The potential of live data streams in a building's human-in-the-loop digital twin to impact its energy consumption

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Abstract

With demand for more intelligent buildings growing, and the use of digital twins increasing, there remains a question over whether the costs of live data streams in digital twins are worth the benefits. This study seeks to address the costs and benefits of live data streams in digital twins and understand their impact in the built environment. Live data streams are harvested from a case study building, including electricity consumption, heat energy consumption, occupancy, room CO_2 concentrations, room temperatures, chiller operating temperatures, variable air volume flowrates, and air handling unit status.

A human-in-the loop digital twin was used, where the harvested data was analysed manually, resulting in improvement actions that were agreed with building stakeholders. Their potential benefits were calculated using results from an EnergyPlus model. Key findings suggested that by adapting building operations, both functionally and altering policy settings, the building could be operated more sustainably. Energy modelling results indicate that these improvements have the potential to provide electricity savings of 197.9 MWh/year and district heating savings of 27.7 MWh/year. An estimation of the energy footprint of the database used shows that 6.33 MWh per year are used for data transfer and storage.

Key Innovations

- Cost-benefit analysis of the potential impact on energy consumption of live data streams in digital twins
- Live data streams harvested in a human-in-the-loop digital twin and analysed to identify interesting cases and improvement opportunities
- Results from stakeholder engagement on harvested data, with energy implications simulated.

Practical Implications

There is potential for live data streams in digital twins to provide benefits that far outweigh their cost. However, for these benefits to be realised, data harvesting and analysis is not sufficient. BMS engineers and mechanical design expertise is needed to identify changes to control strategies and commissioning that can be implemented, and if necessary, amend the mechanical design. In addition to this, physical changes to building operation must be implemented to achieve a benefit. The COM-B model for behavioural change (West and Michie, 2020) provides a good framework in which to consider this challenge, with the digital twin data providing the Capability and Opportunity, leaving Motivation required to achieve the behavioural change necessary to deliver the potential benefits.

Introduction

Demand for more intelligent buildings is growing, and the use of digital twins has been increasing (Boje *et al.*, 2020). There remains a question over whether the costs of digital twins are worth the benefits, with IBM finding that 90% of harvested internet of things data is never used (McGovern, 2020). This paper seeks to address the costs and benefits of live data streams in digital twins and understand their impact on users and businesses in the built environment.

Existing literature provides a range of digital twin implementations and suggested examples (Khajavi *et al.*, 2019; Xie *et al.*, 2020; Daniotti *et al.*, 2022), however for the majority of implementations, there is a lack of quantitative assessment of the benefits of digital twins and live data streams (Cespedes-Cubides and Jradi, 2024). There are previous studies that quantify the benefits of digital twin implementations through energy simulations, for example from optimising equipment setpoints (Hosamo *et al.*, 2022; Petri *et al.*, 2023) or using occupancy data to optimise the amount of conditioned space and equipment schedule (Kim *et al.*, 2023; Piras, Muzi and Tiburcio, 2024). There also remains a lack of studies that carry out a cost-benefit analysis of digital twins.

The present study harvests live data streams from University College London's (UCL) One Pool Street (OPS) building and an EnergyPlus model in a human-in-the-loop digital twin (Abdelrahman *et al.*, 2025). Manual analysis of live data streams is used to identify potential improvement opportunities. These are discussed with building stakeholders, and their impact is assessed using the EnergyPlus simulation. The energy footprint of the live data streams used is also calculated and considered in the light of the potential benefits.

