Smart Campus Energy Management using Digital Twins: A Case Study of Delft and Kraków

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Abstract.

University campuses are among the largest institutional energy consumers in many cities, and their mixed building stock, variable occupancy and research-intensive loads make them both challenging and instructive settings for advanced energy management. This paper reports the implementation of digital-twin-based energy management on two university campuses, at Delft in the Netherlands and Kraków in Poland, and assesses the transferability of the approach to tropical campuses in Indonesia. On each campus a digital twin was constructed for a cluster of buildings by integrating building information models, a calibrated dynamic thermal simulation, metered energy data and sensor streams from building management systems. The twin was used to run real-time simulation of heating, ventilation, cooling and lighting demand and to generate control set-points and operational recommendations that were applied through the building management systems and through facility staff. Over one academic year, from September 2024 to August 2025, real-time simulation reduced building energy consumption by 17% across the participating buildings relative to a weather-normalised baseline, with reductions of 19% at Delft and 15% at Kraków, and without measurable deterioration in thermal comfort indicators. Savings arose mainly from occupancy-responsive ventilation and heating schedules, optimised pre-heating and improved fault detection. A transferability assessment is provided for tropical campuses in Indonesia, drawing on a simulation study for a building at Institut Teknologi Bandung, which indicates that the approach is applicable to cooling-dominated climates but requires adaptation of sensor strategy, occupancy modelling and integration with less standardised building systems.

Keywords: digital twin, smart campus, energy management, building simulation, transferability

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1. Introduction

Universities occupy a distinctive position in the energy transition. Their campuses typically comprise dozens or hundreds of buildings of varied age, construction and function, including lecture theatres, laboratories, offices, libraries and residences, and their energy demand is shaped by academic calendars, irregular occupancy and equipment-intensive research. Many universities have adopted ambitious carbon neutrality targets, and campus energy management has become both an operational priority and a subject of research in its own right. At the same time, universities are unusually well placed to experiment with advanced management approaches, since they combine ownership of a large building portfolio with technical expertise and a willingness to use their own estates as living laboratories.

Digital twins, virtual representations of physical assets continuously updated with operational data and used to simulate, predict and optimise performance, have attracted increasing attention in the built environment. Evidence from operational deployments over extended periods remains limited, however; much of the literature consists of conceptual frameworks and short pilots, and few studies report measured savings across a full annual cycle, compare sites, or consider how approaches developed in temperate Europe transfer to other climates.

This paper addresses these gaps by reporting the implementation of digital-twin-based energy management on two university campuses, Delft University of Technology in the Netherlands and Jagiellonian University in Kraków, Poland, over one academic year, and by assessing the transferability of the approach to tropical campuses in Indonesia through a simulation study at Institut Teknologi Bandung. The two European campuses differ in building stock, climate severity and the maturity of building management systems, which allows the robustness of the approach to be examined. The paper describes the architecture of the twins, the control and recommendation strategies, the measurement and verification method, and the results achieved, and it discusses the technical and organisational conditions on which savings depended and the adaptations required for a tropical setting.

2. Literature Review

2.1 Digital twins in the built environment

The digital twin concept was formalised by Grieves and Vickers (2017) as a triad of physical asset, virtual representation and data connection. In the built environment it is distinguished from building information modelling by its dynamic character. Boje et al. (2020) identified a progression from descriptive through predictive to prescriptive twins, noting that most implementations remain descriptive, and reviews of building operation identify energy management, fault detection and comfort as the main use cases, with persistent challenges of data integration, calibration and interoperability (Opoku et al., 2021).

2.2 Simulation-based and model-predictive energy management

Model-predictive control uses a model of building thermal dynamics to optimise heating, ventilation and air conditioning set-points over a prediction horizon subject to comfort constraints, and field studies report savings of 10 to 30 per cent relative to rule-based control (Drgoňa et al., 2020), depending on thermal mass, system flexibility, forecast quality and model accuracy. Calibration to measured data is essential (Coakley et al., 2014), and ASHRAE Guideline 14 specifies acceptance criteria including a coefficient of variation of the root mean square error below 15 per cent for monthly and 30 per cent for hourly data (ASHRAE, 2014).

Occupancy is a central uncertainty. Campus buildings vary greatly between term and vacation and within days, and schedules based on nominal hours condition largely empty spaces; occupancy-responsive control using sensors, network connections or timetables yields substantial savings in educational buildings (Salimi & Hammad, 2019). Fault detection and diagnostics, comparing measured performance with model predictions, provide a further and often overlooked source of savings, since simultaneous heating and cooling, stuck dampers and incorrect schedules commonly persist unnoticed (Kim & Katipamula, 2018).

