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Table of Contents

10

DIGITAL TWINS AS CATALYSTS FOR SUSTAINABILITY EDUCATION IN UNIVERSITY CAMPUSES: A CASE STUDY AT POLIS UNIVERSITY WITHIN THE FRAMEWORK OF EDUCATION 4.0

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Abstract

In the era of Education 4.0, digital technologies such as Digital Twins (DTs) offer transformative opportunities not only for operational efficiency but also for sustainability education and behavioural transformation. This study explores the role of Digital Twin technologies, integrated with IoT systems, in promoting sustainability awareness, engagement, and behaviour modification among students and faculty at Polis University. Building on a previously implemented digital twin prototype for HVAC and lighting systems, this paper extends its application to the educational and behavioural domains. The case study examines how real-time environmental data visualisations and interactive digital environments can enhance understanding, stimulate eco-friendly decision-making, and align learning outcomes with sustainability goals. Through a mixed-method approach, including surveys, user interaction analytics, and energy data logs, the paper demonstrates how DTs support the principles of Education 4.0personalised learning, digital literacy, and learner empowerment—while fostering a green campus culture. The study provides a conceptual and *technical framework for integrating digital twins into campus curricula and sustainability campaigns.*

Keywords: Digital Twins, Sustainability Education, Education 4.0, university campuses, IoT.

I. INTRODUCTION

University campuses are complex, multifaceted environments where education, technology, and sustainability intersect. As institutions face mounting pressures to reduce carbon footprints and enhance operational efficiency, emerging technologies such as Digital Twins (DTs) and Internet of Things (IoT) devices offer powerful tools to manage and optimise energy consumption, resource allocation, and infrastructure performance (Muka & Marinova, 2023). DTs, digital replicas of physical systems, have been effectively deployed in innovative campus initiatives to enable real-time monitoring and remote control of systems such as HVAC and lighting (Grieves, 2014; Muka, 2023). Their integration with IoT systems enables a dynamic, data-driven representation of physical environments, facilitating predictive maintenance, energy efficiency, and operational automation. In the pursuit of more energy-efficient, intelligent environments, Digital Twin (DT) technologies, which create virtual replicas of physical systems, have gained traction in campus infrastructure management. Previously, digital twins have been applied at Polis University to monitor and automate energy usage in lecture halls through IoT-integrated HVAC and lighting systems, enhancing campus efficiency and reducing energy waste. However, the role of digital twins extends beyond operational optimisation.

Digital twins are virtual replicas of physical systems that integrate real-time data and advanced modelling to simulate, monitor, and optimise the performance of their physical counterparts. They are widely used across domains such as manufacturing, smart buildings, healthcare, urban planning, and education. In manufacturing and industry, digital twins help reduce downtime and improve efficiency by enabling predictive maintenance and performance optimisation. In smart buildings and campuses, they facilitate energy management and sustainability efforts by integrating IoT sensors and providing real-time monitoring and automation. Healthcare applications utilise digital twins to simulate patient-specific data for personalised treatment planning. Urban planners use digital twins to model city infrastructure better to manage traffic, utilities, and environmental resources. Within education, digital twins offer hands-on learning experiences that enhance interdisciplinary skills and promote sustainability awareness. Key features of digital twins include real-time data integration from physical assets via sensors, interactive 3D modelling and visualisation for better understanding and simulation, and predictive analytics powered by artificial intelligence to forecast system behaviour and enable proactive maintenance.

Additionally, digital twins provide interactive feedback through user-friendly dashboards, simulations, and gamification, engaging users and supporting decision-making. Their scalability allows them to expand from individual devices or buildings to complex systems and entire campuses. Furthermore, digital twins support cross-disciplinary collaboration by integrating data from engineering, environmental, behavioural, and policy domains. Remote monitoring and control capabilities enable users to manage systems from web or mobile platforms, enhancing flexibility and accessibility.