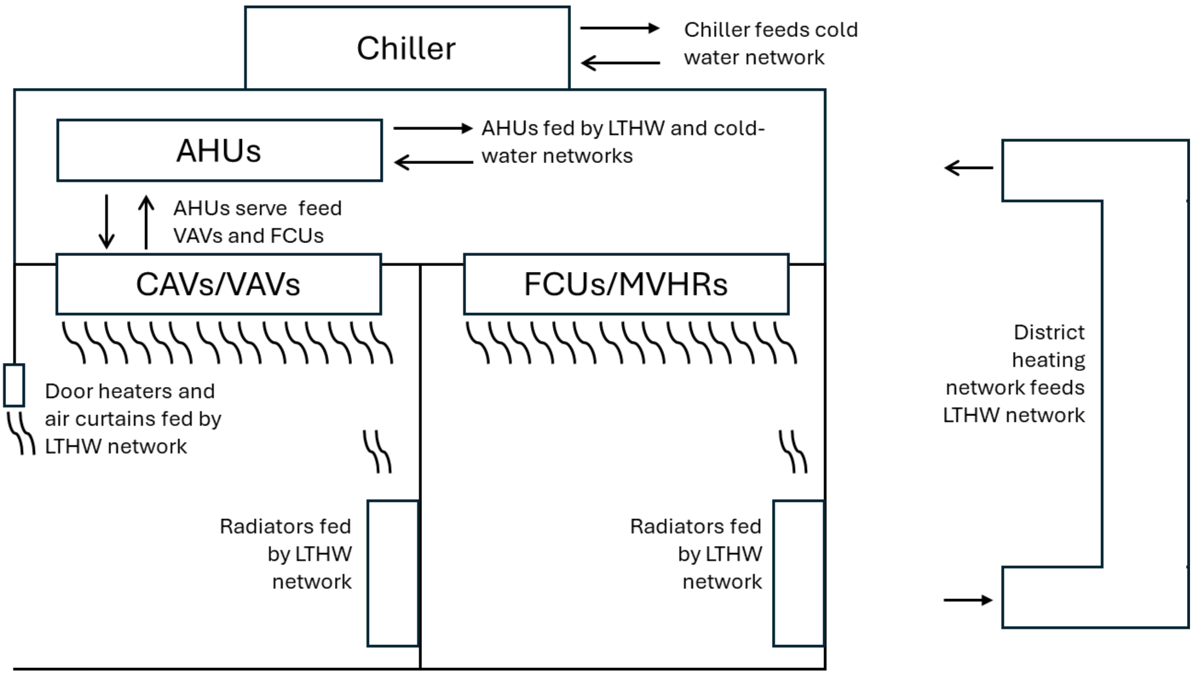

Figure 1 - HVAC schematic to show the emitters in the building including Variable Air Volumes (VAVs), Fan Coil Units (FCUs), radiators, Mechanical Ventilation and Heat Recovery (MVHRs) units, Air Handling Units (AHUs), hot and cold-water networks, chiller and district heating system

Methods

The study uses UCL East One Pool Street (OPS) as a case study to harvest data, identify improvement opportunities, and simulate the impact of these potential improvements using EnergyPlus. This creates a human-in-the-loop digital twin, by manually feeding back data related to the building to the building energy model. Figure 1 shows a schematic of the HVAC systems that exist in the One Pool Street building, Figure 2 shows a photo of UCL East One Pool Street, and Figure 3 shows a screenshot of the BIM model used to generate the energy simulations used. Specifically, the lower four floors of the building, which are called the podium, were considered for identifying improvement actions and carrying out energy simulations. The upper floors contain student accommodation with different occupancy and equipment configurations and have been excluded from this study.

Figure 2 - UCL East One Pool Street showing the podium on the lower floors and residential towers

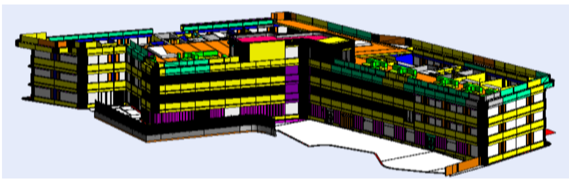

Figure 3 - UCL East One Pool Street podium BIM model

As shown in Figure 1, the primary sources for the hot and chilled water networks are the district heating network and the chiller respectively. These feed the AHUs, radiators and door heaters in the building. The AHUs feed FCUs and VAVs which provide conditioned air to spaces in the building. MVHR units are also used. Table 1 and Table 2 provide details on the types of spaces in the podium and the types of HVAC terminals respectively.

Table 1 - Room and function

Space/zone	Number	Operation	HVAC
BMS	1	24/7	72 zones are conditioned by cooling and heating equipment, with some receiving only heating, some only cooling, and others both.
Cinema	2	Weekdays	
Common	8	Every day	
Corridor	48	Weekday	
Exhibition	1	Every day	
Library	1	Every day	
Lift	24	Weekday	
Lobby	15	Weekday	
Office	35	Weekday	
Plant	14	24/7	
Retail	2	Weekday	
Toilet	12	Weekday	
Total	163	-	

Table 2 - Room and HVAC terminals

HVAC terminals	Number of zones served
Radiator	8
FCU	24
FCU & Radiator	1
AHU-VAV	2
AHU-VAV & Radiator	20
AHU-CAV	16
AHU-CAV & Radiator	1

Data harvesting and analysis

Data that would be included in a digital twin is harvested and visualised. The data harvesting architecture is shown in Figure 4.

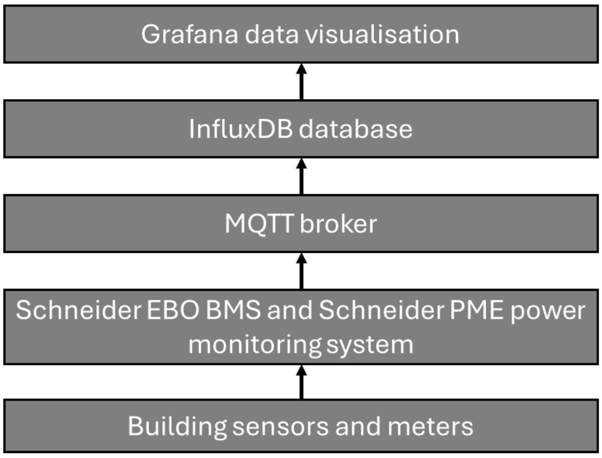

Figure 4 - One Pool Street data harvesting architecture

As shown in Figure 4, BMS data from building sensors and meters is fed to UCL's instance of the Schneider EcoStruxure Building Operation BMS. An MQTT connection to this virtual machine was established using in-built functionality of the Schneider software. Electricity consumption data is fed to UCL's instance of Schneider Power Monitoring Expert. An MQTT connection for this data was set up using a python web-scraper script. InfluxDB was chosen as the preferred database, as an open-source tool was desired to enable transferability of the research. Grafana was chosen for data visualisation as it is another open-source tool that can be easily configured with InfluxDB and produces visualisations in a suitable format.

