Interacting with a Green Smart Home Through its Digital Twin: A First-Person Experience

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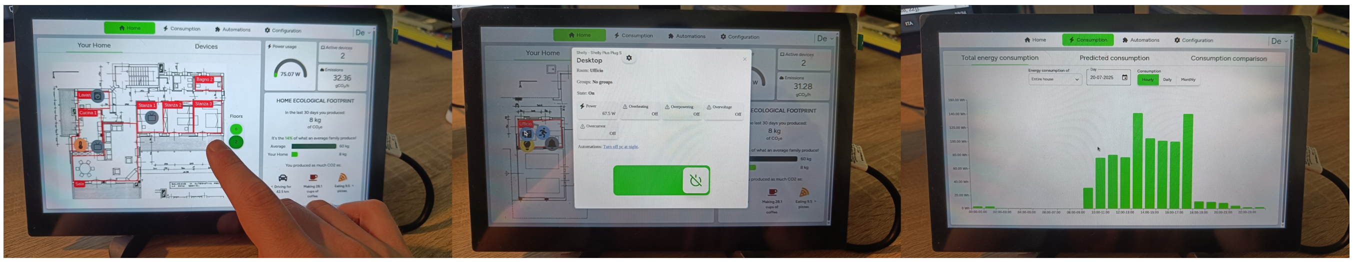

Figure 1: Interacting with the DT (left), activating the desktop computer (center), accessing consumption data (right).

Abstract

The paper presents the architecture and main features of a Digital Twin for green smart homes. A pilot installation in authors' houses is then discussed to highlight the challenges of the setup and long-term usage of the system, as well as to reflect, by means of first-person accounts, on the main advantages and issues of its use outside the lab.

CCS Concepts

• **Human-centered computing → Empirical studies in interaction design**.

Keywords

Smart Home, Digital Twin, Home Assistant

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1 Introduction

Electricity demand is expected to rise at a faster rate through 2026, especially in emerging and developing economies [16]; in particular, a significant portion of the world's energy consumption [17] pertains to electricity consumption of buildings. Eco-feedback technologies were first proposed in the literature (e.g., [11, 19]) and then as commercial devices to enhance the energy consumption awareness of households. The research in that field was focused on designing effective displays to help users understand their energy consumption and thus give them hints for behavior change. Costanza et al. proposed going beyond mere data visualization by promoting the design of interactive energy consumption visualizations [6]. Their system relied on electricity meters to provide information on the power and energy consumption of the whole house. Internet of Things (IoT) technologies permit overcoming this limitation by collecting data from each device easily [14]. The deployment of IoT technologies in houses enables the creation of smart homes. In this field, several studies focus on supporting home management with autonomous systems that are set up by professionals and adapt their behaviors through big data and machine learning [2, 7, 8, 18]. Exploiting IoT technologies and machine learning techniques, a further step has been made with the development of Digital Twins (DTs) of buildings (e.g., [3, 20, 22]). A DT may become a single access point for the users, who can operate on devices of different producers and possibly create automations (i.e., actions to be performed when predefined triggers and conditions are met) involving sensors and actuators that are usually managed separately with dedicated apps. A DT can provide users with information about the energy consumption of the whole house, rooms, device groups, or single devices. However, challenges affecting the interaction between users and DTs are often overlooked in the literature proposals, while the focus is usually on the efficiency and correctness of machine learning algorithms implementing the DT engine [5, 10, 15]. In this paper, we discuss the pilot deployment in two houses of a DT for green smart homes specifically designed by considering users' characteristics, needs, and habits, to ensure that users are able to manage their smart home through the DT and, at the same time, acquire more awareness about energy consumption and home sustainability. A first-person research experience [1, 9, 21] is presented here to reflect on the potential and issues of the developed solution.