As higher education shifts toward Education 4.0, there is an increasing emphasis on learner-centric, digitally enhanced experiences that promote real-world competencies such as sustainability awareness and responsible behaviour. Education 4.0 envisions a personalised, data-driven, and experiential learning environment where students are not just passive recipients of information, but active participants in solving contemporary challenges, including environmental ones. However, the potential of digital twins extends far beyond infrastructure management. In the evolving educational paradigm of Education 4.0, there is a strategic shift toward learner-centric, technologically integrated learning environments. Education 4.0 emphasises personalised learning, digital literacy, experiential engagement, and sustainability as core competencies for the 21st-century learner (Salmon, 2019). The central thesis of this paper is that digital twins, when integrated with IoT systems and educational interfaces, can effectively promote sustainability-oriented behavioural changes among campus populations.

Furthermore, such applications align with the goals of Education 4.0 by fostering digital fluency, systems thinking, and data-driven decision-making. By addressing these questions through a real-world case study and a mixed-methods analysis, this research provides a blueprint for leveraging digital twin technologies not only for operational sustainability but also for shaping eco-conscious, future-ready learners. Digital Twins (DTs) represent a cutting-edge technology that creates virtual replicas of physical systems, enabling real-time monitoring, simulation, and control. This capability positions DTs as pivotal tools for advancing sustainability goals while simultaneously supporting the pedagogical transformation envisioned by Education 4.0.

From a sustainability perspective, DTs facilitate real-time environmental monitoring and optimisation by continuously tracking key parameters such as energy consumption, temperature, lighting, and occupancy within buildings or campuses (Muka & Marinova, 2023; Al-Ali et al., 2020). Through simulation of various operational scenarios, DTs identify inefficiencies and allow for automated or user-informed adjustments, significantly reducing resource waste and greenhouse gas emissions (Singh, 2023). Furthermore, DT platforms enhance behavioural change and environmental awareness by visualising energy-use data, thereby empowering users, including students, faculty, and administrators, to make informed, eco-conscious decisions (Singh, 2023). The integration of predictive maintenance features also supports resource management by anticipating equipment failures and scheduling timely repairs, thereby reducing material waste and extending asset lifecycles (Ozturk, 2021). Moreover, DTs can integrate renewable energy sources into campus management systems, dynamically balancing energy demand and supply to further reduce the campus's carbon footprint.

In the context of Education 4.0, which emphasises learner-centred, technology-enhanced, and competency-based education, DTs offer experiential, personalised learning environments. Through interactive 3D simulations and real-time data visualisation, students engage in active experimentation and problem-solving, fostering more profound understanding and skill development (Fisk, 2017; Voogt et al., 2015). Digital twin implementations naturally support interdisciplinary collaboration, bringing together students from STEM, environmental science, and social sciences to tackle complex sustainability challenges (Voogt et al., 2015). Additionally, by working with live data streams and system models, students develop critical data literacy, systems thinking, and sustainability competencies, equipping them with essential skills for the digital economy and global challenges (Yu & Yu, 2020). The integration of DTs with mobile applications and cloud services further enables remote, flexible access to learning resources, facilitating continuous engagement regardless of physical location (Bishop & Verleger, 2013). This paper builds on a digital twin (DT) prototype developed at Polis University, initially designed for energy-efficient lecture hall management using Unity 3D visualisations and IoT devices. Expanding beyond infrastructure monitoring, the study explores how DTs can support sustainability education and encourage eco-conscious behaviours among university students. It investigates key research questions on the role of DTs in shaping sustainable actions, aligning with Education 4.0 principles, and the challenges and opportunities of implementation. Through a case study and mixed-methods analysis, including system usage data, surveys, and educational strategies, the paper shows that DT technologies can serve as impactful tools for promoting sustainability and behavioural change in higher education.

II. LITERATURE REVIEW

Digital Twin (DT) technologies have evolved into transformative tools for infrastructure management, particularly in smart building and campus settings. A digital twin is a dynamic, digital representation of a physical system that is continuously updated with real-time data from IoT devices, sensors, and user interactions (Grieves, 2014). The digital transformation of campuses must therefore not only improve operational systems but also cultivate sustainable mindsets and behaviours among students, faculty, and administrative staff. This paper proposes expanding digital twin applications into the realm of sustainability education and behavioural change. By enabling students and staff to interact with real-time data about their physical environment, digital twins can serve as powerful educational tools. They offer immersive, feedback-rich experiences that help individuals understand the environmental consequences of their choices, whether adjusting temperature settings, managing lighting, or engaging with broader patterns of resource consumption on campus. In this context, digital twins can serve as both pedagogical and behavioural instruments, visually and interactively communicating environmental data and system performance to end users in real time. By offering immediate feedback loops and contextual awareness, DTs can foster behavioural change by increasing users' understanding of the ecological impacts of their actions. This aligns with psychological theories of behaviour change, such as the Theory of Planned Behaviour (Ajzen, 1991), which emphasise the roles of awareness and perceived control in shaping sustainable decisions. Moreover, the educational use of DTs directly supports Education 4.0's goal of digital empowerment. Through student interaction with campus digital twins, such as virtual models of lecture halls that reflect real-time energy usage, learners can explore sustainability concepts experientially. These digital environments offer opportunities to integrate sustainability into curricula in meaningful, action-oriented ways (Beetham & Sharpe, 2013; Chi et al., 2022).

