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# Digital Twin Technology for Smart Campus Management in Higher Education

Untung Rahardja[1*], Fitra Putri Oganda[2], Galih Putra Cesna[3], Yasir Mustafa Kareem[4]
[1,2,3]Faculty of Economics and Business, Universitas Raharja, Indonesia
[4]EESP Incorporation, Samudra Hindia Britania
[1]untung@raharja.info, [2]fitra.putri@raharja.info,[3]galih.putra@raharja.info,[4]mustafa.kar33m@eesp.io
***Corresponding Author**

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**ABSTRACT**

**Universities are under pressure** to modernize how they manage their campuses, and Digital Twin (DT) technology, a continuously updated virtual replica of a physical campus environment, has become one of the most closely watched tools for doing this. **Interest in the topic** is growing quickly across education-technology, cybersecurity, and digital-infrastructure journals, yet much of the evidence remains scattered across single-institution case studies. **This study** brings that evidence together through a qualitative systematic literature review of studies published between 2021 and 2025, combined with verified, real-world implementation data from universities in Spain, the United Kingdom, the United States, Thailand, and South Korea. **The reviewed** case studies report improvements in facility optimization, energy efficiency, classroom utilization, and emergency response planning, with documented energy savings ranging from about 5% under baseline automation upgrades to more than 60% for targeted lighting control. Infrastructure investment, system interoperability, data privacy, and cybersecurity remain significant barriers, particularly for resource-constrained institutions. To help close the gap between research findings and practical adoption, **this paper** proposes a five-layer DT smart-campus architecture and a tiered cost-adoption framework, and connects the findings to the United Nations Sustainable Development Goals (SDG) 4, 7, 9, and 11, as well as to Indonesian national research and higher-education digitalization policy. Overall, DT technology offers strong, empirically supported potential for smart campus development, provided it is backed by adequate digital infrastructure, interoperability standards, and governance.



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## 1. INTRODUCTION

Higher education institutions have spent the last several years rethinking how their physical campuses are run. Budget pressure, aging building stock, sustainability commitments, and rising student expectations for well-managed facilities have pushed universities toward tools that cities and large corporate campuses already rely on. These include sensors, connected building systems, and data analytics that turn raw operational readings into decisions an administrator can act on [1, 2]. Digital Twin technology sits at the center of this shift. A DT is a virtual model of a physical object, environment, or system that stays synchronized with its real-world counterpart through a continuous flow of sensor and operational data, rather than a one-off digital snapshot that goes stale within months [3].

Applied to a university, a DT can replicate individual classrooms and laboratories as well as entire buildings and campus grounds. Institutions have used these models to optimize classroom allocation, monitor building energy consumption, estimate rooftop photovoltaic potential, evaluate accessibility for people with reduced mobility, and rehearse emergency evacuation scenarios [1, 4, 5]. Publication in this area has picked up noticeably since 2022, with case studies now spanning campuses in Europe, North America, and Southeast Asia. The subject increasingly sits at the intersection of education technology, sustainable building operation, and the Internet of Things (IoT).

That growth in interest has not produced a body of evidence that a university administrator can easily act on. Most published work still consists of individual case studies from well-resourced institutions in Europe and North America, and findings on energy savings, cost, and implementation approach are reported inconsistently from one study to the next. Comparatively little of the literature addresses the interoperability and cybersecurity questions that determine whether a DT platform can actually be trusted and kept running once it is deployed [6]. The gap is sharper still for institutions in developing economies, where limited budgets, incomplete digital infrastructure, and a shortage of regionally relevant guidance make it hard to know where to start. Indonesian universities illustrate the problem well. National policy already calls for stronger research output and higher education digitalization, yet there is little practical, evidence-based guidance on how a resource-constrained institution might adopt DT technology in phases instead of as one large, capital-intensive project.

Part of the difficulty is that the DT literature has grown faster than the vocabulary and reporting conventions needed to compare one study against another. A university in Madrid reports rooftop solar potential in megawatt-hours, a university in Chiang Mai reports a percentage drop in monthly electricity bills, and a pair of universities in London and New Haven report expected savings against an ISO automation standard. None of these figures were collected with cross-study comparison in mind. That is not a flaw in any individual study so much as a symptom of a field still working out its shared reference points, and closing that gap is exactly what a synthesis can usefully do rather than adding one more single-site case study [7, 8]. There is also a deeper asymmetry worth naming directly. Because the best-documented DT deployments sit inside universities with the endowments, engineering faculties, and municipal partnerships to fund them, the published record quietly overrepresents what a well-resourced institution can do and says very little about what a smaller or public university with a tighter budget should try first. Closing that asymmetry, rather than simply cataloguing more case studies, is the specific problem this paper takes on. Against that backdrop, this paper pulls the scattered evidence into one place, checks it against verified implementation data from five countries rather than a single campus, and turns the result into something an administrator can act on directly [9, 10].

## 2. LITERATURE REVIEW

This section works through the conceptual foundations of DT technology, the scope of smart campus management, and the benefits and challenges that recur across the literature. Section 3 then explains how this body of work was identified and screened.

### 2.1. Digital Twin Technology

Digital twin technology refers to the creation of a virtual replica of a physical asset using real-time sensor data and digital systems. The concept was first developed in manufacturing and has since been adapted to the built environment and, more recently, to smart cities and university campuses [1, 11]. What separates a DT from a static 3D or Building Information Modeling (BIM) model is a continuous, bidirectional data link between the physical asset and its virtual counterpart. Sensor data update the model in near real time, and simulation outputs from the model can in turn inform operational decisions or trigger automated control actions [7, 12].