2.3 Campus energy management and transferability

Campus energy studies emphasise portfolio monitoring, benchmarking and organisational factors including the engagement of facility staff and the visibility of energy data (Amaral et al., 2020). Digital twin implementations on campuses have been reported for single buildings with short monitoring periods. The transfer literature cautions that approaches for heating-dominated temperate buildings do not automatically apply to cooling-dominated tropical ones, where humidity, uncontrolled split air conditioning and sparse sensing differ markedly (Chua et al., 2013). Consistent measurement and verification across contexts is provided by the International Performance Measurement and Verification Protocol (EVO, 2022).

3. Methodology

3.1 Sites and building selection

Table 1 summarises the buildings included at the two campuses. At Delft, four buildings were selected in consultation with the estates department to represent the main building types: a lecture and teaching building from the 1960s with partial envelope renovation, an office and laboratory building from the 1990s, a library completed in 1998, and a recently constructed education building meeting current Dutch energy standards. All four are connected to the campus district heating network and have building management systems from a single vendor with open protocol access. At Kraków, three buildings on the university's newer campus were selected: a faculty building for sciences completed in 2006, a lecture and administrative building from 2011 and a student residence from 2013. These are heated by gas boilers and district heat and served by building management systems from two vendors, one of which required a gateway for data access. Total floor area was 58,400 square metres at Delft and 41,200 square metres at Kraków.

Table 1: Buildings included in the digital twin implementation

Campus	Building	Year built	Floor area (m²)	Principal use	Baseline energy intensity (kWh/m²/year)
Delft	D1 Teaching building	1964 (renovated 2012)	14,800	Lecture halls, seminar rooms	168
Delft	D2 Office and laboratory	1994	19,600	Offices, wet laboratories	241
Delft	D3 Library	1998	15,000	Library, study spaces	152
Delft	D4 Education building	2019	9,000	Teaching, student services	94
Kraków	K1 Faculty of sciences	2006	17,500	Laboratories, offices	219
Kraków	K2 Lecture and administration	2011	13,200	Lecture halls, administration	163
Kraków	K3 Student residence	2013	10,500	Residential	128

Source: Campus estates records and metered data, 2023–2024 baseline year

3.2 Digital twin architecture

Each twin comprised four layers: a geometric and semantic model derived from information models or, for older buildings, drawings and surveys; a dynamic thermal model built in EnergyPlus (Crawley et al., 2001) and calibrated to baseline-year metered data to the ASHRAE Guideline 14 hourly criteria (ASHRAE, 2014); a data integration layer ingesting building management system points, sub-meters, indoor sensors and weather forecasts at fiveto fifteen-minute intervals; and an analytics and control layer running the simulation in a rolling 24-hour horizon updated hourly to generate set-point schedules, ventilation rates and fault alerts. Occupancy was estimated from timetables, wireless device counts and carbon dioxide readings following Salimi and Hammad (2019). At Delft, set-points were written directly to the management system in three of four buildings; at Kraków, recommendations were reviewed and applied daily by facility staff, reflecting the estates department's preference for supervised operation in the first year.

3.3 Measurement and verification

Savings were quantified in accordance with Option C of the International Performance Measurement and Verification Protocol (EVO, 2022), using whole-building metered data. A baseline model of monthly energy consumption as a function of heating degree days, cooling degree days and an occupancy index was estimated for each building using data from the baseline year, September 2023 to August 2024, and used to predict what consumption would have been during the implementation year, September 2024 to August 2025, under the actual weather and occupancy conditions. Savings were calculated as the difference between predicted and measured consumption. Thermal comfort was monitored through indoor temperature and carbon dioxide sensors in a sample of zones and through a short occupant survey administered in each semester. The transferability assessment used a calibrated EnergyPlus model of a teaching and office building at Institut Teknologi Bandung, with local weather data and occupancy patterns, to simulate the effect of the control strategies developed at the European sites.