Digital twins (DTs) are uniquely positioned to serve both operational and pedagogical functions within university campuses. Their core capabilities, real-time monitoring, system simulation, data visualisation, and user interaction align well with key goals in sustainability education and behaviour modification. From a behavioural perspective, DTs provide immediate feedback loops that help users understand the impact of their actions on environmental parameters, such as energy use, temperature control, and lighting conditions (Grieves, 2014; Muka & Marinova, 2023). This feedback fosters "situated learning," in which knowledge is acquired in context and reinforced through direct interaction (Beetham & Sharpe, 2013). Behavioural science suggests that such immediacy and contextualisation can be powerful levers for change. According to the Fogg Behaviour Model (FBM), sustainable behaviours are more likely when users are motivated, able, and prompted at the right moment (Fogg, 2009). DT platforms serve as these "digital prompts," using real-time environmental data to visualise the effects of decisions and encourage eco-conscious choices.

The visual representation of consequences increases perceived behavioural control—one of the core factors in the Theory of Planned Behaviour (Ajzen, 1991)—thereby increasing individuals' likelihood of acting sustainably. Education 4.0 represents a pedagogical shift aligned with the Fourth Industrial Revolution, emphasising personalised, technology-driven, and skills-oriented learning (Salmon, 2019). It promotes student empowerment, interdisciplinary knowledge, and real-world problem-solving, particularly in areas such as digital literacy and sustainability. Central to Education 4.0 is the use of digital tools and data analytics to enhance learning experiences and outcomes. Smart campuses, embedded with IoT and DT systems, exemplify this paradigm. These environments facilitate not only operational optimisation but also new modes of teaching and learning, such as real-time data-based lessons and experiential learning modules (Beetham & Sharpe, 2013). By allowing students to interact directly with live environmental data from their campus, DTs provide a bridge between theoretical knowledge and real-world application. The application of DTs in educational simulations is gaining attention for its potential to create immersive and engaging learning experiences. The emergence of Education 4.0 calls for reimagining teaching and learning environments as more learner-centred, competency-driven, and digitally integrated (Salmon, 2019).

Digital twins can model complex systems such as buildings, vehicles, or cities in 3D environments where learners can experiment, visualise outcomes, and receive immediate feedback (Chi et al., 2022). These applications are efficient in serious games designed for learning rather than entertainment. In the context of sustainability, DT-enhanced simulations can demonstrate the impact of individual and collective actions on energy use, emissions, and resource management. For example, students may interact with a virtual campus that reflects live IoT data and explore how behavioural adjustments, such as dimming lights or altering HVAC settings, affect overall energy consumption. These environments promote systems thinking and ecological literacy, two core goals of sustainability education (Xie, 2023). The pedagogical use of DTs in higher education is still an emerging field. However, early evidence suggests strong potential to increase student engagement, improve comprehension of complex concepts, and foster long-term behaviour change. Digital Twin (DT) technologies are revolutionising infrastructure management, particularly in smart campus contexts. The implementation of DTs in Polis University has demonstrated successful energy efficiency through real-time monitoring and control of lighting and HVAC systems (Muka & Marinova, 2023). Digital twins contribute to these educational dimensions in several key ways: Personalised Learning: DTs provide individualised feedback on energy use and behavioural patterns, enabling students to explore sustainability through their own decisions and actions. Interfaces can be customised to reflect different user profiles or roles (e.g., student, faculty, administrator), thereby tailoring learning outcomes to individual experiences (Beetham & Sharpe, 2013).