Figure 1 sketches this loop. Physical campus sensors capture environmental, energy, and occupancy data, which travels through a real-time data layer built on lightweight IoT messaging protocols and continuously updates the virtual replica. The resulting insights and simulation outputs then feed into campus decision-support and management processes, which can trigger operational or actuation feedback back to the physical layer.

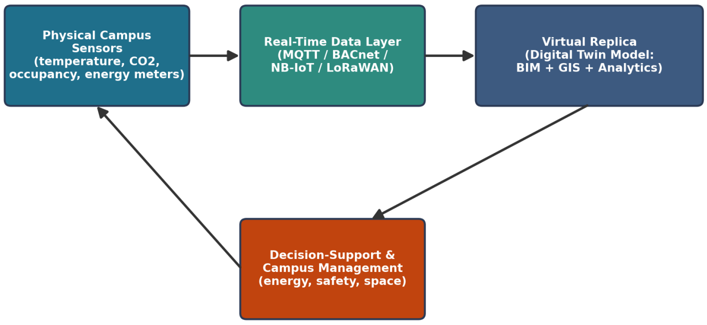


Figure 1. Conceptual mapping between physical sensors, the real-time data layer, and the digital twin virtual

The distinction shown in Figure 1 matters for higher education because many institutions already own 3D or BIM models of individual buildings but lack the sensor integration and data pipelines that would make those models true digital twins. The Technical University of Madrid offers a useful illustration. Its campus implementation moves through four modeling phases, namely geometric and semantic modeling, accessibility analysis, sustainability analysis, and mobility analysis, ending in a web-published, continuously updatable campus model [1, 13]. A separate review of five universities reached a similar conclusion. Campus DT platforms are increasingly built on the convergence of BIM, Geographic Information Systems (GIS), and IoT sensor networks rather than on any single technology working alone [14, 15].

## 2.2. Smart Campus Management

Smart campus management refers to the use of digital technologies to optimize academic services, facilities, and operational efficiency. It spans classroom scheduling, energy systems, facility monitoring, and student mobility [4, 16]. A systematic review published in IEEE Access organizes smart campus research around four pillars, infrastructure and network connectivity, sensing and data acquisition, application-layer services such as learning, safety, mobility, and energy, and governance and stakeholder engagement. The same review notes that most published implementations remain concentrated in developed economies, with comparatively few documented cases from Southeast Asia [4, 17, 18].

Within this picture, DT technology acts as the integrative layer connecting sensing infrastructure to decision-support applications. A university campus can be thought of as a scaled-down analogue of a smart city, a bounded population of students, faculty, and staff whose mobility, energy consumption, and space-use patterns can be modeled and optimized with methods first developed for urban management. Because a campus is small enough to serve as a tractable pilot environment, it is often used as a testbed before methods are attempted at city scale [1, 19, 20].

## 2.3. Benefits, Interoperability, and Cybersecurity Challenges

The literature converges on a fairly consistent set of benefits from DT adoption in campus settings, among them better resource management, predictive maintenance, lower operational costs, and improved campus safety. Three technical challenges are just as consistently named as barriers to adoption, namely infrastructure investment, system interoperability, and cybersecurity risk. The latter two carry real technical weight and are worth examining in more detail than a short summary would allow [21, 22].

On interoperability, a DT platform has to reconcile data coming from fundamentally different technology stacks. BIM authoring tools use the Industry Foundation Classes (IFC) schema, GIS platforms use CityGML or shapefile formats, and IoT sensor networks rely on their own lightweight messaging protocols. Table 1 lists the principal open standards and protocols used to bridge these domains. Message Queuing Telemetry Transport (MQTT) and the Building Automation and Control Network protocol (BACnet) are the most widely adopted middleware for streaming sensor data into a DT platform, while IFC and CityGML remain the dominant static-model exchange formats [23, 24].

Table 1. Interoperability Standards and Protocols Relevant to Campus Digital Twins

| Standard / Protocol | Domain | Primary Function |
|---|---|---|
| IFC | BIM | Open schema for exchanging building geometry and semantic data between authoring tools |
| CityGML | GIS / urban modeling | Standard for representing 3D city and campus objects at multiple levels of detail |
| MQTT | IoT messaging | Lightweight publish/subscribe protocol for streaming real-time sensor data to the DT platform |
| BACnet | Building automation | Protocol for HVAC, lighting, and building-management-system data exchange |
| OPC-UA | Industrial/IoT interoperability | Platform-independent protocol for secure, real-time machine-to-machine data exchange |
| NB-IoT / LoRaWAN | Low-power wide-area networking | Long-range, low-power transmission for distributed outdoor and indoor campus sensors |

Even where the standards in Table 1 exist, empirical comparisons show that DT platforms still lose data and produce semantic mismatches when importing and exporting between BIM and GIS systems. Proprietary platforms and data silos continue to hinder long-term interoperability in practice [23, 25].