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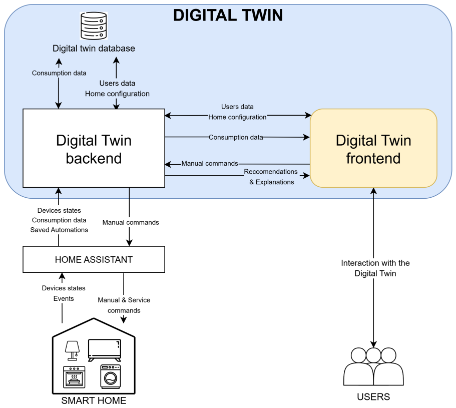

Figure 2: Digital Twin's architecture scheme

2 The Proposed Digital Twin

The developed DT offers a set of features designed to enhance users' control and their knowledge of the devices' states and behaviors. First of all, the DT provides a real-time representation of the smart home through a map, allowing users to view the current status of connected devices and interact with them directly (see Fig. 1 - left). From the component that opens when a device is selected, users can check its current state, consumption value, and execute control actions (e.g., turning on and off a desktop computer in Fig. 1 - center). Before deploying an action, the system evaluates potential unintended effects using a Deep Learning model [13] and prompts the user with a warning if any anomalies are detected. To enhance users' awareness of their energy consumption patterns, consumption information is visualized on a dedicated page of the application through bar charts (Fig. 1 - right), where users can customize the view by selecting the desired time range and data granularity (hourly, daily, or monthly). Moreover, the system provides insights into future consumption by allowing users to generate forecasts of energy usage for the upcoming hours, according to the consumption of the past ones [13]. In addition, the DT offers an automation management feature, which is essential in smart home environments as it enables automatic devices' behaviors. Before deployment, the system simulates each automation to detect potential conflicts or unintended interactions with already saved automations, ensuring safety within the smart space [4, 12].

The DT presents itself as a traditional web application where the frontend is responsible for data visualization and interaction with users, and the backend implements the logic of the system. A third actor in the architecture is represented by Home Assistant (HA) (https://www.home-assistant.io), an open-source home automation platform that provides local control and integration of smart devices through a unified interface. In this work, it serves as the middleware between the DT and the smart home, managing device integrations, automation deployment, state monitoring, and command execution. Figure 2 presents the overall architecture of the DT.

3 Pilot Deployment

To validate the system and identify potential limitations, a pilot test was conducted in the homes of the two authors. Each setup was equipped with a range of appliances, offering diverse functionalities and control capabilities. These included:

- **A Raspberry Pi 5**: tasked to run the system and act as the main entry point for the application. The device is connected to a **touch screen** used for interacting with the system;
- **Shelly smart plugs**: to enable switching on/off appliances and provide real-time monitoring of energy consumption.
- **Shelly smart lights**: to allow on/off control, adjustment of brightness, color, and temperature, along with real-time consumption monitoring.
- **Shelly H&T sensors**: to provide real-time readings of temperature and humidity.
- **TP-Link motion sensors**: to detect movements.

Each installation served a different role. The first, referred to as the development house (D), worked as a living laboratory for about ten months. It helped the incremental implementation of features and enabled the collection of appliances' consumption data. The second, the test house (T), was deployed as a beta testing site. In addition to the devices presented in the list above, house T had access to 3 Daikin Air Conditioning units. The researcher living in house T interacted with the DT within their daily routines for approximately one month and provided feedback regarding usability, perceived issues, or suggestions for improvement. Some of her first-person accounts about this experience are reported here. Information on the right panel of the Home page (Fig. 1 - left) proved to be very engaging, since it provides the current overall power demand through a colored widget that shows when such demand is high or not. It also allows a better understanding of the different power cycles of appliances like the dishwasher or the air conditioner that, when in operation, require much less power than expected. Similarly, the component that helps users assess their environmental impact in terms of total mass of CO_2-equivalent emissions and relatable metrics was considered effective. The user found the direct activation/deactivation of air conditioner units from the DT map to be faster and more intuitive than using the dedicated app. On the other hand, switching on/off the lights through the DT resulted to be uncomfortable, leading to a reflection on the utility of smart lights: their color and brightness tailoring is fascinating, and they could be involved in some automations; but, in daily life this behavior appears less desirable than manually switching on a light when needed. As to the setup, the smart plugs proved to be too bulky; thus, it was difficult to connect all the desired appliances. The graphs showing energy consumption proved useful, especially those related to each single device; however, the automatic visualization scale of the bar charts did not help compare the device consumptions, and a dedicated graph for such comparison (e.g., a pie chart) was expected.

In summary, the pilot deployment of the DT in the authors' houses yielded reflections on its limitations and possible improvements for daily usage and appropriation. The DT installation requires some degree of technical knowledge; thus, an automatic procedure will be developed to guide the end user in the installation. Using a fixed touch screen proved to be not optimal for the control of all devices; a companion app would help in those situations where the user is in a different room. Future work will include long-term trials of the DT in further houses.

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