A. Competency-Based Education: By simulating real-world systems, DTs provide students with experiential learning opportunities to develop competencies in systems thinking, data literacy, environmental ethics, and decision-making. These competencies are essential for addressing global challenges and align with the Sustainable Development Goals (SDGs) (Ozturk, 2021).

B. Technology-Driven Learning: Digital twins embody the integration of IoT, AI, simulation, and cloud computing—technologies that underpin the Fourth Industrial Revolution. Learning in DT-enabled environments exposes students to cutting-edge tools and encourages innovation, a central aim of Education 4.0 (Xie et al., 2023).

C. Behavioural Change Models in Sustainability: The Theory of Planned Behaviour (Ajzen, 1991) and the Fogg Behaviour Model (Fogg, 2009) offer frameworks for understanding how real-time feedback and contextual prompts can influence sustainable behaviours. DTs operationalise these theories through interactive, feedback-driven platforms.

D. Education 4.0 and Smart Learning Environments Education 4.0 promotes competency-based, personalised, and digitally enabled learning (Salmon, 2019). DTs enhance this by embedding learning within real-world contexts and offering responsive, data-driven experiences.

E. DTs in Educational Simulations and Games: Digital twins facilitate immersive simulations that reinforce complex concepts through interactivity and visual feedback. These have been shown to increase engagement and comprehension in sustainability education (Chi et al., 2022).

Behavioural change is a critical dimension of sustainability, especially within institutions such as universities, where collective action significantly affects ecological footprints. The Theory of Planned Behaviour (TPB) posits that an individual's behaviour is directly influenced by their intention to act, which, in turn, is shaped by attitudes, subjective norms, and perceived behavioural control (Ajzen, 1991). TPB has been widely applied in environmental psychology to explain eco-friendly behaviours such as energy conservation, recycling, and the use of public transportation (Kollmuss & Agyeman, 2002). Another influential model, the Fogg Behaviour Model (FBM), focuses on the convergence of motivation, ability, and prompts. According to Fogg (2009), for a behaviour to occur, all three elements must converge at the exact moment. In smart environments, digital prompts—such as real-time feedback or visualisations—can effectively nudge users toward desired behaviours. Digital twins, when integrated into user interfaces or gamified platforms, can offer these prompts by visualising the environmental consequences of user actions (e.g., energy use after adjusting room temperature). By enhancing user awareness and reinforcing perceived control, DTs can be instrumental in initiating and sustaining sustainable behaviours. The case study at Polis University contributes to this growing body of knowledge by integrating DT technology not only for infrastructure management but also as an active agent in behavioural and educational transformation.

III. METHODOLOGY

To effectively teach sustainability using digital twins (DTs) within the framework of Education 4.0, this study employs a blended methodology that integrates project-based learning (PBL), experiential learning, and interdisciplinary collaboration. This pedagogical approach aligns with the goals of Education 4.0, which emphasises personalised, technology-driven, and competency-based education tailored to 21st-century skills (Fisk, 2017; Yu & Yu, 2020).

Project-Based Learning (PBL) serves as the core instructional strategy. Students are tasked with identifying sustainability challenges in their university environment, such as excessive energy consumption in classrooms or inefficient lighting systems, and addressing them by developing or enhancing digital twin solutions. This method allows students to apply theoretical knowledge to real-world problems, encouraging critical thinking and solution-oriented design (Thomas, 2000).

Complementing PBL, **experiential learning** is integrated to deepen engagement. Students interact directly with physical IoT devices (e.g., ESP8266 microcontrollers and DHT11 sensors) and their digital representations in Unity 3D. This hands-on experience not only supports conceptual understanding but also enables learners to observe the tangible impact of digital twins on energy use, thereby promoting environmentally responsible behaviours (Kolb, 1984; Muka & Marinova, 2023).