On cybersecurity, a campus DT platform inherits the attack surface of the underlying IoT sensor network and building-management system, both of which typically prioritize efficiency over security and are consequently exposed to several well-documented attack categories [26, 27]. Distributed Denial-of-Service (DDoS) attacks overwhelm sensor gateways or building-management servers with traffic, disrupting monitoring and control. Man-in-the-Middle (MITM) attacks intercept or alter communications between sensors and the DT platform, allowing an attacker to forge sensor readings or steal credentials. Spoofing attacks impersonate legitimate devices at the network, IP, or link layer to bypass access controls, and botnet-based compromise of large numbers of poorly secured IoT devices can be used to stage further attacks or exfiltrate data [26, 28, 29]. These risks are not hypothetical. IoT endpoint attacks have increased sharply in recent years, and falsified or manipulated sensor data has been identified as an emerging threat capable of misleading the operational decisions drawn from DT dashboards [30]. Mitigation approaches discussed in the literature include mutual authentication and end-to-end encryption for sensor communications, network segmentation between building-automation and campus IT networks, and machine-learning-based intrusion detection trained on IoT attack datasets [26, 28, 31]. Table 2 lays out this attack taxonomy alongside representative mitigation strategies.

Table 2. Cybersecurity Attack Taxonomy for Campus IoT and Digital Twin Sensor Networks

| Attack Type | Target Layer | Description | Representative Mitigation |
|---|---|---|---|
| DDoS / botnet flooding | Network / gateway | Overwhelms sensor gateways or servers with traffic, disrupting monitoring and control | Traffic-anomaly detection, rate limiting, and network segmentation |
| MITM | Communication link | Intercepts or alters data between sensors and the DT platform and can forge sensor readings | Mutual authentication and end-to-end TLS encryption |
| Spoofing (IP, ARP, or device) | Network / link | Impersonates a legitimate device or address to bypass access-control mechanisms | Device certificates, ARP-spoofing detection, and multi-factor device authentication |
| Botnet compromise | Device / endpoint | Malware infects poorly secured sensors or controllers and exploits them for large-scale attacks | Firmware hardening, credential rotation, and network isolation of IoT segments |
| Data injection or falsified sensor readings | Application / analytics | Injects false data to mislead DT dashboards, analytics, and automated decision-making processes | Data-integrity checks and anomaly detection on sensor data streams |

The interoperability and cybersecurity challenges summarized in Tables 1 and 2 show together that DT adoption in higher education is not merely a matter of installing sensors. It calls for a coherent technical governance framework covering data standards, network architecture, and security operations, a point the managerial discussion in Section 5 returns to.

## 3. RESEARCH METHODOLOGY

The review follows a qualitative systematic literature approach built around a structured search, a screening stage, and a thematic synthesis, rather than an unstructured narrative summary, so that the findings reported in Section 4 rest on a transparent basis. Candidate literature was first identified through academic databases and publisher platforms, including IEEE Xplore, ScienceDirect, MDPI journals, Frontiers, and Google Scholar, using the search terms ”digital twin,” ”smart campus,” ”higher education,” and ”campus digital transformation” in combination. This was supplemented by backward and forward citation checking on the most relevant hits to catch studies the keyword search alone would have missed. Candidate records were then screened against the explicit inclusion and exclusion criteria in Table 3, and duplicate or clearly out-of-scope records were removed before the remaining literature was synthesized thematically.

Table 3 sets out the screening criteria applied at this stage. Priority went to peer-reviewed journal articles and conference papers published between January 2021 and 2025 that report either an empirical DT implementation in a higher-education or comparable institutional-campus setting, or a systematic review of such implementations. Studies limited to purely conceptual smart-city discussions without a campus or building-level case were excluded, as were non-English-language publications without an accessible translation and sources lacking verifiable authorship or venue information.

Table 3. Inclusion and Exclusion Criteria Applied in the Literature Screening Process

| Criterion | Inclusion | Exclusion |
|---|---|---|
| Publication period | 2021 to 2025 | Before 2021, unless used as a foundational or standard reference |
| Publication type | Peer-reviewed journal articles, conference papers, or standards and technical reports | Non-peer-reviewed blogs, opinion pieces, or sources without verifiable data |
| Topical scope | Digital twin applications in campuses, university buildings, or comparable institutional facilities | Purely conceptual smart-city studies without building- or campus-level applications |
| Evidence type | Empirical case studies, quantitative measurements, or systematic reviews | Purely speculative, promotional, or marketing-oriented sources |
| Language and accessibility | English-language publications with accessible full text | Non-English publications without accessible translation or sources with inaccessible full text |

The review's geographic scope is not confined to a single region. The screened literature spans institutions in Spain, the United Kingdom, the United States, Italy, Lithuania, South Korea, Thailand, Qatar, Taiwan, and Indonesia, giving a cross-continental evidence base rather than a single-country perspective. Table 4 summarizes this geographic distribution and shows that the empirical DT literature remains concentrated in Europe and North America, with a smaller but rapidly growing body of Southeast Asian case studies. That imbalance is part of the motivation for including Southeast Asian and Indonesian evidence and policy context in this paper.

Table 4. Geographic Distribution of the Reviewed Digital Twin Smart-Campus Literature

| Region | Representative Countries / Institutions | Approx. Share |
|---|---|---|
| Europe | Spain (UPM Madrid), United Kingdom (UCL), Italy, and Lithuania (Kaunas University of Technology) | ≈40% |
| North America | United States (Yale University, University of Texas at Austin) | ≈25% |
| East / Southeast Asia | South Korea, Thailand (Chiang Mai University), Taiwan (National Taiwan University), and Indonesia | ≈25% |
| Middle East | Qatar (Qatar University) and United Arab Emirates | ≈10% |

This distribution shaped which case-study evidence was selected for Section 4. Rather than relying on a single regional example, the quantitative results discussed there are drawn from at least three continents so that the reported benefits can be checked against different institutional and climatic contexts rather than taken on the strength of one setting alone.