Using this process provided Grafana dashboards showing live data for analysis on room temperatures, room CO_2 concentrations, heat meter power consumption, hot and cold-water network temperatures, HVAC system flow rates, pressures and temperatures, occupancy data from light motion sensors, and electricity consumption data from 250 electricity meters and submeters. Where possible, design values were obtained to give an idea of intended performance for comparison. There is no automated dynamic comparison between the live data and EnergyPlus simulation. This means that conventionally collected-timestamped data could have been used to determine improvement actions and assess their potential benefit. However, live data streams were preferred as it automated data collection, enabled the use of live dashboards for data analysis and stakeholder review and provides the foundation for dynamic comparison of measured data and simulated results.

Review Meetings

Independent review meetings were held with building stakeholders including UCL Estates, One Pool Street Facilities Management, the UCL sustainability team, and the UCL Information Services Division. Each month for 12 months, the harvested data for the most recent period was presented, and where possible design values for the parameters shown were presented alongside. The resulting discussion identified actions that would improve the building's energy performance. The value of these improvements is used to give an indication of the benefits of the live data streams of the building. In this way, the operational data was analysed manually, to agree with building stakeholders the best ways to optimise energy efficiency considering the identified improvement opportunities. This process, also known as contextual inquiry in system design (Holtzblatt and Jones, 1993), provides human input and consideration into the initial solutions, which can be adapted into digital twin implementations. It focuses on the potential improvements that a digital twin implementation could deliver, without the development of a fully automated digital twin application.

Energy footprint of digital twin data

Snapshots of the digital twin database were taken across 5 minutes, 3 hours, 7 hours and 10 hours and stored locally in .csv files. The size of the pre and post amble for messages sent over TCP/IP was added. From this, the average data transfer rates for the live data streams were estimated using literature values for the energy consumption of data transfer and storage. The rate was compared across the snapshots for consistency to provide a reasonable indication that the samples made were valid. Based on literature values of 1.8 kWh/GB (Cucchietti *et al.*, 2022) for data transfer, and 0.05 kWh/GB/year (Shehabi *et al.*, 2016) for data storage, the average annual energy footprint of data storage and transfer was calculated for an installation with two end users and one central database.

Energy plus simulation

The building performance simulation model of OPS was manually developed using Grasshopper-Honeybee, based on detailed design drawings, as shown in Figure 5. Subsequently, the initial IDF file was enriched with comprehensive HVAC configurations using the schematic drawing, Building Information Modelling (BIM) file, and device manuals to determine capacity and performance, ensuring it was ready for simulation.

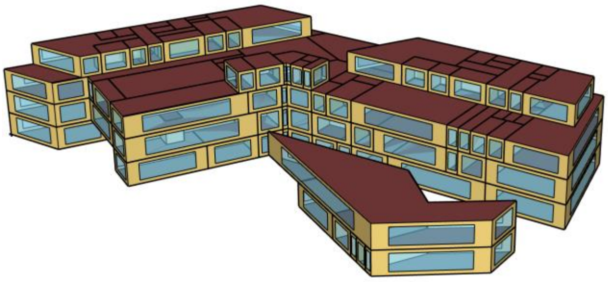

Figure 5 - 3D visualisation of the building performance simulation model for OPS

Due to data limitations, several parameters critical for building performance simulation are unavailable beyond the BIM data and device manuals. The thermal properties of the building envelope and internal heat gains, both essential for performance simulation, are determined based on relevant building regulations, considering the construction age. Table 3 summarises the key thermal properties of the building envelope.

Table 3 -Thermal properties of envelope

Envelope	Parameter	Unit	Value
Roof	U-value	$W/m^2{\cdot}K$	0.18
External wall	U-value	$W/m^2{\cdot}K$	0.26
Floor slab	U-value	$W/m^2{\cdot}K$	0.18
Window	U-value	$W/m^2{\cdot}K$	1.60
	SHGC	$W/m^2{\cdot}K$	0.25

EnergyPlus 23.2 was used to conduct a whole-year building performance simulation. The simulation employed weather data from an on-site weather station where it was available, and International Weather for Energy Calculation (IWEC) files from ASHRAE data for London Gatwick airport (ASHRAE, 2019) where there were gaps in the measurement data from the on-site weather station. IWEC is a widely used dataset derived from historical records, representing typical climate conditions and ensuring reliable inputs for building performance simulations. The breakdown of months showing when IWEC weather data and on-site measured weather data were used are shown in Table 4. The energy meter data covers a full year from June 2024 to May 2025.

Table 4 - List of Months in which On-site Weather Data and IWEC Weather Data Was Used

Month	Weather data used
January	On-site (2025)
February	IWEC
March	On-site (2025)
April	On-site (2025)
May	On-site (2025)
June	On-site (2024)
July	On-site (2024)
August	IWEC
September	IWEC
October	IWEC
November	IWEC
December	On-site (2024)

Results

This section contains the results from analysing the live data streams and stakeholder reviews, highlighting 6 key improvement actions as identified scenarios. It also contains the results of the energy simulation, including model validation and the simulation results for the identified scenarios. The results from the analysis of the resource footprint are also provided.