A **blended learning** environment further supports Education 4.0 goals by combining online and in-person modalities. Online platforms provide instructional content on sustainability, intelligent systems, and IoT programming, while face-to-face sessions facilitate collaborative problem-solving and technical troubleshooting. Flipped classroom techniques are employed to maximise in-class application of concepts (Bishop & Verleger, 2013). The methodology also emphasises **collaborative and interdisciplinary learning**, reflecting the complexity of sustainability challenges that require diverse expertise. Student teams are composed of individuals from engineering, architecture, and environmental studies backgrounds, fostering peer learning and systems thinking. Tools such as web-based dashboards, collaborative project management software, and mobile applications are used to coordinate and present outcomes. In alignment with **challenge-based learning (CBL)** principles, open-ended sustainability questions guide the learning process. For example, students might be asked: *"How can digital twins be used to reduce carbon emissions in university dormitories?"* Such questions promote inquiry, creativity, and innovation, core skills advocated by Education 4.0 frameworks (Voogt et al., 2015). The integration of these methods positions digital twin technology not only as a technical tool for optimisation but also as a pedagogical instrument for sustainability education. Students gain practical skills in IoT, data analysis, and intelligent systems design while internalising the values of environmental stewardship and responsible innovation.

IV. CASE STUDY

To integrate digital twin (DT) technologies into sustainability education within the Education 4.0 framework, this study adopts a Project-Based Learning (PBL) methodology. PBL offers a learner-centred, inquiry-driven approach that empowers students to engage with authentic, real-world problems and develop solutions through active collaboration and technological innovation (Thomas, 2000; Bell, 2010). This methodology aligns closely with the goals of Education 4.0, which emphasises personalised, experiential, and competency-based learning tailored to the needs of the digital age (Fisk, 2017; Yu & Yu, 2020). In this context, students are not passive recipients of information but active participants in the development, deployment, and analysis of a DT system aimed at reducing energy consumption and promoting sustainable behaviour on a university campus. The foundation of this project was the existing physical infrastructure at Polis University in Tirana, Albania, where previous implementations of digital twins integrated with IoT technologies had already demonstrated measurable gains in energy efficiency (Muka & Marinova, 2023). These systems employed ESP8266 microcontrollers, DHT11 temperature and humidity sensors, light sensors, and motion detectors to enable the monitoring and remote control of HVAC and lighting systems. This real-world infrastructure provided an ideal testbed for students to explore the intersections of engineering, data analytics, sustainability, and digital modelling. Within the PBL framework, students were organised into interdisciplinary teams composed of architecture, environmental science, and engineering students. Their task was to extend the capabilities of the existing DT prototype, focusing not only on technical improvements, such as expanding the number of controllable devices and enhancing wireless communication, but also on its educational and behavioural applications. This hands-on, collaborative learning process was structured around several project phases: system understanding, problem identification, design iteration, real-time simulation, and testing of the DT's ability to influence energy use and user awareness.

IV. 1 Digital Infrastructure

The digital infrastructure for each task was developed using Unity 3D, which served as the primary platform for visualising the DT environment. In Figure 1, you can see a fully detailed 3D model of the lecture hall. The IoT devices were designed in Fusion 360 and imported into Unity, where they were programmed in C# to simulate environmental responses and control logic based on real-time sensor input. This virtual environment allowed students and administrators to interact with the DT via a web interface and mobile apps, enabling remote monitoring and control of temperature, lighting, and device activity. Integration with Apple's HomeKit and Android-based platforms ensured cross-device compatibility and enhanced user accessibility. The DT model maintained real-time synchronisation with the physical devices via wireless communication, providing a live, responsive simulation that reflected actual environmental conditions. The system could detect temperature fluctuations, light levels, and occupancy, allowing the DT to automatically adjust HVAC settings and lighting configurations to minimise energy waste. This dynamic mirroring of physical conditions served as a powerful pedagogical tool, making abstract sustainability principles tangible and immediate. By embedding this project within a PBL framework, students gained practical experience in IoT systems, C++ and C# programming, and digital modelling, while also engaging in a reflective analysis of the sustainability impacts of their work. This mirrors key aspects of Education 4.0, which stresses the development of not only technical proficiency but also higher-order skills such as critical thinking, systems design, teamwork, and ethical decision-making (Voogt et al., 2015; Yu & Yu, 2020). In addition to the technical outcomes—such as improved automation, expanded scalability through multi-relay integration, and enhanced user interface design—the educational outcomes were significant. Students reported increased awareness of energy consumption patterns, a stronger understanding of smart infrastructure, and greater confidence in applying technology for social and environmental good. The project also emphasised real-time data literacy, encouraging students to interpret sensor outputs and make informed decisions based on empirical feedback. Finally, by using the physical and digital DT infrastructure as both an educational tool and a sustainability intervention, this project demonstrated how smart campus technologies can support both operational efficiency and pedagogical transformation. It serves as a replicable model for universities seeking to embed Education 4.0 principles into their sustainability efforts, showing that digital twins are not just engineering systems but also powerful educational instruments for behavioural change and environmental stewardship.

