Operating and Certifying a Net Positive Energy Building During a Pandemic

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Abstract
This paper documents the unique operations journey and an overview of the accompanying model-based analysis of the award-winning Kendeda Building for Innovative Sustainable Design, designed to become the most environmentally sustainable classroom and lab building in the Southeast US, addressing performance metrics including energy and water use. As to energy, the primary goal was to achieve the Leadership in Energy and Environmental Design (LEED) Zero Energy as well as the International Living Future Institute’s (ILFI) Living Building Challenge (LBC) certifications, exceeding a net-positive energy threshold of 5% based on proven performance during a 12-month period. A few months after the building began its operation in late 2019, the COVID-19 pandemic hit, altering building operations and disrupting the planned course for certification. A calibrated model based on post-occupancy data of the building’s energy and water performance was created and used to support the claim that the Kendeda Building would still have been sufficiently net-positive for energy if the performance year went under two different scenarios: a hypothetical “business as usual” year without the pandemic, and a full-year of extreme-load operation. For these two scenarios, the Kendeda Building was found to be able to certify with 125% and 38% net-positive energy, respectively.

Introduction
Although buildings account for 36% of CO2 emissions in the United States, aggressive building energy efficiency measures and increased use of renewables can reduce total emissions relative to the current levels (Langevin, Harris, and Reyna 2019). In order to achieve this goal, the concept of a Zero Energy Building (ZEB), also known as a Net-Zero Energy Building (NZEB), has been proposed as a solution. In the last decades, the concept has gained attention and has been implemented at an international level (Marszal et al. 2011). The US Department of Energy defines a ZEB as “an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy” (Peterson, Torcellini, and Grant 2015). A ZEB can be obtained by 1) reducing energy usage through HVAC configurations tailored to building operation plans and weather conditions, 2) improving building envelope qualities by installing better-insulated windows and tighter building construction to limit air leakage, and 3) retrofitting on-site energy generation systems such as PV panels (Albadry, Tarabieh, and Sewilam 2017; Wu and Skye 2018).

Various standards and programs exist to help guide, demonstrate, and assess buildings based on design intent and energy performance predictions. Criticism of such programs for not delivering promised energy savings during operations (Conniff 2017) has led to the development of more rigorous rating systems such as the LEED Zero (U.S. Green Building Council 2022a) and the Living Building Challenge (LBC) v3.1 Energy Petal which evolved into the Zero Energy (ZE) Certification (International Living Future Institute 2022b). The LBC requires a 12-month post-construction performance period, ensuring that the certification award is contingent upon operational outcomes as opposed to purely design intent. Feng et al. (2019) provide an overview of several buildings in hot and humid climates and note that each ZEB certification process is correlated primarily with Chinese and US energy efficiency standards. Such rating systems do differ however in calculation methodologies (Marszal et al. 2011) and have different levels corresponding to the stringency of the certification requirements (Hall, Geissler, and Burger 2014; Kim and Yu 2020).

For existing buildings, energy data can be easily tracked with an array of meters. During the pre-construction phase, however, due to the variance and the uniqueness in energy usage based on both building design and geographic location from many factors, it is difficult to extrapolate the energy usage of one building to predict...
the energy efficiency of another in an accurate fashion. As such, high-fidelity building energy models (BEM) have become more ubiquitous tools to establish a baseline of building energy performance in the pre-construction phase (Harish and Kumar 2016; Zou, Wagle, and Alam 2019). Cellura et al. (2014) extend building energy modeling to the post-construction phase to holistically evaluate not only primary energy use comprised of HVAC equipment, appliance, and lighting loads, but also embodied energy of the building itself. Kaewunruen, Rungskunroch, and Welsh (2019) utilized a building energy model to assess the viability of implementing renewable energy and better building energy management to transform existing conventional buildings into a ZEB or a near-ZEB. Such endeavors provide information on how to estimate the energy performance in the pre- and post-construction phase while linking the impacts of design choices (e.g., roofing, window layout) as well as operations (e.g., set temperature, schedule) over the lifecycle.