Scenarios identified

The building temperatures were observed to be around 21°C, through winter and summer months. Figure 6 for example, shows the temperature in the open plan office 201, as well as the outdoor temperature between the 15th of August and the 21st of August.

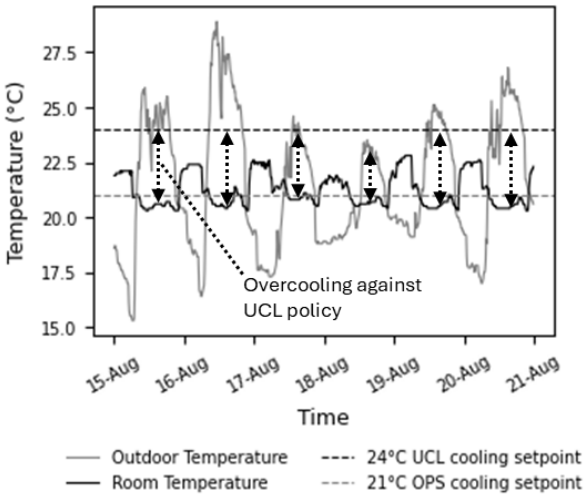

Figure 6 - Temperatures in open plan office 201 between 15th – 21st of August, highlighting the building being cooled below outdoor temperatures below 24°C, which is the cooling setpoint suggested in the UCL heating and cooling policy

Figure 6 shows a general temperature profile in room 201, where temperatures increase at night, and reduce in the day. Outdoors, temperatures increase during the day above the temperature in room 201 and reduce at night below the temperatures in room 201. This indicates that active cooling is likely being used during the day in room 201. It is UCL policy to not use active cooling on buildings below 24+2°C. The BMS description of operations document shows that during summer and winter periods, the target space temperature for rooms is 21°C ± 1°C. This is in line with the temperatures observed over summer. Therefore, in the example shown in Figure

6, the room is being cooled to ~3°C below the guidelines provided in the UCL policy.

From looking at energy consumption data, it was also found that building systems in the podium space of One Pool Street which is used for research and teaching were not shut down over Christmas and Easter. Stakeholder review meetings agreed that this was the case, and that energy savings could be made by shutting down the podium's building systems over these periods. At weekends, this analysis was extended to parts of the podium that are reserved for staff and PhD students, with common rooms for students staying in the residential towers and library spaces remaining open.

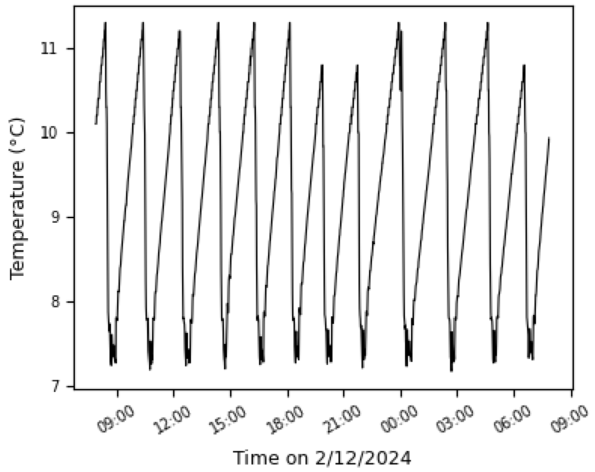

Figure 7 - Chiller outlet temperature over a typical 24h period showing that the chiller is operating 24h per day and cycling by turning on for approximately 20 minutes and then remaining off for approximately 2 hours.

Figure 7 shows that the main chiller for the building is running 24 hours per day, and this is the case throughout the entire year. Therefore, it was also identified that installing a smaller jockey chiller and running that under more consistent high percentage load could deliver energy consumption reductions. The chiller outlet temperature is designed to cycle between 13°C and 7°C, whereas Figure 7 shows the chiller running between ~11°C and ~7.5°C. It was agreed that increasing this range would provide further energy performance benefits.

Monitoring the primary low temperature hot water (LTHW) outlet temperature identified that the return temperature to the district heating system was between 61°C and 75°C, with an inlet temperature of 78°C. The design return temperature is 42.8°C, and this low ΔT across the primary low temperature hot water network could lead to less efficient operation of the system. This and the cases described in this section were analysed against a baseline state of current operations using an EnergyPlus simulation described in the next sections.

From analysing live data streams with building stakeholders, 8 cases were put forward to be simulated using the EnergyPlus model described (see Figure 5). These scenarios are shown in Table 5.