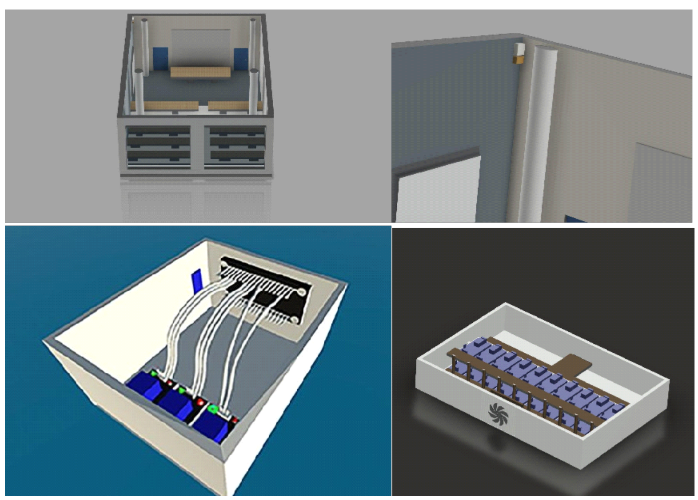

Figure 1. Digital Twin of the lecture hall and the prototype

Source: The author

The benefits include real-time visibility and control, enabling continuous monitoring and management of campus resources and empowering timely decisions to enhance sustainability and efficiency. Predictive maintenance and performance optimisation help anticipate equipment issues before they occur, reducing downtime and improving overall system reliability. This approach also enables faster innovation and development cycles by providing a dynamic virtual environment for testing and implementing new sustainability solutions. Initially tested in a single lecture hall, the solution is cost-effective and scalable, enabling expansion of smart campus management across multiple buildings and facilities.

IV. 2 Educational Integration

The expansion of this DT infrastructure into educational activities marked a significant step toward aligning campus digitisation with Education 4.0 objectives. Faculty members at Polis University incorporated digital twin systems into sustainability-focused courses in engineering and environmental design. These integrations included:

A. Sustainability Curricula: Students engaged with real-time DT dashboards to learn about building energy dynamics, HVAC system efficiency, and the principles of passive environmental control. Through lab exercises or diploma thesis development, we required them to simulate energy scenarios and propose energy-saving modifications.

B. Workshops and Hackathons: Interdisciplinary workshops brought students from design, engineering, and computer science backgrounds together to build or expand upon existing DT models. These events fostered collaborative learning and innovation while reinforcing concepts such as systems thinking and ecological design.

C. Mobile/Web Interfaces for Interaction: Web-based dashboards enabled students to monitor energy usage in lecture halls. Interfaces provided options to simulate behaviour-based changes, such as reducing lighting levels or adjusting HVAC settings, with live feedback on estimated energy savings.

D. Gamification Elements: To enhance engagement and drive behaviour change, the university implemented gamification features. A leaderboard displayed students or departments with the most significant energy savings based on their interactions with DT settings. Additional incentives, such as "Green Badges" and rewards for consistent reductions, created a competitive but educational atmosphere.

Feature	Purpose	Outcome
Leaderboard	Encourage competition	+32% interaction increase
Green Badges	Recognition of savings	Improved retention
Notifications	Behavioral prompts	Higher compliance

Table 1. Gamification Features Used in the DT System

Source: The author

This educational integration demonstrates how digital twins can serve not only as operational tools but also as experiential learning platforms aligned with 21st-century educational goals (Salmon, 2019). To operationalise the use of DTs in sustainability education and behaviour change, this paper proposes a three-tiered model structured around Data Interaction, Behavioural Feedback, and Reflective Learning (see Fig. 1):

A. Data Interaction Layer

Users interact with digital twin systems via mobile or desktop dashboards that visualise real-time data from IoT sensors embedded in campus buildings (temperature, humidity, energy use). This layer emphasises accessibility, transparency, and active exploration.