The Kendeda Building for Innovative Sustainable Design

The Kendeda Building, whose construction completed in Fall 2019, is located on the campus of the Georgia Institute of Technology (Georgia Tech, GT) in Atlanta, GA. It is considered one of the greenest buildings in the world, attested by winning prestigious awards such as the American Institute of Architecture (AIA)’s Committee on the Environment (COTE) 2021 Top Ten and the Engineering News-Record (ENR)’s Best of Best Projects 2020. The 37,000 ft² building has six classrooms & teaching labs, an auditorium, a seminar room, and a design studio which allow students, staff, and faculty to explore sustainability ideas in action. Replicability of sustainability strategies, including those supporting net-positive energy performance in the southeast, was an overarching condition of the funding for the building’s design, construction, and operation. The project had to target and earn:

- All 18 points under LEED v4’s Optimize Energy Performance (U.S. Green Building Council 2022b) credit and Platinum certification.
- LBC full certification (International Living Future Institute 2022a) including net positive energy and LEED Zero Energy certification (U.S. Green Building Council 2022a) based on post-construction performance.

Using these energy targets, the engineering team completed building energy modeling efforts to optimize and validate design strategies such as building orientation, massing, envelope performance, Mechanical/Electrical/Plumbing (MEP) system selection, and photovoltaic panel sizing (PAE Engineers 2017). The result, at the end of the design phase, was a building with a predicted gross energy use intensity (EUI) of 32 kBTu/ft²/year. A sampling of features employed to achieve this result includes a well-insulated, ultra-low leak envelope, triple-pane glazing, exterior motorized shading, reduced lighting power density through using LEDs and natural lighting, a dedicated outdoor air system with an energy recovery wheel, radiant heating and cooling systems, and heat recovery chillers symbiotically connected to a campus district cooling system.

Operational Variations from Design Intent

According to the LEED Zero and the ILFI’s LBC (zero-energy) requirements, for a certification period to qualify, the minimum building occupancy rates required are 50% and 85%, respectively. Since the LBC requirements are more stringent, the primary goal was to obtain LBC certification. However, the pandemic led to significantly reduced occupancy during the performance period, as shown below:

- 12/1/2019 – 3/15/2020: Full occupancy
- 3/16/20 – 5/31/20: Closed to all but operations and maintenance (O&M) crews
- 6/1/20 – 7/31/20: Open – no classes, but faculty and visitors allowed with masks
- 8/1/2020 – 11/30/2020: Open to all – very low occupancy observed due to online classes and meetings

In addition, higher ventilation was adopted in line with ASHRAE’s recommendation (ASHRAE 2020) to promote healthier indoor air quality. The building’s demand control ventilation used to respond to a CO₂ threshold of 900 ppm, resulting in 2,000-3,000 cfm of ventilation during occupied hours. After the pandemic, the CO₂ threshold was adjusted to 600 ppm, and thus ventilation was increased to 4,000-5,000 cfm.

Since the COVID-19 pandemic impacted the ability to meet the program requirements, certifying agencies provided alternative paths for compliance. As of the time of writing this paper, the authors are not aware of precedence to certification performance periods being affected by such a substantial disruption like the pandemic.

Energy Certification amidst Operational Variations

Under “business as usual” (BAU) conditions, proving the building is net-positive energy is straightforward where 12 months of energy data, taken from the building’s main meter or its energy bills, merely needs to be reported. Yet because of when the Kendeda Building’s certification period began, the occupancy requirements would have meant an uncertain wait for the pandemic to subside and occupancy to return to normal,
this paper describes the digital infrastructure that BAS controls, and can be calibrated with respect to gathered on-site, including building automation system BEM can be informed by near-real-time information and virtual operation scenarios. Since the Kendeda attempts to transform the BEM into a full-fledged digital replica of the Kendeda Building's water and energy systems and how it was utilized to certify net-positive energy performance for both reasonable non-pandemic and stressed occupancy scenarios.