Table 5 - Cases to be simulated based on identified scenarios

#	Name	Strategy
0	Baseline	Baseline
1	Setpoint	Changing the cooling setpoint in summer from 21 ± 1°C to 24 + 2°C following UCL policy
2	Holiday shutdown	Christmas and Easter shutdown for the heating
3	Weekend shutdown	Shutdown unoccupied spaces at weekends
4	Jockey chiller	Separate chiller for room 102 computer room with 24/7 operation.
5	Heating loop ΔT	Reduce district heating return temperature from the measured average temperature of 69.2°C to the design temperature of 42.8°C
6	Chilled loop ΔT	Adjusting the maximum and minimum temperatures that the chiller outlet temperature cycles between from 11.3°C and 7.5°C to 13°C and 7°C in line with the design range of the chiller
7	All together without jockey chiller	Adding a jockey chiller is cost intensive and therefore a separate combined scenario without this addition is simulated
8	All together	All together

Model validation

The validation of the baseline building energy simulation against actual energy consumption data from energy bills confirms the reliability of the simulation model, as presented in Table 6. Mean Bias Error (MBE) is introduced to assess the reliability of the simulation model, as defined in Eq. 1.

Table 6 - Model validation

Item	Simulation (Year)	Measured (Year)	MBE (Monthly)
Chiller electricity (kWh/m²·year)	10.55	11.61	9.12%
Whole-building electricity (kWh/m²·year)	105.10	103.83	-1.22%
District heating (kWh/m²·year)	31.88	28.16	-13.21%

$$MBE = \frac{\sum_{i=1}^{N_{month}} (m_i - s_i)}{\sum_{i=1}^{N_{month}} m_i} \quad (1)$$

where m_i and s_i denote the measured data and simulated data points, respectively.

For the full year, the total electricity EUI was recorded at 103.83 kWh/m²·year, which is only slightly lower than the simulated value of 105.10 kWh/m²·year, showing a close alignment between simulated and measured consumption. A possible source of discrepancy could arise from the inclusion of electricity consumption from the tower parts of the building, which serves residential purposes and has a lower energy demand intensity. However, isolating this consumption is not straightforward, as both the podium and tower share the same primary distribution board monitored by an electricity meter. The Mean Bias Error of 9.21% for the chiller's electricity consumptions also shows good alignment between the simulated and measured energy consumptions.

For district heating, the simulated EUI for the full year is 31.88 kWh/m²·year, slightly higher than the recorded value of 28.16 kWh/m²·year, showing a reasonable alignment between measured and simulated values. It should be noted that for the purpose of model validation, Domestic Hot Water energy consumption was excluded from the simulated and measured energy consumption data. For the measured district heating energy consumption, the DHW energy use was estimated using the measured district heating energy consumption in months that do not require heating (May – October).

The simulated and measured energy consumption results used for validation are shown in Figure 8.

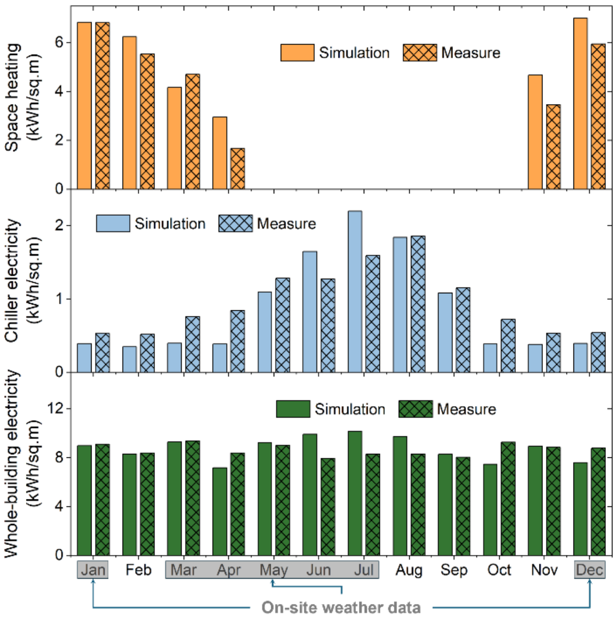

Figure 8 - Simulated and measured energy consumptions used in validation highlighting the months for which on-site weather data was used

The overall comparison, as shown in Table 6 and Figure 8, shows the robustness of the simulation model in representing actual energy performance. The calculated monthly MBE is within the International Performance Measurement and Verification Protocol defined allowable limit of 20% (Coakley, Raftery and Keane, 2014). This provides sufficient validation of the baseline model as a tool for evaluating building energy performance and assessing the impact of different energy-saving strategies. It should be noted that the monthly MBE of the simulated energy consumption is outside of the tighter allowable limit of 5% set by ASHRAE guideline 14 (Coakley, Raftery and Keane, 2014), which indicates that there is some uncertainty in the simulation results. As the building operates over time and more information becomes available, incorporating detailed data such as a full year of actual weather conditions, domestic hot water usage, actual occupancy, actual lighting operation, and refined thermal properties of the building envelope can further refine the calculation process and improve accuracy.

Simulation results

The identified scenarios and baseline state which correspond to the current operation of the building were simulated using EnergyPlus. The simulation results are shown in Figure 9, Table 7, and Figure 10.

