MODELING AND SIMULATION OF A CAMPUS LIVING BUILDING: A CASE STUDY IN UNCERTAINTY ANALYSIS AND STRESS TESTING

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ABSTRACT

The Living Building Challenge is the most rigorous performance-based challenge for buildings in the world. The energy petal of version 3.1 of the challenge mandates 105% net positive energy generation for an entire year of operation. Building simulation plays an important role in predicting building performance; however, there are several assumptions made regarding the expected use of the building, and there is inherent uncertainty associated with building parameters that serve as inputs to the energy models. Ignoring these uncertainties may lead to a false sense of security that the building will meet the strict targets. This paper explores the use of low- and high-resolution tools to check the performance at the whole-building as well as zonal level, and quantify the risk of not achieving energy targets.

INTRODUCTION

Building simulation is integral to supporting decision-making throughout the building's life cycle and is critical in determining the building's performance. Several parameters are taken into account while arriving at the predicted performance of the building, those dealing with physical attributes of the building and others depending on the behavior of occupants within the building. These parameters are often uncertain and are based on best guesses. Therefore, they cannot be ascribed a single deterministic value and are better represented by a range of possible values to capture their uncertainty; however, the impact of uncertainty is rarely considered in the design process along with building performance simulation to aid decision-making [Kotireddy et al. 2019; Chong et al. 2015]. When it comes to designing high-performance buildings and those that are designed to achieve certifications, there is an even greater need to make accurate predictions about the building's performance. It is critical to incorporate the uncertainty in building parameters and quantify the risk of the building not achieving its said targets and enable better decision-making for stakeholders and designers.

This paper attempts to incorporate uncertainty in the building performance analysis for the Kendada Building for Sustainable Design, constructed on the Georgia Tech campus as an education and research facility. It is designed as a high-performance building and makes use of several energy saving techniques. The project is supported by the Kendeda fund and is intended to become the first Living Building Challenge 3.1 certified facility of its size and function in the Southeastern United States [Living Building, Georgia Tech].

The first part of the study focuses on reduced order modeling using the Energy Performance Calculator (EPC) to understand the impact of sources of uncertainty in various aspects of model development on predicted building performance. The EPC was developed by the High Performance Building Lab at Georgia Tech and is an Excel tool based on ISO 13790-2008. It uses simplified thermodynamic process with a quasi-steady-state formulation of heat balance and aggregated building parameters such as general geometry, envelope properties, internal loads, and schedules. It makes certain assumptions regarding usage scenarios as well as heating, ventilating, and air conditioning (HVAC) system types and efficiency. It then calculates space heating and cooling loads and translates them into delivered energy using normatively defined macro system efficiency factors. It employs utilization factors to compensate for the discrepancy caused by ignoring dynamic effects [Qi Li et al. 2015]. Previous comparative studies [Kim et al. 2013; Lee et al. 2014] deem EPC to be capable of providing estimates of building energy consumption with acceptable accuracy. The analysis is done as a first order assessment, and is considered adequate to quantify the risk of the building not achieving its energy goals.

To ensure that the building delivers the desired performance over its lifespan, it is valuable to quantify a so-called performance robustness of the proposed building design [Kotireddy et al. 2019]. It is unfeasible to make subjective estimates for the large number of unknowns in future scenarios regarding building operation and external conditions. In lieu of this, "stress

tests" are defined in the second part of the study as hypothetical scenarios that subject the building to extreme conditions of occupancy and weather, and then assess the interior conditions to determine whether the HVAC system can handle the excess load. The ability of the building to handle loads under these situations in comparison to its performance under regular building operation and weather is indicative of its resilience in extreme load scenarios. These stress tests provide a way of transforming unknowns in the future into actionable information for the decision maker [Kotireddy et al. 2019].

The analysis is done using a detailed dynamic model in DesignBuilder. It is a higher resolution and more granular analysis of the building, accounting for complex zone interactions. It allows determining the zonal performance of the HVAC system, which was not possible using the EPC.

Case Study

The building is 34,400 ft^2 and has spaces dedicated for classrooms, labs, offices, makerspace, and a 170-person auditorium. The building is fully occupied following the start of classes in January 2020, with substantial construction completed in mid-2019.

Figure 1. Kendeda Building West entrance. Source: Miller Hull

It is connected to the campus chilled water for cooling and water-to-water heat pumps, which use the campus chilled water system as a heat source and provide heat to the building, exporting back the chilled water. It includes radiant floors for heating and cooling and an energy-efficient dedicated outdoor air system (DOAS) for ventilation.

The predicted energy use intensity (EUI) for the building calculated by energy consultants using IES is 34 kBtu/ft^2/year. This is 66% more efficient than the average building of the same size and occupancy [Living Building, Georgia Tech].