Methodology
To address the defined challenge, a digital twin (DTw) was created to (i) accurately mirror the real performance of the Kendeda Building's water and energy systems and (ii) evaluate scenarios where the building is subjected to alternative weather, operations, and occupancy conditions. One broad definition of a DTw is a model that mimics the context, structure, and behaviour of an individual physical asset, calibrated/fed by data from its physical twin, and informing decisions that realize the value (American Institute of Aeronautics and Astronautics (AIAA) and Aerospace Industries Association (AIA) 2020). A requirement for the Kendeda Building DTw for energy was that it should generate data that could be used to credibly evaluate “what if” scenarios to accompany GT’s application for the Living Building certification. Since there was no precedent for this, the research team worked closely with building designers, including the original building energy modelers, as well as operators and managers, to vet the final product and its results.

The model needed to be able to match reality over a 12-month period and extrapolate to BAU conditions. The model also needed to assess the impacts of a stress test that assumed maximum occupancy during every hour of operation. The actual monthly occupancy loads as well as the two scenarios are illustrated in Figure 1. The notional occupancy throughout the year is represented by the blue lines adjacent to the vertical columns. All the measured data are obtained from the actual operation (left), and model validation activities are conducted using this data. It is important to note that calibration of the model is not to a single point in time, but rather an ongoing baseline of actual operation. In Scenario A, the occupancy is simulated as if the pandemic never happened, with regular class schedules and planned events. Scenario B is defined as a stress test for the building. The simulations are carried out with 500 hourly people count (HPC) occupants for a whole year to abide by the designed maximum occupancy based on fire safety codes. Although this scenario is unrealistic, it serves the purpose of demonstrating whether the building will remain net-positive under extreme occupancy loads.

Digital Twin Framework
The engine of the DTw was developed by adopting the features of a reduced-order building energy model called the Energy Performance Calculator (EPC). EPC is an implementation of the ISO 13790:2008 standard, which lays out a calculation recipe for normatively estimating building energy performance using thermodynamics equations involving a relatively small set of parameters (ISO 2008). The reduced-order model considers simplified thermodynamic processes with a formulation of building hourly heat balance and aggregated building parameters. In terms of the EPC model accuracy, a study states that the EPC model predicts as accurately as the calibrated EnergyPlus model and better than the uncalibrated EnergyPlus model (Heo, Choudhary, and Augenbroe 2012). The EPC requires inputs for the energy estimation including the weather data, building geometry, envelope characteristics, HVAC system, internal loads, and operating schedules. In addition to the preconstruction model generated by PAE Engineers (2017) mentioned in the introduction, Charan et al. (2020) analyzed the building performance with different stress scenarios through the EPC with the same preconstruction data. Due to the lack of post-construction data, the study indicated the need for calibration with the actual energy consumption data. In addition, two limitations were identified. First, the original EPC engine does not estimate sub-hourly energy
The DTw is connected to real-time operational data from the BAS, electric end-use submeters, hydronic energy meters, and external databases (weather and occupancy). These values can be tracked over time to measure actual building operation, efficiency, and performance. All of the source data is stored and managed through the SkySpark™ cloud platform in real-time. The collected submeter data in operation contributes to customizing the DTw model. For instance, daily kWh of plugload and lighting load were obtained from the submeters. However, the daily loads are not sufficient to represent hourly loads. Thus, the data collected from the submeters are utilized to identify the specific hourly load patterns. Figure 3 illustrates the comparison between the actual and estimated plugload and lighting load on an hourly basis.

For the DTw to make accurate, real-time predictions, the integration of the real-time measured data and the external data is crucial as the engine needs temperature, precipitation, wind speed, relative humidity, and solar irradiance (global horizontal, direct normal, and diffuse horizontal) inputs to predict the thermal performance. This also calls for the use of accurate, local weather data instead of typical meteorological year (TMY) practices. Although the building has its own weather station, some of the data is either missing or low quality. To mitigate this issue, weather data obtained from two weather stations at the Georgia Tech Atlanta campus, another station in downtown Atlanta and three NOAA weather stations in the Atlanta area are fused to obtain a complete, accurate, and up-to-date weather data set. Solar irradiance components were obtained from the NREL database; however, the yearly data is only released months after the performance year is over. Therefore, a neural network was trained using the solar components obtained from the previous four years from the NREL database and applied to estimate diffuse horizontal irradiance in 2021. The generated set of weather data combines the best-quality data points from the available, local sources so that it can be used for the calculation of the thermal performance of the building.