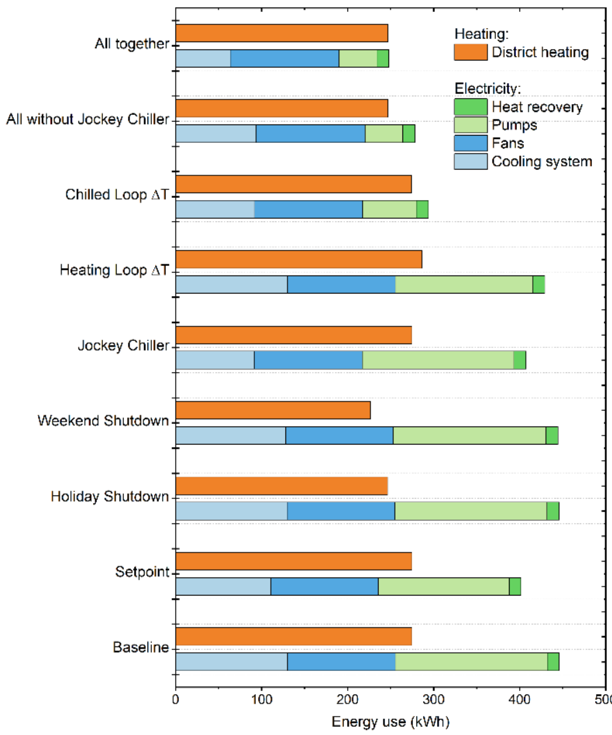

Figure 9 - Simulated energy consumption for scenarios studied

Table 7 - Simulation results for each scenario

Strategy	**Electricity use (10^3 kWh)**				**District heating (10^3 kWh)**
	Cooling system	Fans	Pumps	Heat recovery	
Baseline	129.90	125.64	176.60	13.96	274.73
Setpoint	110.92	124.76	152.28	13.66	274.73
Holiday Shutdown	129.76	125.59	176.65	13.97	246.34
Weekend Shutdown	127.81	125.49	177.29	13.88	226.54

Strategy	Electricity use (10^3 kWh)				District heating (10^3 kWh)
	Cooling system	Fans	Pumps	Heat recovery	
Jockey Chiller	91.34	125.64	176.60	13.96	274.73
Heating Loop ΔT	129.89	125.60	159.59	13.96	286.32
Chilled Loop ΔT	92.04	125.64	62.29	13.96	274.22
All together except jockey chiller	93.92	126.14	44.23	14.01	247.04
All together	63.78	126.14	44.23	14.01	247.04

* unit: 10^3 kWh/year

The simulation results also indicate the energy-saving percentages for both electricity and heating energy use under various scenarios, as shown in Figure 10. Among the individual strategies, the "Chilled Loop ΔT" scenario delivers the highest electricity savings at 10.2%, while the "weekend shutdown" scenario achieves the greatest heating savings at 17.5%. The "Heating Loop ΔT" scenario leads to a negative heating saving of -4.2% yet still offers electricity savings due to the reduced flow rate of the hot water pumps. Meanwhile, the "chilled loop ΔT" scenario proves to be another highly effective method for reducing electricity consumption in the cooling system, particularly because the building includes a BMS room with a 24/7 cooling demand and an oversized chiller is installed. Moreover, the "all together except jockey chiller" strategy suggests that the energy-saving effects of each setpoint-adjustment strategy can be additive to some extent, with limited offsets between them. When integrating all strategies and the jockey chiller, as represented by the "all together" scenario, the total energy savings increase significantly, reaching 45.8% for electricity and 10.1% for heating, demonstrating the cumulative benefits of combining multiple energy-saving strategies.

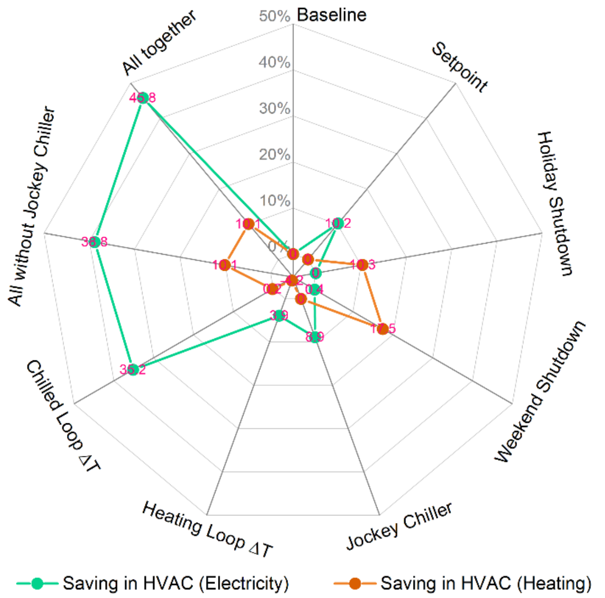

Figure 10 - Energy savings for scenarios studied

Live data streams energy consumption

The energy footprint was calculated to be 6,025 kWh/year due to data transfer, and 71 kWh due to data storage, for a total estimated energy consumption of 6.33 MWh/year. The energy required for model creation and EnergyPlus simulation was calculated as 7.41kWh. This means that the data transfer and storage energy costs incurred by live data streams made up only 2.25% of the potential energy savings achieved from the analysis of live data streams.