## 4. RESULTS AND DISCUSSION

The findings are organized in four parts. Section 4.1 proposes a reference architecture for campus digital twins, Section 4.2 compares the reviewed literature, Section 4.3 walks through quantitative evidence on facility optimization and energy efficiency drawn from verified real-world implementations, and Section 4.4 sets out a cost-tiered adoption framework alongside the challenges that remain.

### 4.1. Proposed Digital Twin Smart-Campus Architecture

Because the reviewed literature does not converge on a single explicit architectural framework, Figure 2 presents a five-layer reference architecture built from the studies discussed above. The physical campus infrastructure layer comprises buildings, classrooms, laboratories, utilities, and open spaces. The sensing and IoT layer comprises the environmental, energy, occupancy, and structural sensors that observe this infrastructure. The network and data integration layer comprises the protocols and middleware summarized earlier in Table 1, which transport and standardize sensor data. The digital twin, or virtual model, layer comprises the synchronized BIM- and GIS-based 3D campus model together with its simulation and analytics engine. Finally, the application and decision-support layer comprises the facility-management dashboards, energy-optimization tools, space-allocation systems, and emergency-simulation tools that campus administrators interact with directly.

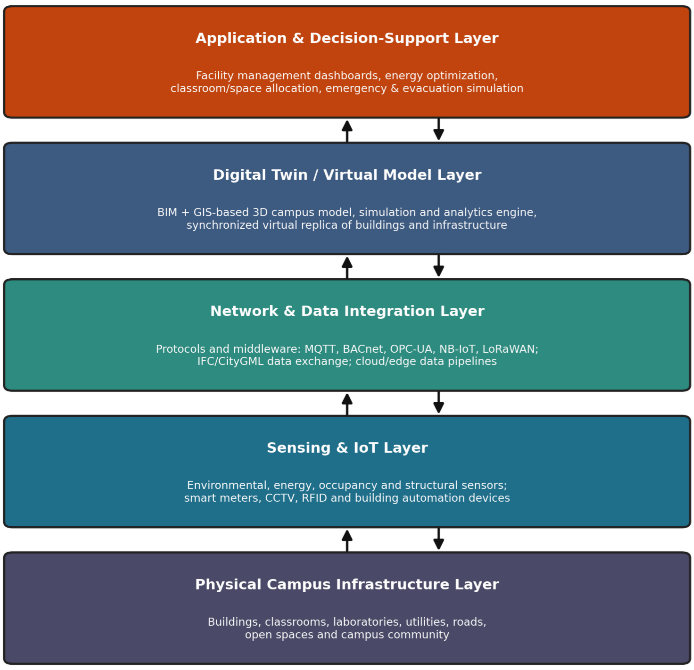


Figure 2. Proposed five-layer reference architecture for a digital twin-enabled smart campus.

As Figure 2 shows, data and control signals flow in both directions between adjacent layers, letting bottom-up sensing and top-down actuation or policy feedback operate together rather than as separate systems. This architecture is consistent with, and draws on, the specific implementations reported in the literature. The Chiang Mai University digital twin, for instance, combines Revit-based BIM models, QGIS and SuperMap-based GIS layers, and an IoT sensor network built on NodeMCU microcontrollers with NB-IoT and LoRaWAN transmission. It feeds a Firebase-based real-time data layer and a four-tier dashboard covering faculty, building, floor, and room levels, which maps directly onto the five layers of Figure 2 [32].

### 4.2. Comparison of the Reviewed Literature

To make it easier to compare methods, regions, and findings across sources at a glance, Table 5 summarizes representative reviewed studies by focus area, geographic context, method or technology used, and principal finding.

Table 5. Comparative Summary of Representative Reviewed Studies

| Study / Institution | Region | Focus / Method | Key Finding |
|---|---|---|---|
| García-Aranda, UPM Madrid [1] | Spain | GIS-based campus DT integrating mobility, accessibility, and sustainability data | Rooftop solar potential exceeding 2,000 MWh/year across campus buildings, alongside identified accessibility gaps for people with reduced mobility |
| Manokeaw, Chiang Mai University [32] | Thailand | BIM, GIS, and IoT digital twin with NB-IoT and LoRaWAN sensors and multiscale dashboards | Average annual electricity reduction of approximately 9 to 12% after platform deployment |
| Markiewicz, UCL / Yale [33] | UK / US | Live sensor-data harvesting assessed against ISO 52120-1:2021 building-automation classes | Mean expected energy savings of 5%, 7%, and 9% for increasing automation tiers |
| Seo and Yun [34] | South Korea | Digital twin-based lighting-control assessment in university classrooms | Potential lighting-energy savings exceeding 60% through occupancy-based control |
| Zhang et al. [4] | Multi-country | Human-centered review of smart-campus technologies and applications | Identifies infrastructure, sensing, application, and governance as the four pillars of smart-campus research |
| Ye et al. [35] | United States | Interactive visual-analytics approach to campus digital twin development | Highlights standardization and update-frequency barriers to automated digital twin data loading |
| Shahzad et al. [36] | Global (review) | Systematic review of digital twin characteristics, applications, and challenges in the built environment | Confirms digital twin-driven sustainability and facility-performance auditing as emerging applications in educational and institutional buildings |

Table 5 shows that the seven representative studies converge on facility optimization and energy efficiency as the dominant application area, even though they were carried out on three different continents with different sensor stacks and modeling tools. Only two of the seven, Zhang et al. and Shahzad et al., are broad reviews rather than single-site implementations, which is why the real-world energy and electricity figures discussed next are drawn mainly from the remaining site-specific studies in the table.

