A Conceptual Framework to Foster Sustainability with Gamified Digital Twins

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Abstract

This paper advocates for a Human-Centered Interaction Design perspective in the design of gamified Digital Twins to support sustainability. We propose a conceptual framework for socio-technical system design grounded in three goals: supporting a sense of purpose, enhancing awareness, and fostering engagement. We discuss the applicability of the framework through two case studies (smart home management and elderly assistance) chosen to illustrate its relevance across distinct application domains.

CCS Concepts

• **Human-centered computing → Interaction design theory, concepts and paradigms**.

Keywords

Digital Twin, Gamification, Sustainability, Human-Centered Design

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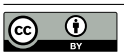
1 Introduction

The United Nations has defined 17 interconnected Sustainable Development Goals (SDGs) addressing environmental protection, health, inclusion, responsible consumption, and institutional accountability [6]. In other terms, sustainability should be considered not only in environmental terms, but also in relation to social equity, well-being, and responsible innovation. Aligning the purposes of designing socio-technical systems with one or more SDGs may contribute to long-term societal benefits rather than just short-term outcomes and specific needs of target users. Design for sustainability can be achieved by incorporating into the system a way to make sense of what is happening in a particular context and mechanisms to explore the impact of alternative decisions, thereby enabling more responsible decision-making. We believe that Digital Twins (DTs) represent the right tool for realizing socio-technical systems that foster sustainability. Advances in sensing technologies, connectivity, cloud computing, and artificial intelligence have transformed DTs, originally conceived as static or simulation-based models of physical systems, into continuously synchronized systems integrating real-time, historical, and contextual data [1, 9]. This allows a DT to obtain a complete overview of its physical counterpart by monitoring and predicting its behavior, and providing users with up-to-date information and reasoning capabilities, enhancing decision-making. Despite these advanced features, DT research remains strongly technology-driven, focusing primarily on architectures, synchronization mechanisms, and analytics, while aspects related to user-DT interaction remain marginal [2, 5, 7, 8]. In this paper, we advocate for a Human-Centered Design perspective in DT research to conceive DTs as socio-technical systems and align their design with sustainability purposes. To this end, we propose a conceptual framework to foster sustainability that leverages DT's potential for user awareness and gamification mechanisms to ensure user engagement. The paper briefly describes this conceptual framework and illustrates its instantiation in two case studies: the management of green smart homes and the monitoring of health and behaviour data from elderly individuals.

2 Conceptual Framework

Building on previous work that first investigated DTs focusing on definitions, characteristics, applications, and design implications [1] and later analysed the existing scientific literature to determine the extent to which Human-Computer Interaction is part of the design process of DTs [2], we are now working on the development of a human-centered design methodology for gamified DTs to foster sustainability. Figure 1 illustrates the conceptual framework underpinning our methodology. The diagram shows the three pillars of the framework: *Purpose*, *Awareness*, and *Engagement*.



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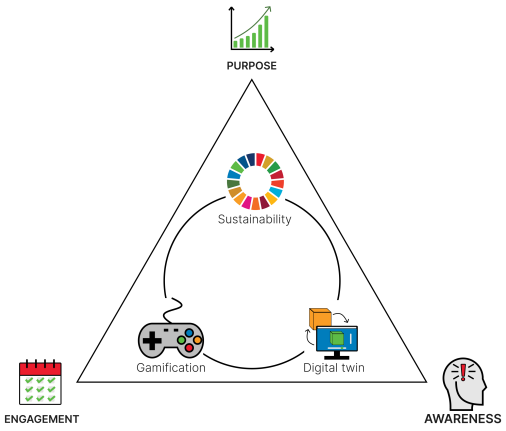

Figure 1: Diagram representing the conceptual framework. On the outside, the triangle shows the interrelation between the pillars of the framework, while on the circle, the core elements that we chose to operationalize the pillars in our case studies are displayed.

Purpose reflects the values that enable the system to support responsible decision-making over time. In our framework, *Sustainability* operationalizes purpose broadly, encompassing environmental impact, well-being, equity, and responsible innovation, in line with the United Nations SDGs [6]. Aligning socio-technical system design with sustainability aims to contribute to long-term societal benefit.