Limitations

This study only considers live data streams as compared to the building design and ideal operation of the building. It does not consider the practical aspects of implementing the proposed strategies. For example, the BMS graphical interface only provides a temperature setpoint for supply temperatures from equipment and room temperatures. It does not provide separate setpoints for heating and cooling. Therefore, the BMS controls would need to be recommissioned to enable this. This could be achieved by separating the heating and cooling control, or by including a larger tolerance on the setpoint, for example setting the temperature setpoint of 22°C ± 2°C would mean the building is heated up to 20°C, and cooled down to 24°C.

The ΔT across heating and chilled loops is also not simple to increase in practice. It requires tuning of entire systems across the buildings including chiller runtimes, compressor sequencing, setpoints, pump speeds and flow rates. This would take time and iterative adjustment to achieve the optimum ΔT across both control loops, and likely would not meet ideal design values. For the chilled loop, this could be addressed in BMS control logic, by taking the following steps in the order they are listed:

1. Check that the design pressure setpoint for the chilled water loop is not overly conservative to minimise pump speed. This can be done by sensing the portion of the chilled water loop the furthest distance from the chiller and ensuring there is a minimum flow of ~10kPa.
2. Add up all flow rates in the secondary chilled water circuit and run the primary pumps to achieve a flow rate of the total of the secondary flow rates + 10m^3/h to minimise bypass.
3. Use a large buffer vessel in the primary chilled water loop to increase the chiller's modulation time.

The limitations raised in this section mean that real savings will likely be lower than those identified in the simulations presented in this paper. It also means that from an analysis of live data streams, only a list of possible, recommended interventions can be made, and these should be ordered by their ease of implementation to allow those with the lowest cost and disruption to be implemented first. For this study this means that BMS control changes including investigating the chilled water design and recommissioning the BMS controls should be carried out first, and changes to the mechanical design, in this case the addition of a jockey chiller should be added as a final change if there is still a worthwhile cost-benefit relationship after all other changes have been made. With respects to the jockey chiller, since the 24/7 cooling load comes from a BMS room, it may be more cost-effective to install a separate direct expansion cooling unit for this area only, rather than a jockey chiller which is capable of handling low cooling loads throughout the building.

Discussion

The results from the simulation of improvement scenarios and of the energy footprint of the data used to identify these scenarios show that there is potential for enhancing energy efficiency using digital twins. This is in line with the wider field, with a number of studies finding energy savings based on digital twin data (Hosamo *et al.*, 2022; Kim *et al.*, 2023; Petri *et al.*, 2023; Zhang *et al.*, 2023; Piras, Muzi and Tiburcio, 2024; Spudys, Jurelionis and Fokaides, 2025). Similarly to the work presented in this paper, these studies do not provide measured energy savings. This shows that more than data is needed to achieve the promises made by digital twin for cost reductions and decarbonising the built environment.

These results are an indication of potentially improved future scenarios, but supplementary data is needed that provides context and a broader picture of understanding of how the systems are working and the complex relations between them. This is required to fully determine the correct improvement actions and would require expertise that is currently held by individual experts with multiple models. Although some implementation plans have been identified, further BMS operation planning is also needed to implement the improvement actions identified in this study. This relies on mechanical and BMS designers to combine the results presented in this paper in combination with an overall understanding of building systems to build additional models to come up with viable interventions and savings.

The COM-B model of behavioural change (West and Michie, 2020) states that capability, opportunity, and motivation lead to a behavioural change. Digital twin data can provide the capability and opportunity. However, additional motivation is needed to optimise a building's performance and energy efficiency. In the present case, there are clear risks associated with the scenarios presented in Figure 9. Adding a jockey chiller, for example, carries a high equipment and installation cost, and causes disruption to the normal operation of the building. Amending setpoints and shutting down environmental conditioning in unoccupied spaces requires the facility manager's time and carries a risk of occupants being dissatisfied with the result. These risks could be seen to outweigh the benefits of reducing energy consumption. Contractual and role-specific motivations of all stakeholders will also impact whether a change is implemented or not.

Overall, this study shows that there is potential for live data streams in digital twins to achieve energy efficiency improvements in the built environment, but that future work is necessary to solve challenges with defining the practical implementation steps, and physical implementation of improvements identified using this data.

Conclusion

This study presented a case study in UCL East One Pool Street to assess the impact of live data streams in a building's human-in-the-loop digital twin on its energy consumption. It used BMS and electricity consumption monitoring data to identify improvement opportunities. These were reviewed with building stakeholders and simulated using an EnergyPlus model of the building. The model was validated using measured energy consumption data, and on-site weather data where it was available, and IWEC weather data for London Gatwick where on-site weather data was not available. Future work should be to obtain a full year of weather data from the on-site weather station and use this to calibrate and validate the EnergyPlus model to further improve its accuracy. The results showed that if all identified improvements were implemented, an energy saving of 197.9 MWh/year for electricity and 27.7 MWh/year for heating could be achieved against an energy of footprint of 6.33 MWh/year for the data transfer and storage of the digital twin data used. However, the necessary changes were not implemented. This shows that live data streams in digital twins have the potential to reduce a building's overall energy consumption, however additional steps are needed to realise these benefits.