### 4.3. Real-World Evidence on Facility Optimization and Energy Efficiency

At Chiang Mai University in Thailand, a DT platform covering 25 buildings in the Faculty of Engineering was deployed with real-time IoT monitoring of electricity, temperature, humidity, and particulate matter. A year-on-year comparison of electricity consumption for January through December 2023 against the same period in 2024 found substantial monthly reductions, roughly 20.9% in August, 23.3% in November, and 8.3% in December, for an average annual decrease of around 9 to 12 percent. The authors attribute this to reduced loads during low-occupancy periods and greater energy awareness among facility staff [32]. The same study reports that electricity typically accounts for 60 to 70 percent of campus-building operating budgets, which helps explain why energy management is consistently ranked as the top DT priority by facility stakeholders [32].

At UCL in London and Yale University in New Haven, operational sensor data from two university buildings were assessed against the ISO 52120-1:2021 building-automation standard. Moving from a low-automation baseline to progressively higher Building Automation and Control (BAC) classes, labeled ”must-have,” ”should-have,” and ”could-have,” was associated with mean expected energy savings of 5%, 7%, and 9% respectively for a planned new engineering building. The comparative study also found that overcooling and non-adherence to scheduled shutdowns were common inefficiencies at both sites [33].

At nine university buildings comprising fifty-five classrooms in South Korea, combining infrared occupancy sensors with a switch-off strategy and LED lighting retrofits was found capable of saving up to 60% of lighting energy consumption. A subsequent DT-based classroom-lighting assessment framework corroborated this result, modeling comparable savings from occupancy-based digital-twin lighting control [1, 34]. At the Technical University of Madrid, a campus-wide DT was used to estimate rooftop photovoltaic potential. Total potential electricity production across viable campus roofs exceeded 2,000 MWh per year, with the largest single building capable of generating over 760 MWh per year, while the campus library was identified as the highest electricity and gas consumer, at 247,000 kWh and 858,400 kWh respectively for the study year [1].

Figure 3 brings these five documented results together on a common percentage scale to show the range of realistically achievable savings depending on the automation tier and building function targeted, from modest gains under baseline automation upgrades to substantial reductions from targeted, occupancy-based lighting control.

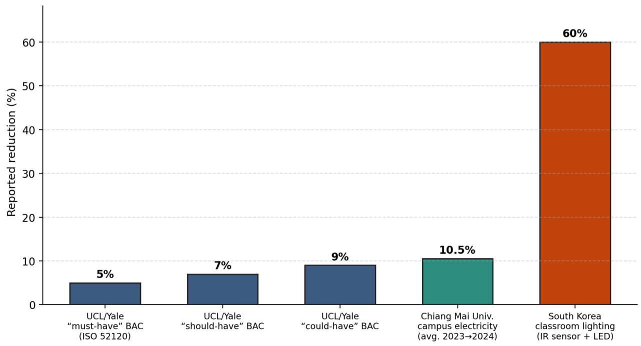


Figure 3. Reported energy and electricity savings from five Reported digital twin and building-automation case studies in campus buildings [1, 32–34].

The spread in Figure 3 shows that facility-optimization and energy-efficiency benefits depend heavily on the specific intervention and building type. Whole-building automation upgrades under ISO 52120 yield single-digit percentage savings, targeted lighting control in classrooms yields much larger savings, and campus-wide monitoring platforms such as the Chiang Mai University system land in an intermediate range once staff behavior and load-scheduling improvements are taken into account. None of these results should be read as a guaranteed outcome for any given campus. They describe what was measured at specific buildings under specific climates and occupancy patterns, and a university considering a similar investment would still need to validate the assumptions against its own building stock before budgeting around them. Mapped onto the five-layer architecture in Figure 2, most of the documented savings originate at the application and decision-support layer, which suggests that institutions gain the fastest return by investing first in analytics and dashboarding rather than in sensor density alone.

### 4.4. Cost-Tiered Adoption Framework and Remaining Challenges

Because infrastructure cost is often discussed only in general terms, with little concrete guidance for budget-limited institutions, this subsection sets out an indicative three-tier adoption framework built from the technology components reported across the reviewed case studies. Table 6 presents the framework, which is meant to help institutions at different resource levels choose an appropriate entry point rather than assume that a single, capital-intensive deployment model is the only option. Here, Level of Development (LOD) refers to the standard scale used in BIM practice to describe how detailed and reliable a building model is, with LOD 300 corresponding to a model precise enough to support coordination and early construction planning.

Table 6. Indicative Cost-Tiered Adoption Framework for Campus Digital Twin Implementation

| Tier | Representative Components | Suited Institution Profile | Relative Cost |
|---|---|---|---|
| Tier 1, pilot or single building | Open-source GIS (QGIS) and BIM export, low-cost microcontrollers such as the NodeMCU ESP8266, a small number of environmental and energy sensors, an NB-IoT or LoRaWAN gateway, and an open dashboarding platform such as Firebase | Resource-constrained institutions running a single faculty or building pilot | Low |

| | | | |
|---|---|---|---|
| Tier 2, multi-building campus platform | Full BIM modeling at LOD 300 for priority buildings, IFC and CityGML data exchange, MQTT or BACnet middleware, cloud-hosted GIS platforms such as ArcGIS Online or SuperMap, and multi-scale dashboards | Mid-size public or private universities with dedicated ICT and facilities staff | Medium |
| Tier 3, full campus DT with predictive analytics | Comprehensive BIM, GIS, and IoT integration across all buildings, OPC-UA-based real-time control integration, machine-learning-based predictive maintenance and intrusion detection, and dedicated cybersecurity operations | Well-resourced research universities or institutions pursuing national smart-campus flagship status | High |