B. Behavioural Feedback Layer

Digital twins provide real-time feedback on environmental outcomes (e.g., CO_2 reductions from adjusting HVAC settings), nudging users toward sustainable choices. Gamification features such as leaderboards, sustainability badges, or achievement milestones are used to reinforce positive behaviours.

C. Reflective Learning Layer

Users are encouraged to reflect on their interactions and decisions via in-app prompts, classroom discussions, or learning modules. Educators may integrate this data into formal lessons on climate change, smart systems, or environmental management. This reflection bridges technical interaction with critical understanding.

This model promotes a shift from passive awareness to active engagement, enabling universities to foster a culture of sustainability through immersive, data-rich environments. When implemented at scale, it can also inform institutional strategies by aggregating behavioural insights to improve campus-wide policies and energy models (Signh, 2023).

IV.3 Behavioural Monitoring & Data Collection

To evaluate the impact of DT integration on sustainability behaviour and awareness, the university conducted a mixed-method assessment including both quantitative and qualitative approaches:

- Pre- and Post-Surveys: Surveys administered before and after engagement with DT systems assessed students' knowledge of energy consumption, perceived behavioural control, and intention to engage in eco-friendly actions (Ajzen, 1991).
- System Usage Logs: Data from the DT dashboard and mobile applications recorded the frequency and types of student interactions with the platform (e.g., temperature adjustments, energy reports accessed, simulations run). This data provided insights into which features were most engaging or educational.

- Classroom Participation Metrics: Instructors documented student engagement during workshops and classes using digital twins, tracking participation rates, design proposals submitted, and peer feedback activity.

The following metrics were analysed to assess behavioural and learning outcomes:

- Energy Awareness: Changes in students' self-reported understanding of energy use and sustainability concepts before and after using the DT system.
- Comfort Decisions: Frequency and rationale behind adjustments made by users to HVAC and lighting systems, reflecting their concern for comfort versus energy efficiency.
- Environmental Footprint: Aggregated data from DT logs estimated the collective energy savings generated by student and faculty interactions over a semester, helping quantify behaviour-driven impact.

Metric	Pre-intervention	Post-intervention
Awareness (%)	38	81
Self-Reported Behavioural Intention (%)	52	87
Energy Use Reduction (%)	Baseline	-14.3

Table 2. Behaviour and Awareness Metrics

Source: The author

Preliminary results indicate that students who regularly engaged with the DT platform demonstrated higher sustainability literacy and reported greater motivation to conserve energy both on and off campus (Muka, 2023). Moreover, gamification and real-time feedback features significantly increased user interaction frequency, reinforcing DTs' potential to drive behavioural change.

V. CONCLUSIONS

This study demonstrated the strong potential of Digital Twin (DT) technologies, integrated through a Project-Based Learning (PBL) approach, to enhance sustainability education within the Education 4.0 framework. At Polis University, students engaged directly with real-time digital replicas of campus infrastructure, gaining technical skills in IoT, programming, and 3D modelling while also developing a deeper understanding of sustainability and their own environmental impact.

Quantitative results showed significant gains in energy literacy, with an accurate understanding of HVAC energy dynamics increasing from 38% to 81%, and in behavioural shifts, with 73% of students reporting greater awareness of their role in campus energy use. Classrooms using the DT system regularly achieved a 14.2% reduction in energy consumption, with an additional 5.6% reduction when gamification features were active. These findings confirm the value of real-time feedback and interactive systems in promoting sustained behavioural change. Faculty and students praised the system's clarity and impact, though concerns around data privacy and accessibility highlight the need for robust onboarding, equitable access, and clear data policies. The system's modular and open-source design supports scalability and adaptability, making it feasible for deployment across broader campus contexts or other institutions.

Future work will focus on expanding the DT system campus-wide, integrating renewable energy data, developing VR-based immersive learning environments, and embedding DT tools into Learning Management Systems. Long-term studies and cross-campus collaborations are also planned to assess sustained impact and replicability.

In conclusion, DT systems offer a replicable, engaging, and data-driven way to bridge technical education and sustainability action. As both educational tools and smart infrastructure solutions, they empower students to become informed, active participants in addressing environmental challenges, making them vital to the future of sustainability education.

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