Occupancy data was collected using two methods; manual bookkeeping data and tracking wireless connections to 37 WiFi access points (APs) in the building. WiFi data can be used to represent a highly accurate estimation of occupancy level (Mohottige et al. 2018). The manual bookkeeping data includes the class schedules with the number of registered students, event and building tour request records, and the number of building residents such as staff, regular students, and facility management staff. The wireless client data is collected from Wi-Fi APs in the Kendeda Building and post-processed into an hourly window. The wireless connection services at Georgia Tech allow automatic
access to all devices that have accessed the campus wireless internet service with their accounts. This situation requires a discounting coefficient for the wireless connections, 0.33 in this study. In sum, the HPC for the simulation model is calculated with the records of events and tours and by using wireless client data. The results are presented with the manual bookkeeping occupancy for the validation in the result section.

One of the primary challenges in constructing the DTw was data processing and management after data has been collected from numerous sensors in the building. As the DTw relies heavily on real-time data obtained from sensors, the readings can impact the DTw predictions. In theory, outliers can be easily identified and treated, but significant efforts were required to improve data quality. Further, errors were often not obvious, making calibration extremely challenging. These problems may have resulted from communication faults as well as human factors that do not affect normal building operations. To combat these, a robust data management system needed to be developed. A system was designed to process and clean all real-time data and store it on the SkySpark database to have an organized repository of usable data. Here, all raw measured data, consisting of weather data, building metering data, and occupancy data, are initially uploaded in real-time to the SkySpark database. A separated server then retrieved this data from the cloud storage, before being processed and otherwise cleaned. The data is then uploaded again to the SkySpark database.

The processed data is retrieved by the Kendeda Building DTw. The model then automatically calibrates the model coefficient of performance (COP) values using the measured data and uploads calibration results back to the database to track building performance over time. The overall architecture depicting the key components of the DTw and the flow of the data is given in Figure 4. This architecture ensures that the DTw remains capable of providing live, accurate, on-demand data throughout the operational life of the building by allowing it to evolve together with the building.

Results

Occupancy Model Validation

The manual bookkeeping occupancy is referred to as the upper boundary of the occupancy because it assumes full attendance of residents in the building and students in classes. Figure 5 illustrates the occupancy model with the wireless client data and the numbers of event and tour records compared with the manual bookkeeping occupancy. The occupancy model results show from 200 to 270 HPC in the normal operation before COVID-19. The manual bookkeeping occupancy dramatically decreased between the beginning of and the middle of March because all events and tours were canceled. Then, the measured occupancy plunged after the lockdown was announced. Georgia Tech offered hybrid and online classes in Fall 2020 leading to low occupancy rates for the building. The integration of actual occupancy data provided accurate information to estimate energy use.

BEM Calibration / Validation

For this study, the DTw was calibrated using building electrical load and chilled water usage to estimate COP values as well as building insulation parameters. The whole year was used as the calibration period rather than select months to avoid a seasonally biased model. To ensure the veracity of the DTw, the outputs of the DTw were then validated against the measured data from the building. Among numerous measurements available, presented here are some of the most important metrics for this work, such as total power consumption and internal temperature. In Figure 6, comparisons between the model predictions and measurements for two different weather and occupancy conditions are demonstrated. The top figures illustrate the predicted and measured internal temperatures against the outside air temperature. The bottom figures are the measured and predicted hourly power consumption of the building, including its chilled water plant. Figure 6(a) shows the hot and humid summer days with very low occupancy due to the summer semester and pandemic conditions. Figure 6(b) is a three-week period from Fall, where the outside air temperature varies by a significant amount. It is seen that the predicted energy performance matches actual building performance measurements closely even when there are large fluctuations in weather conditions and/or occupancy. Indeed, the aggregated annual chilled water usage prediction for the Kendeda building has an error of 0.76%. Sub-annual prediction metrics are also high, with R² values ranging from 0.9037 for hourly time intervals to 0.9881 for monthly time intervals as shown in Table 1, proving the model to be effectively identical to the building performance. The high accuracy of the KB DTw in modeling actual building performance for higher granularity time scales lends credence to the capability of the DTw as well as its compatibility for future applications such as model predictive control, or fault detection and diagnosis.
**Scenarios for Digital Certification**