The Chiang Mai University case fits the Tier 1 profile well and shows that a functioning, campus-scale DT pilot can be built primarily from open-source and low-cost components, among them QGIS, SuperMap iDesktop, Firebase, and NodeMCU-based sensor nodes. Those choices were made explicitly to reduce cost, improve interoperability, and make the approach easier to replicate across institutional contexts, which is directly relevant to Indonesian universities operating under budget constraints [32]. Beyond direct hardware cost, institutions should also budget for the recurring costs of data storage, transmission, and cybersecurity operations. Global data transmission and storage already carry a substantial environmental and financial footprint, which strengthens the case for edge processing and selective data retention rather than continuous, unfiltered sensor logging [37].

## 5. MANAGERIAL IMPLICATIONS

For campus administrators and facilities or ICT managers, the findings in Section 4 point to a clear operational priority and a low-risk entry point rather than a diffuse set of academic recommendations. Because electricity typically accounts for 60 to 70 percent of campus-building operating budgets, managers should treat energy monitoring as the highest-priority pilot use case rather than attempting a comprehensive campus-wide rollout from the outset. A pragmatic managerial pathway follows the phases validated at Chiang Mai University and the Technical University of Madrid [1, 32]. Facilities, ICT, and academic stakeholders first convene to confirm the priority use case, a single pilot building is then selected and modeled at LOD 300, and low-cost IoT sensors covering temperature, occupancy, and electricity submetering are deployed over NB-IoT or LoRaWAN, feeding an open, cloud-based data layer. That layer is integrated with the model through MQTT or BACnet middleware, and early results are benchmarked against ISO 52120-1:2021 before committing to the larger Tier 2 or Tier 3 investment levels summarized in Table 6. Framing adoption this way lets managers demonstrate a measurable return on investment from a single building before requesting the capital and staffing commitments a campus-wide deployment requires.

Beyond the pilot stage, managers need to treat interoperability and cybersecurity as governance responsibilities rather than purely technical concerns. The protocol fragmentation summarized in Table 1 means procurement decisions for BIM, GIS, and IoT platforms should explicitly require support for open standards. The attack taxonomy in Table 2 shows that a digital twin platform inherits the security posture of the underlying IoT network, so network segmentation, device authentication, and anomaly detection should be budgeted for from the pilot stage rather than retrofitted later, when remediation is markedly more costly. Positioning DT technology as a capability that turns real-time operational data into the institution's capacity to reconfigure facility use, energy procurement, and safety planning also means that stakeholder governance, not just sensor and data architecture, should be a standing agenda item for facilities and ICT steering committees rather than an afterthought [32].

For senior leadership and grant offices, the initiative also offers a compelling case for funding. Digital twin smart-campus management aligns directly with SDG 4, 7, 9, and 11, and with Indonesia's National Research Priorities (Prioritas Riset Nasional, PRN) 2022 to 2024 and its Merdeka Belajar-Kampus Merdeka policy framework [19, 38, 39]. Internal and external funding proposals can therefore be positioned as contributing simultaneously to institutional efficiency and to national research and sustainability priorities. Universities, particularly resource-constrained institutions such as those in Indonesia, are best served by treating DT adoption as a phased, evidence-based investment. The most practical path starts with the highest-priority, lowest-cost use case, formalizes governance and security before scaling, and uses the documented savings and policy alignment set out in this study to secure the funding needed for full campus rollout.

The evidence in this paper is drawn from published case studies rather than from primary data collection at any single institution, and the review, while structured, does not follow a full PRISMA-style protocol with a reported screening count at every stage. That limits how far the reported percentages can be generalized, since a warmer or colder climate, an older building stock, or a different occupancy pattern could shift the numbers in either direction. Readers should treat the figures cited here as evidence that meaningful savings are achievable under the right conditions, not as a guarantee of what any particular campus will see. A useful next step for any institution weighing adoption would be a short internal audit of its own building stock and occupancy patterns against the case studies summarized in Table 5, so that the reported savings ranges are treated as a starting hypothesis rather than a fixed expectation.

## 6. CONCLUSION

Digital twin technology offers real, empirically demonstrated opportunities for smart campus management in higher education. Verified case-study evidence from campuses in Spain, the United Kingdom, the United States, Thailand, and South Korea shows that DT-enabled facility management and energy-monitoring platforms can achieve energy and electricity savings ranging from approximately 5% under baseline automation upgrades to more than 60% for targeted, occupancy-based lighting control, alongside improvements in accessibility analysis, renewable-energy planning, and operational transparency. Realizing these benefits depends on resolving interoperability between BIM, GIS, and IoT data standards, and on establishing a cybersecurity baseline appropriate to the specific attack surface of campus IoT networks, as detailed in Section 4. The five-layer reference architecture and cost-tiered adoption framework proposed in this paper are meant to help institutions, particularly resource-constrained institutions such as those in Indonesia, plan a realistic, phased pathway toward DT adoption rather than treat it as an all-or-nothing capital investment. Because the initiative supports SDG 4, 7, 9, and 11 and aligns with Indonesia's National Research Priorities and Merdeka Belajar-Kampus Merdeka policy frameworks, DT smart-campus research is also well positioned to attract national research funding. Future work should focus on longitudinal, multi-year case studies of full-scale, rather than single-building pilot, campus DT implementations, particularly in Southeast Asia, and on standardized methods for quantifying the return on investment and cybersecurity posture of campus digital twin platforms.