Future work should focus on identifying what the processes are that can deliver the improvements promised by the technical potential of digital twins and further investigate the costs of digital twins beyond their energy footprint. Additionally, the foundations of a digital twin application presented in this paper should be developed further to use live data streams to dynamically update the EnergyPlus model or automatically optimise building control, and the impacts on energy consumption should be measured to more clearly assess the impact of live data streams in digital twins.

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References

Abdelrahman, M. *et al.* (2025) 'What is a Digital Twin anyway? Deriving the definition for the built environment from over 15,000 scientific publications', *Building and Environment*, 274, p. 112748. Available at: https://doi.org/10.1016/j.buildenv.2025.112748.

ASHRAE (2019) *Weather Data Download - London Gatwick 037760 (IWEC)*. Available at: https://energyplus.net/weather-location/europe_wmo_region_6/GBR/GBR_London.Gatwick.037760_IWEC (Accessed: 27 June 2025).

Boje, C. *et al.* (2020) 'Towards a semantic Construction Digital Twin: Directions for future research', *Automation in Construction*, 114, p. 103179. Available at: https://doi.org/10.1016/j.autcon.2020.103179.

Cespedes-Cubides, A.S. and Jradi, M. (2024) 'A review of building digital twins to improve energy efficiency in the building operational stage', *Energy Informatics*, 7(1), p. 11. Available at: https://doi.org/10.1186/s42162-024-00313-7.

Coakley, D., Raftery, P. and Keane, M. (2014) 'A review of methods to match building energy simulation models to measured data', *Renewable and Sustainable Energy Reviews*, 37, pp. 123–141. Available at: https://doi.org/10.1016/j.rser.2014.05.007.

Cucchietti, F. *et al.* (2022) *carbolytics, an analysis of the carbon costs of online tracking*. Barcelona. Available at: https://carbolytics.org/report.html (Accessed: 22 February 2022).

Daniotti, B. *et al.* (2022) 'The Development of a BIM-Based Interoperable Toolkit for Efficient Renovation in Buildings: From BIM to Digital Twin', *Buildings*, 12(2), p. 231. Available at: https://doi.org/10.3390/buildings12020231.

Holtzblatt, K. and Jones, S. (1993) 'Contextual Inquiry: A Participatory Technique for System Design', in *Participatory Design*. CRC Press.

Hosamo, H. *et al.* (2022) 'Digital Twin of HVAC system (HVACDT) for multiobjective optimization of energy consumption and thermal comfort based on BIM framework with ANN-MOGA', *Advances in Building Energy Research*, 17(2), pp. 125–171. Available at: https://doi.org/10.1080/17512549.2022.2136240.

Khajavi, S. *et al.* (2019) 'Digital Twin: Vision, Benefits, Boundaries, and Creation for Buildings', *IEEE Access*, 7, pp. 147406–147419. Available at: https://doi.org/10.1109/ACCESS.2019.2946515.

Kim, J.B. *et al.* (2023) 'Digital Twin Framework for Smart Campus to Reduce Greenhouse Gas Emission', in *2023 IEEE Smart World Congress (SWC)*. *2023 IEEE Smart World Congress (SWC)*, pp. 1–8. Available at: https://doi.org/10.1109/SWC57546.2023.10448799.

McGovern, G. (2020) *World Wide Waste*. Silver Beach. Available at: https://gerrymcgovern.com/world-wide-waste/ (Accessed: 9 January 2022).

Petri, I. *et al.* (2023) 'Digital twins for performance management in the built environment', *Journal of Industrial Information Integration*, 33, p. 100445. Available at: https://doi.org/10.1016/j.jii.2023.100445.

Piras, G., Muzi, F. and Tiburcio, V.A. (2024) 'Enhancing Space Management through Digital Twin: A Case Study of the Lazio Region Headquarters', *Applied Sciences*, 14(17), p. 7463. Available at: https://doi.org/10.3390/app14177463.

Shehabi, A. *et al.* (2016) *United States Data Center Energy Usage Report*. Energy Technologies Area, Berkeley Lab. Available at: https://eta.lbl.gov/publications/united-states-data-center-energy (Accessed: 17 August 2022).

Spudys, P., Jurelionis, A. and Fokaides, P. (2025) 'Digitizing buildings sustainability assessment: Integrating energy audits, operational energy assessments, and life cycle assessments for enhanced building assessment', *Energy*, 316, p. 134429. Available at: https://doi.org/10.1016/j.energy.2025.134429.

West, R. and Michie, S. (2020) 'A brief introduction to the COM-B Model of behaviour and the PRIME Theory of motivation [v1]', *Qeios* [Preprint]. Available at: https://doi.org/10.32388/WW04E6 (Accessed: 4 November 2024).

Xie, X. *et al.* (2020) 'Digital Twin Enabled Asset Anomaly Detection for Building Facility Management', *IFAC-PapersOnLine*, 53(3), pp. 380–385. Available at: https://doi.org/10.1016/j.ifacol.2020.11.061.

Zhang, J. *et al.* (2023) 'Multi-indicator adaptive HVAC control system for low-energy indoor air quality management of heritage building preservation', *Building and Environment*, 246, p. 110910. Available at: https://doi.org/10.1016/j.buildenv.2023.110910.