful: *"Sometimes we have problems monitoring the conditions of the ripening chambers, especially at weekends, and if these problems aren't detected in times, they can lead to spoiled cheese being thrown away."* Collaboration between stakeholders in the supply chain (in this case the cheesemakers and the certification body) was also one of the elements they valued, and they called for the integration of other stakeholders in the supply chain, particularly milk producers and veterinarians: *"(...) have access to animal health records, because if there is a problem with a sheep, there will be a problem with the milk it produces and, gradually, with the cheese we make from it."*

Certification body representatives also recognized the value and relevance of such a platform: *"There is an urgent need for systems that help us in our mission as certification bodies for regional food products that have a deep link with the territory and heritage of the region."* They also mentioned that *"an added value of this system is that it is based on the specification and control plan, which gives us a comprehensive view of the whole* *process and serves as a valuable support mechanism to facilitate communication and transparency between the certification body and cheese producers."* The experts also said that *"(...) do not have enough inspectors to audit as much as we would like, and we believe that such a system could help us to monitor the work carried out in the various cheese dairies, even at a distance, as well as assisting us to select potential inspection targets."* However, the interview ended with the caveat that some cheese dairies lack digital skills: *"Most cheese dairies are small and the people who run them and work there don't have (...) a high level of digital literacy, so these factors could be as obstacle; not to mention the fact that they may also think this type of system is only there to control them."* These are legitimate concerns that can be overcome through awareness-raising.

The specialist in intangible cultural heritage also highlighted the importance of the system *"for recording the traditional ways of making cheese and preserving them for future memory,"* accentuating the need to record all the steps: *"It's necessary to record the step-by-step and check that they comply with the traditional matrix since it's 'industrialized' cheesemaking process and with the passage of time become forgotten."* He also emphasized that *"capturing video makes it possible to record detailed related to know-how that is often omitted from textual or audio records* [usual in this area of knowledge]*, as well as to understand the occurrence of a deviation that could alter the tradition."* He also added that *"by cross-referencing the records of various cheese dairies, we can capture unknown singularities, which may be results of previously unknown deviations."* Traditionally, the process of passing on a traditional practice is done from generation to generation, but *"in the absence of an older cheesemaker who can personally ensure that the knowledge is passed on, this system could do so complemented by the records of the traditional matrix."* Finally, he pointed out that this system could be transposed to other elements of intangible cultural heritage: *"we can also apply it to other types of manufacture, whether food or handicrafts, for example, the case of Estremoz rattles or Biscainho's black clay crockery; above all, those that have certain procedures that are decisive in the final result, and in which no step can be omitted to the detriment of altering the final results."*

The feedback received by the managers of the Estrela Geopark was also very encouraging and perfectly in line with the Geopark's mission, vision and objects: *"Our main purpose is to contribute to sustainable development of the Estrela Geopark territory, through networking, with the aim of enhancing the different dimensions of the heritage of this territory and, at the same time, stimulating the socio-economic development of the people who live here, and this project is exactly in line with all of this."* They also said that *"in recent years the have been increasingly concerned with the valorization of existing endogenous products, which led us to join the GEOfood brand created by Magma Geopark in 2020, and the implementation of the brand in the Geopark territory is one of the challenges we have, and we believe that this system can help us in this monitoring process."* With regard to the cultural heritage protection dimension, the Geopark managers emphasized: *"The conservation and safeguarding of intangible cultural heritage plays a fundamental role both UNESCO, as established in the 2003 Convention, and for its Geoparks, which seek to collect traditional practices so that is not lost and can be passed on to future generations, and this system allows us to both collect and understand how practices evolve and vary from territory to territory."*

Our conclusions in the first DSR design cycle are that (1) the DT meets the needs of the various stakeholders, (2) there may be difficulties in its uptake by cheesemakers, either due to practical issues or low levels of digital literacy, (3) there is a need for systematic and methodical control of artisanal production process, and (4) it is imperative to preserve, protect and pass on intangible cultural heritage to future generations.