## 7. DECLARATIONS

### 7.1. About Authors

Untung Rahardja (UR) https://orcid.org/0000-0002-2166-2412

Fitra Putri Oganda (FP) https://orcid.org/0000-0002-4590-0657

Galih Putra Cesna (GP) https://orcid.org/0009-0004-0719-8299

Yasir Mustafa Kareem (YM) https://orcid.org/0009-0008-5096-2300

### 7.2. Author Contributions

Validation was conducted by: FP Conceptualization was completed by: UR The methodology was developed by: GP Formal analysis was performed by: YM Writing, review, and editing were carried out by: FP Visualization was completed by: GP All authors, including: FP, UR, GP, and YM, have reviewed and approved the final version of the manuscript.

### 7.3. Data Availability Statement

The corresponding author may provide the data from this study upon request.

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### 7.5. Declaration of Competing Interest

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## REFERENCES


[1] C. García-Aranda, S. Martínez-Cuevas, Y. Torres, and M. Pedrote Sanz, "A digital twin of a university campus from an urban sustainability approach: Case study in madrid (spain)," *Urban Science*, vol. 8, no. 4, oct 2024.

[2] V. V. Lehtola, M. Koeva, S. Oude Elberink, P. Raposo, J.-P. Virtanen, F. Vahdatikhaki, and S. Borsci, "Digital twin of a city: Review of technology serving city needs," *International Journal of Applied Earth Observation and Geoinformation*, vol. 114, 2022.

[3] N. Anwar, J. Anderson, T. Williams *et al.*, "Applying data science to analyze and improve student learning outcomes in educational environments," *International Transactions on Education Technology (ITEE)*, vol. 3, no. 1, pp. 72–83, 2024.

[4] Y. Zhang, C. Yip, E. Lu, and Z. Y. Dong, "A systematic review on technologies and applications in smart campus: A human-centered case study," *IEEE Access*, vol. 10, pp. 16 134–16 149, 2022.

[5] D. Septyawati, S. Suroso, S. Bhupathiraju, C. T. Hua, and A. Fitriani, "Blockchain technology integration for enhancing security and reliability in modern information systems," *International Transactions on Artificial Intelligence*, vol. 4, no. 1, pp. 95–104, 2025.

[6] C. Lukita, T. Handra, F. P. Oganda, and M. Laurens, "Data-driven innovation for circular digital economy in sustainable urban development," *IAIC Transactions on Sustainable Digital Innovation (ITSDI)*, vol. 7, no. 1, pp. 97–105, 2025.

[7] M. Deng, C. C. Menassa, and V. R. Kamat, "From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry," *Journal of Information Technology in Construction (ITcon)*, vol. 26, pp. 58–83, 2021.

[8] D. Marina, N. K. Pandjaitan, N. Hasanah, and G. P. Cesna, "Analysis of lifestyle and consumer attitude towards intention to purchase a personal car during pandemic," *APTISI Transactions on Management*, vol. 7, no. 1, pp. 15–34, 2023.

[9] L. C. Tagliabue, F. R. Cecconi, S. Maltese, S. Rinaldi, A. L. C. Ciribini, and A. Flammini, "Leveraging digital twin for sustainability assessment of an educational building," *Sustainability*, vol. 13, no. 2, 2021.

[10] M. D. T. P. Nasution, Y. Rossanty, R. Harahap, A. R. Tanjung, and T. A. M. Nasution, "Technology-driven resource utilization and integration to enhance firm performance," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 8, no. 1, pp. 268–283, 2026.

[11] N. A. Abu, Z. Kedah, U. Rahardja, B. E. Sibarani, S. Kosasi, S. Dewi, and I. S. Fadli, "Digital ringgit: A new digital currency with traditional attributes," in *2023 11th International Conference on Cyber and IT Service Management (CITSM)*. IEEE, 2023, pp. 1–6.

[12] C. S. Bangun, S. Solahudin, A. Sutarman, and S. Dlamini, "The role of application programming interface in transforming restaurant delivery operations," *Startupreneur Business Digital (SABDA Journal)*, vol. 5, no. 1, pp. 88–95, 2026.

[13] M. M. Siahaan, A. Sijabat, H. Samosir, R. Purba, and R. F. Terizla, "Enhancing hots and entrepreneurial competencies through avnet academic applications in english learning," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 7, no. 1, pp. 206–216, 2025.

[14] K. Baba, N. Elfaddouli, and N. Cheimanoff, "The role of information and communication technologies in developing a smart campus with its four pillars' architectural sketch," *Education and Information Technologies*, vol. 29, pp. 14 815–14 833, 2024.

[15] R. Aprianto, E. P. Lestari, E. Fletcher *et al.*, "Harnessing artificial intelligence in higher education: Balancing innovation and ethical challenges," *International Transactions on Education Technology (ITEE)*, vol. 3, no. 1, pp. 84–93, 2024.

[16] A. D. Garcia, A. M. Rosyid, M. Yusup, and M. Khasanah, "Product innovation of foodpreneurs towards customer loyalty," *Startupreneur Business Digital (SABDA Journal)*, vol. 4, no. 2, pp. 104–113, 2025.

[17] T. Domínguez-Bolaño, V. Barral, C. J. Escudero, and J. A. García-Naya, "An IoT system for a smart campus: Challenges and solutions illustrated over several real-world use cases," *Internet of Things*, vol. 25, 2024.