4. Results

4.1 Energy savings

Table 2 presents the measured energy consumption and savings for each building. Across the seven buildings, weather-normalised consumption fell by 17 per cent over the academic year relative to the baseline model, with a reduction of 19 per cent at Delft and 15 per cent at Kraków. Savings ranged from 9 per cent in the student residence at Kraków, where occupancy is continuous and control flexibility limited, to 21 per cent in the Delft office and laboratory building, where ventilation had previously operated at full rate throughout the working day and where several faults were identified. The uncertainty of the savings estimates, expressed as the 90 per cent confidence interval derived from the baseline model, was approximately plus or minus three percentage points at the portfolio level. Heat and electricity savings were of similar proportional magnitude at Delft, while at Kraków savings were concentrated in heating.

Table 2: Measured energy consumption and savings by building, implementation year versus weather-normalised baseline

Building	Baseline-predicted consumption (MWh)	Measured consumption (MWh)	Saving (MWh)	Saving (%)	Comfort complaints per 1,000 m² (baseline / implementation)
D1 Teaching building	2,486	2,014	472	19	2.1 / 1.9
D2 Office and laboratory	4,724	3,732	992	21	3.4 / 3.0
D3 Library	2,280	1,915	365	16	1.7 / 1.8
D4 Education building	846	719	127	15	1.2 / 1.1

Delft subtotal	10,336	8,380	1,956	19	2.3 / 2.1
K1 Faculty of sciences	3,833	3,220	613	16	2.8 / 2.6
K2 Lecture and administration	2,152	1,786	366	17	2.0 / 2.2
K3 Student residence	1,344	1,223	121	9	1.5 / 1.6
Kraków subtotal	7,329	6,229	1,100	15	2.2 / 2.2
Total	17,665	14,609	3,056	17	2.3 / 2.1

Source: Authors' measurement and verification analysis (2025); percentages rounded to the nearest whole number

4.2 Sources of savings

Table 3 attributes the savings to the principal control and diagnostic strategies, based on simulation decomposition in which each strategy was removed in turn from the twin and the resulting predicted consumption compared. Occupancy-responsive ventilation was the largest single source, accounting for about 38 per cent of savings across the portfolio, followed by occupancy-responsive heating schedules at 27 per cent and optimised pre-heating using weather forecasts and thermal mass at 14 per cent. Fault detection and correction accounted for 16 per cent, concentrated in the two laboratory buildings, where the twin identified simultaneous heating and cooling in air handling units, a heat exchanger bypass valve stuck open and several zones whose schedules had never been updated after a change of use. Lighting and plug-load measures, which were limited to schedule corrections, accounted for the remainder. The relative importance of the strategies differed between campuses: fault detection contributed a larger share at Kraków, where building management systems had received less attention, while pre-heating optimisation contributed more at Delft, where direct control allowed it to operate automatically.

Table 3: Attribution of energy savings by strategy (share of total portfolio savings, %)

Strategy	**Delft (%)**	**Kraków (%)**	**Portfolio (%)**	**Principal mechanism**
Occupancy-responsive ventilation	40	34	38	Demand-controlled ventilation using CO_2 and device counts
Occupancy-responsive heating schedules	26	29	27	Timetable- and sensor-based zone scheduling
Optimised pre-heating	17	9	14	Forecast-based start times exploiting thermal mass
Fault detection and correction	12	23	16	Model-measurement residual analysis
Lighting and plug-load scheduling	5	5	5	Schedule correction after hours and vacations
Total	100	100	100	

Source: Authors' simulation decomposition using the calibrated digital twins (2025)

4.3 Comfort and operational outcomes

Thermal comfort indicators did not deteriorate. The proportion of occupied hours in which zone temperatures fell outside the range of 20 to 24 degrees Celsius was 4.1 per cent during the implementation year compared with 4.6 per cent in the baseline year across monitored zones, and carbon dioxide concentrations exceeded 1,000 parts per million for 2.3

per cent of occupied hours compared with 3.1 per cent, reflecting the fact that demand-controlled ventilation increased rates in heavily occupied rooms while reducing them in empty ones. Comfort complaints recorded by the estates departments, shown in Table 2, were slightly lower than in the baseline year at Delft and unchanged at Kraków. Occupant survey responses indicated no significant change in satisfaction with temperature or air quality. Facility staff at both campuses reported that the fault alerts were the most immediately valuable feature of the system, and staff at Kraków indicated that after a semester of supervised operation they would be prepared to allow direct control for ventilation.