Awareness goes beyond real-time data access or system-state visualization, encompassing the ability of users to understand and make sense of complex environments through a socio-technical system. In this sense, *Digital Twins* act as mediating artifacts that support sensemaking rather than mere monitoring by showing trends, interdependencies, uncertainties, and alternative scenarios, enabling informed decision-making.

Engagement concerns the role of interaction mechanisms that foster long-term involvement, appropriation, and meaningful use of the system. *Gamification* features can foster sustained involvement by reinforcing learning processes, encouraging reflection, and supporting a sense of competence and contribution.

3 Case Studies

We briefly present here two case studies to illustrate how the framework can be applied in practice.

The first case study is the Green Smart Home (GSH) Digital Twin [3], a system developed in the frame of a National Italian project. Its main *purpose* is to foster sustainability by increasing users' awareness of their energy consumption and ecological footprint while supporting them in controlling their smart homes. Through direct device control, the creation of automated behaviors, and the presentation of consumption reports, the DT enhances inhabitants' *awareness* of the smart home and its consumption patterns. In its current configuration, the GSH system contributes to SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production) by providing information on energy consumption, emissions metrics, and automation optimizations. However, this sustainability focus remains largely energy-centered, leaving other sustainability dimensions unexplored. In particular, SDG 10, which promotes Reduced Inequalities, is not explicitly considered. Integrating this perspective would help ensure that the benefits of smart home technologies are equally available to users with diverse socio-economic backgrounds, abilities, and levels of digital literacy. Moreover, as highlighted in [4], user *engagement* represents a critical challenge for the GSH system, as users often struggle to remain motivated once the initial novelty fades. For this reason, we suggest integrating gamification features into the GSH digital twin. If redesigned with gamification in mind, the system can not only inform users but also actively support them in building long-term behavioral changes that align with broader sustainability goals.

The second case study concerns a new system to be designed, the Elderly Digital Twin (EDT), a socio-technical system based on wearable sensors that aims to collect health and behaviour data from older adults in their residences or hospitals and monitor them remotely. The system's users are a multi-stakeholder ecosystem: the elderly being monitored, their caregivers (nurses, family members, and the like), and healthcare professionals (physicians). The system's main *purpose* is to contribute to SDG 3 (Good Health and Well-being) and SDG 10 (Reduced Inequalities) by supporting equitable, continuous, and dignity-preserving care. By promoting accessible and reliable digital health infrastructures, the system can also contribute to SDG 9 (Industry, Innovation and Infrastructure). In this way, sustainability concerns not only clinical effectiveness but also long-term inclusion and respect for personal autonomy. While wearable sensors can collect large amounts of physiological and behavioural data, clinicians and caregivers often struggle to extract actionable insights from discrete, heterogeneous, and often noisy data streams. The EDT serves as a mediator that facilitates *awareness* across the socio-technical system and transforms heterogeneous data streams from wearables into a synchronized, interpretable digital representation, supporting shared understanding among all stakeholders. Finally, to ensure the long-term appropriation of this technology, gamification is introduced as a strategic *engagement* tool.

4 Conclusion

This paper investigates the human-centered design of gamified Digital Twins that foster sustainability, shifting the focus from technology-driven approaches toward a more balanced distribution of decision-making between users and technologies. Building on a novel conceptual framework structured around three pillars, *Purpose*, *Awareness*, and *Engagement*, the paper illustrates how the core elements selected to operationalize these pillars (Sustainability, Digital Twin, and Gamification) can be instantiated through two case studies.

The current limitations of the developed systems are also highlighted, which we plan to overcome by leveraging the framework's full potential. In turn, the insights gained from implementing the case study prototypes will inform the theoretical foundations of our future research. In particular, we aim to develop a human-centered design methodology that guides the selection of tools and methods

across diverse work scenarios. The overarching objective is to articulate a general methodological approach that concretely supports designers and users in shaping their socio-technical systems and co-evolving with them over time.

Declaration on Generative AI

During the preparation of this work, the authors used Grammarly and ChatGPT for text revision, paraphrasing, rewording, grammar, and spelling checks. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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