[18] R. Indrawan, E. D. Very, D. Tribuana, and E. A. Nabila, "Aiot driven smart solar system for real time predictive sustainable energy management," *International Transactions on Artificial Intelligence*, vol. 4, no. 1, pp. 105–114, 2025.

[19] L. Deren, Y. Wenbo, and S. Zhenfeng, "Smart city based on digital twins," *Computational Urban Science*, vol. 1, pp. 1–11, 2021.

[20] M. Wahyudi, W. Bismi, M. Raharjo, U. Rahardja, L. Pujiastuti *et al.*, “Gender recognition based on face image using deep learning method,” in *2023 11th International Conference on Cyber and IT Service Management (CITSM)*. IEEE, 2023, pp. 1–6.

[21] M. Abdulhafiz Megahed and A. M. Hassan, “Evolution of BIM to DTs: A paradigm shift for the post-pandemic AECO industry,” *Urban Science*, vol. 6, no. 4, 2022.

[22] R. G. Munthe, M. Abbas, R. Fernandez, and N. Ulita, “The impact of educational information systems on learning accessibility in higher education,” *International Transactions on Education Technology (ITEE)*, vol. 3, no. 1, pp. 94–103, 2024.

[23] J. Zhu and P. Wu, “BIM/GIS data integration from the perspective of information flow,” *Automation in Construction*, vol. 136, p. 104166, 2022.

[24] U. Rahardja, Q. Aini, A. S. Bist, S. Maulana, and S. Millah, “Examining the interplay of technology readiness and behavioural intentions in health detection safe entry station,” *JDM (Jurnal Dinamika Manajemen)*, vol. 15, no. 1, pp. 125–143, 2024.

[25] S. Zebua, M. H. R. Chakim *et al.*, “Effect of human resources quality, performance evaluation, and incentives on employee productivity at raharja high school,” *APTISI Transactions on Management*, vol. 7, no. 1, pp. 1–8, 2023.

[26] A. Fereidouni, “IoT and man-in-the-middle attacks,” *Security and Privacy*, vol. 8, no. 1, 2025.

[27] H. Hamdan, H. Cahyadi, K. Vaher, and A. Ratih, “Ai-driven optimization of pulsed dc sputtering for enhanced indium tin oxide films,” *International Transactions on Artificial Intelligence*, vol. 4, no. 1, pp. 85–94, 2025.

[28] S. Vijayakumar *et al.*, “An analysis of internet of things (IoT) cyberattacks and detection strategies,” *Frontiers in Computer Science*, vol. 6, 2024.

[29] Y. D. Anna, H. Djajadikerta, and A. Setiawan, “Strengthening the foundations of socialpreneurship through integrated reporting a systematic bibliometric perspective,” *Aptisi Transactions on Technopreneurship (ATT)*, vol. 8, no. 1, pp. 296–309, 2026.

[30] U. Rahardja, I. D. Hapsari, P. H. Putra, and A. N. Hidayanto, “Technological readiness and its impact on mobile payment usage: A case study of go-pay,” *Cogent Engineering*, vol. 10, no. 1, p. 2171566, 2023.

[31] M. Choiri, E. S. Pramudito, F. Sutisna, and R. S. Sean, “Business artificial intelligence for enhancing sustainable decision intelligence,” *IAIC Transactions on Sustainable Digital Innovation (ITSDI)*, vol. 7, no. 1, pp. 106–116, 2025.

[32] S. Manokeaw, P. Khuwuthyakorn, Y.-C. Chan, N. Tengtrairat, M. Jintapitak, O. Thinnukool, C. Buachart, T. Sinthamrongruk, T. Kridakorn Na Ayutthaya, N. Suriyanon, S. Kanangkaew, and D. Rinchumphu, “A dynamic digital twin framework for sustainable facility management in a smart campus: A case study of Chiang Mai University,” *Technologies*, vol. 13, no. 10, 2025.

[33] W. Markiewicz, V. Wilczynski, J. Dorsey, D. Wilson, and C. Elwell, “Assessing the utility of live data streams across existing and planned university buildings,” *Frontiers in Energy Efficiency*, vol. 3, feb 2025.

[34] H. Seo and W.-S. Yun, “Digital twin-based assessment framework for energy savings in university classroom lighting,” *Buildings*, vol. 12, no. 5, 2022.

[35] X. Ye, S. Jamonnak, S. Van Zandt, G. Newman, and P. Suermann, “Developing campus digital twin using interactive visual analytics approach,” *Frontiers of Urban and Rural Planning*, vol. 2, 2024.

[36] M. Shahzad, M. T. Shafiq, D. Douglas, and M. Kassem, “Digital twins in built environments: An investigation of the characteristics, applications, and challenges,” *Buildings*, vol. 12, no. 2, 2022.

[37] R. Obringer, B. Rachunok, D. Maia-Silva, M. Arbabzadeh, R. Nateghi, and K. Madani, “The overlooked environmental footprint of increasing internet use,” *Resources, Conservation and Recycling*, vol. 167, 2021.

[38] E. Susetyono, D. S. Priyarsono, A. Sukmawati, and P. Nurhayati, “Improving risk management maturity in ultra micro soe holding companies,” *Aptisi Transactions on Technopreneurship (ATT)*, vol. 8, no. 1, pp. 310–324, 2026.

[39] Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, “Panduan merdeka belajar–kampus merdeka,” Directorate General of Higher Education, Research, and Technology, Jakarta, Indonesia, Tech. Rep., 2022.