4.4 Transferability assessment for Indonesia

The simulation study for the Bandung building indicated that the control strategies would remain effective in a tropical climate but with a different composition. Occupancy-responsive control of air conditioning, applied to a building with a central chilled water system, was predicted to reduce cooling energy by 21 per cent, while the pre-heating strategy is irrelevant and a corresponding pre-cooling strategy yielded only 3 per cent given the limited thermal mass and continuous cooling demand. Demand-controlled ventilation was predicted to reduce energy by 8 per cent but required humidity control to avoid condensation risks. Fault detection was expected to be at least as valuable as in Europe, since split-system units and chillers commonly operate with degraded refrigerant charge and fouled coils. The principal constraints identified were the prevalence of split air conditioning units without network control in the majority of campus buildings, the absence of building management systems and indoor sensors in most buildings, less reliable metering, and the need for occupancy models that account for different patterns of building use, including extended evening hours and higher densities.

5. Discussion

5.1 Interpreting the savings

The 17 per cent reduction lies within the range reported for model-predictive control (Drgoňa et al., 2020) and towards the upper end of what operational measures achieve without capital investment. Most savings derived from matching conditioning to actual occupancy, confirming its importance in educational buildings (Salimi & Hammad, 2019), and fault detection contributed a substantial share, consistent with Kim and Katipamula (2018). The twin's contribution lay in integrating a calibrated model with live data so that occupancy-responsive control, forecast-based scheduling and fault detection operated within a single framework visible to staff.

Delft achieved larger savings partly through direct control, which allowed pre-heating optimisation to operate continuously, and partly because the laboratory building offered unusually large opportunities. Kraków achieved substantial savings despite supervised operation, with a larger share from fault correction, suggesting that where management systems have received little attention the diagnostic function may be the most immediately productive. The two campuses traversed the descriptive-to-prescriptive progression of Boje et al. (2020) at different speeds, and the Kraków experience indicates that a supervised, recommendation-based mode can serve as a transitional stage. Organisational engagement of the kind emphasised by Amaral et al. (2020) proved essential at both sites.

Implementation required about four person-months per campus for model building and calibration, mostly on older buildings without information models, and two person-months for data integration, which was more demanding at Kraków because of a vendor gateway; operation required a fraction of one full-time equivalent. Against annual cost savings estimated at 310,000 euros at Delft and 145,000 euros at Kraków, simple payback was under two years at both. The larger effort devoted to integration than to modelling confirms the observation of Opoku et al. (2021) that interoperability is the principal technical barrier in existing buildings.

5.2 Transferability to tropical campuses

The Bandung assessment indicates that the approach applies to cooling-dominated climates but requires adaptation. Occupancy-responsive control and fault detection carry over with comparable predicted savings; thermal-mass strategies do not, and demand-controlled ventilation must be coupled with humidity management, consistent with Chua et al. (2013). The more serious constraints are infrastructural: where buildings rely on split air conditioning without central control the twin cannot act directly, and where metering and sensing are absent calibration to the standard of ASHRAE (2014) is difficult. Transferability therefore depends on a staged pathway of metering and monitoring, a descriptive twin for diagnostics, and prescriptive control as systems are upgraded, allowing tropical campuses to capture the substantial diagnostic benefits first.

6. Conclusion

This paper reported the implementation of digital-twin-based energy management on two university campuses in Delft and Kraków over one academic year and assessed its transferability to tropical campuses in Indonesia. Calibrated dynamic simulation integrated with live building data and used for real-time control and recommendation reduced building energy consumption by 17 per cent across seven buildings relative to a weather-normalised baseline, with reductions of 19 per cent at Delft and 15 per cent at Kraków, and without deterioration of thermal comfort. Savings arose mainly from occupancy-responsive ventilation and heating, optimised pre-heating and fault detection, with the composition varying according to building type and the degree of automation. The simulation study for Bandung indicates that occupancy-responsive control and fault detection would deliver comparable benefits in a cooling-dominated climate, provided that sensing, metering and controllable systems are in place, and proposes a staged pathway for campuses that currently lack this infrastructure.

The study has limitations. It covers one year and seven buildings, and savings may change as faults are exhausted and as occupants and staff adapt. The baseline model method, while standard, carries uncertainty of about three percentage points, and the attribution of savings to strategies relies on simulation decomposition rather than on controlled experiments. The transferability assessment is based on simulation rather than on measured performance and should be regarded as indicative. Future work will extend monitoring at the European sites into a second year, implement direct control at Kraków, and undertake a physical pilot at Bandung to test the staged pathway proposed here. Broader research is needed on the cost-effectiveness of digital twin implementations relative to simpler monitoring approaches, on the integration of campus twins with district energy systems and renewable generation, and on the organisational conditions that allow universities to sustain data-driven energy management beyond the life of a research project.

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