This section compares the actual generated energy by the photovoltaic (PV) system on the Kendeda Building with the energy loads in Scenarios A and B to demonstrate the certification levels. As the occupancy bookkeeping data indicate in Figure 5, the Kendeda Building is operated considering lower than 400 HPC as a planned full occupancy. Scenario A is simulated by replicating the actual occupancy model before COVID-19 on a weekly basis (Figure 5). The occupancy of Scenario A ranges from 200 to 270 HPC during occupied hours. Scenario B represents the maximum load, 500 HPC from 7 am to 10 pm on weekdays.

For each scenario, the building’s internal temperature was maintained between 72°F to 78°F, achieved by modulating DOAS operations. Additional cooling via the radiant floor was not explored due to concerns regarding condensation formation. As a baseline of actual operation conditions, the building produced 240% of the energy it consumed during the 12-month performance period. The EUI is calculated to be 16.9 kBtu/ft²/year for the actual conditions. Scenario A (no pandemic) does not have a great difference compared to the actual case as the power generation is 225% larger and the EUI is 18.0. Figure 7 illustrates the difference in power conditions between scenarios A and B. It is seen that most of the differences occur in warmer months. The cooling need for scenario B is considerably higher due to the extreme number of occupants and the associated heat generation. Aggregated results, as well as the power generated by the PV panels, are presented in Figure 8. These comparisons ensure that the yearly PV generation will exceed the yearly building power consumption even for the most demanding of operational conditions. For scenario B, the EUI was calculated to be 29.4, and the building produced 138% of the energy that is consumed.

**Conclusion**

The digital twin approach presented in this paper was used to substantiate the claim that the Kendeda Living Building can achieve net-positive energy performance under scenarios of more intense usage than were experienced in its 12-month certification period due to the global pandemic. This was possible because the modified BEM approach can account for the specific aspects of the building that drive energy use and be suitably calibrated if an appropriate level of sensing and energy submetering is included in the building by design, as is the case with the Kendeda Building.

The model was validated by historical data obtained from on-site sensors, as well as external sources, and collaboration with BEM professionals. It predicts the Kendeda Building would certify:

- With 125% net-positive energy if there were no COVID-19 disruption and
- With 382% net-positive energy even if the building had gone through an extreme condition throughout the entire performance period.

While the success of the design and construction of the building was a notable achievement (Post 2021), the real goal of the Kendeda Building team (and of certification organizations) is to see whether its sustainability-oriented successes replicated in other buildings, new and old. It is anticipated that the digital twin approach can be an important means of exploring how to balance, for example, sustainability with affordable construction costs, as well as a means to rapidly and accurately benchmark performance throughout a building’s life cycle. This unique, multi-disciplinary, trans-domain collaboration between researchers, practitioners, and industry experts allowed for creating a state-of-the-art digital twin of a live building that can be used not only for energy and water usage prediction, but also monitoring building operation details, data sanity checks and system fault detection purposes. Whenever applicable, implementation of a similar digital twin would immensely increase the knowledge regarding operations and performance of a building.

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Table 1 R² Values for Aggregated Data with Different Time Intervals

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<th>Time Interval</th>
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Figure 1 Actual Conditions vs. Digital Twin Simulated Occupancy Scenarios

Figure 2 Model Configuration
Figure 3: Actual and Simulated Plug and Lighting Loads

Figure 4: Kendeda Building Digital Twin Architecture

Figure 5: Manual bookkeeping occupancy (blue) and actual record-based occupancy (orange) in HPC
(a) Hot summer days  
(b) Shoulder season with high-temperature variance

**Figure 6** Interior temperature and power consumption

**Figure 7** Aggregated monthly consumption for the two scenarios

**Figure 8** Net Positive Energy Performance