4.4. Design Principles for Food Heritage Digital Twins

This section presents five design principles, which aim to compile the knowledge gained from this DSR design cycle. To systematize the design principles, we used the anatomy established by Gregor et al. [11]: *"DP Name: For Implementer I to achieve or allow for*

Aim A for User U in Context C, employ Mechanism M1, M2, …, Mn involving Enactors E1, E2, …, En because of Rationale R."

DP1: Authenticity Preservation. For DT developers to preserve the authenticity of traditional food-making processes for cultural heritage experts in the context of intangible cultural preservation, employ accurate digital replication, continuous community engagement, and iterative validation with domain experts, involving local artisans, cultural historians, and anthropologists, because maintaining the integrity of traditional practices ensures cultural authenticity.

DP2: Sustainability Monitoring. For system architects to optimize resource use and ensure sustainable production for cheesemakers in the context of artisanal industries, implement real-time monitoring of resources, predictive analysis for resource optimization, and feedback loops for process improvement involving environmental scientists and supply chain managers because proactive resource management contributes to environmental and economic sustainability.

DP3: Compliance Assurance. For quality assurance teams to validate adherence to certification standards for certification bodies in the context of food heritage products, apply automated compliance checks, traceability systems, and certification workflows involving compliance officers and regulatory authorities because systematic and transparent validation processes ensure product integrity and trust.

DP4: Cultural Continuity. For preservation specialists to ensure the continuity of food heritage practices for future generations in the context of cultural conservation, establish digital archiving, knowledge transfer initiatives, and community-driven content creation, involving archivists, cultural practitioners, and digital librarians, because preserving knowledge and practices contributes to the enduring legacy of food heritage.

DP5: Seamless Integration. For technology integrators to maintain the continuity of cheesemakers' daily tasks without introducing new barriers for artisanal producers in the context of traditional cheesemaking, employ intuitive user interface design, minimal disruptive technology implementation, and user-centered training programs, involving user experience designers, process engineers, and educational specialists, because facilitating a seamless transition to digital aids preserves operational efficiency and user acceptance.

These design principles serve as guidelines for future efforts to develop DT that aim to preserve and safeguard elements of intangible cultural heritage (e.g., local food).

5. Conclusions

This research adopted a DSR approach to develop a heritage DT for the artisanal production of Serra da Estrela cheese, encapsulating centuries-old cheesemaking practices while integrating modern digital technologies for preservation. The main achievements were the design of a dynamic digital replica of the cheesemaking process, which allows the simulation, analysis, and optimization of the cheesemaking process in a virtual environment, ensuring compliance with traditional practices and promoting resource optimization for sustainability.

This study extends the application of DT from physical manufacturing processes to the preservation of intangible cultural heritage of traditional food products. The evaluation of heritage DT by local communities is another important contribution to integrating DTs into traditional local manufacturing. For practitioners, the project serves as a blueprint for the use of heritage DT in the preservation and maintenance of cultural practices to ensure their transmission to future generations. It also emphasizes the integration of empirical findings into the design process, ensuring that the DT remains relevant and effective in real-world applications.

The study faced certain limitations, in particular, the potential resistance of cheesemakers due to varying levels of digital literacy and the inherent complexity of the DT system. This is the first complete DSR design cycle aiming to deploy a full-scale heritage DT in the region. In addition, the reliance on extensive stakeholder feedback and iterative design may limit the speed at which the DT can be widely implemented and adapted across different regions or practices.

Future research should focus on improving the usability of the DT interface to ensure wider adoption by craftspeople with different technical skills. Additionally, it will be important to adopt a theoretical lens to extend the contribution, such as knowledge management (knowledge codification) or transaction cost theory (asset specificity and elimination of information asymmetry). Further development could also explore the application of DT technology to other forms of intangible cultural heritage, broadening the scope of preservation efforts. In addition, exploring the integration of advanced analytics and machine learning could provide deeper insights into optimizing traditional practices, thereby supporting the sustainability and resilience of cultural heritage in the digital age.

Acknowledgements

This work is financed through national funds by FCT – Fundação para a Ciência e Tecnologia, I.P., in the framework of the Project UIDB/00326/2020 and UIDP/00326/2020. The second author is funded by FCT under the Ph.D. grant 2022.09950.BD.

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