Achieving a 105% net positive energy, as mandated by Living Building Challenge v. 3.1, requires 366 MWh on-site generation; however, an additional safety factor of 15% is considered in the photovoltaic (PV) design to account for potential changes in the realization and operation of the building and inherent uncertainty in the energy model. The proposed PV array consists of 913 solar panels of 360 W and is sized at 328 kW, making the building 40% net positive in year 1 of operation.

The building is expected to hold regularly scheduled classes, labs, tours, as well as host evening and weekend events. Achieving net positive energy for a variable schedule in the hot and humid climate of Atlanta makes it a challenging project. The next section describes the methodology adopted for the study.

METHODOLOGY

The methodology section is structured as follows. The first part deals with the risk analysis using EPC. The EUI is first established deterministically using EPC, and then uncertainty is incorporated in the analysis for year 1 as well as year 25, to ascertain risk for the building of not being net positive beyond the first year of operation.

The next part deals with stress testing using the DesignBuilder model. It describes the building's HVAC system in more detail and defines stress tests for the building.

Part I: Risk Analysis

EPC requires inputs for the building location, weather file, building geometry, envelope characteristics, internal loads, HVAC system, and schedules. It also has the capability of defining the PV system and calculating energy generation. It calculates the heating and cooling need and energy consumption on an hourly or monthly basis.

The building zones are identified based on areas with similar usage and similar heating and cooling setpoints. The zone areas are entered in EPC along with the corresponding internal loads and schedules for the zone. Within the calculations, these loads and schedules are applied to the building zone and are then aggregated for the building as a whole, treating it as a single zone.

The results from modeling the building deterministically using EPC indicate an EUI of 32.1 kBtu/ft^2/year, or an energy consumption of 315,167 kWh, which is close to the predicted EUI for the building. Taking the PV into account results in an energy generation of 440,000 kWh, making the building net postitive with an EUI of -12.6 kBTU/ft^2/year.

To integrate sources of uncertainty to the deterministic EPC model, the @Risk plugin for Excel is used. It allows adding probability distributions to uncertain parameters to represent a range of values that are more representative than a single deterministic value [Hopfe et al. 2013]. This recognizes that in the mapping from a design proposal to the constructed and operated artifect, many "realization uncertainties" enter into the picture.

It then runs a Monte Carlo simulation to propagate all uncertainties through the building energy model. This generates the outcomes in the form of probablility distributions, for example for yearly or monthly energy consumption. The Monte Carlo approach is based on running many samples, where each sample picks a different set of values from the probability functions of the individual parameters.

Using @Risk with EPC allows inclusion of uncertainty within the building performance tool, which is not offered in most tools today [Chong et al. 2015]. Its built-in functionality for sampling values and running Monte Carlo simulation within minutes, rather than manually changing inputs and generating multiple output files, make it suitable for practical use.

Various scenario and physical uncertainties are considered for the analysis, as shown in Table 1. The infiltration refered to here is due to uncontrolled flow of air through the building envelope.

Table 1. Physical and Scenario Parameters

Physical Parameters	Scenario Parameters
PV power coefficient	Occupancy
Air infiltration	Lighting loads
Heating coefficient of performance (COP)	Equipment loads
Cooling COP	Setpoint schedules

The scenario uncertainty may change during the building's lifetime and include occupant related influences that result in unpredictable usage of the building [Hopfe et al. 2011; Seerig et al. 2016]. Taking these uncertainties into account is important while considering the robustness of a building during unforseeable use [Hopfe 2011; Hopfe et al. 2013].

The uncertainty in physical parameters is usually standardized and measureable [Seerig et al. 2016]. It may arise due to a deviation from design specification [De Wit 2001] or due to wear and tear of the system over time.

To assess the impact of the uncertainty, the anticipated variation must be clearly defined [Macdonald 2002]. This is done by assigning probability distributions to the uncertain parameters. Probability distributions must be selected to best represent the uncertainty and variability in the parameter, and appropriate mean, minimum, and maximum values must be defined.

The most appropriate distributions are assigned to the different parameters as per the uncertainty quantification (UQ) repository, as described in Lee et al. [2013]. Some assumptions are case specific and cannot be taken from the basic UQ repository. In those cases they are based on discussions with the facilities management team at Georgia Tech regarding the expected deviation in occupancy and the use of various spaces.

A truncated normal distribution is selected to represent the scenario parameters with a standard deviation of 0.1, and the expected mean value is taken from the design specifications. The mean value of occupancy varies space to space. A triangular distribution is used to represent certain physical parameters with maximum and minimum values. The maximum value in the distribution represents the expected value and the decreasing values represent the deviation from design specification due to wear and tear.

Table 2. Physical and Scenario Parameters

Parameter	Classification	Distribution	μ	σ
Appliance load	Scenario	Normal	0.74 W/ft^2	0.1
Lighting load	Scenario	Normal	0.47 W/ft^2	0.1
Infiltration	Physical	Normal	1.08 ACH	0.1
			Max.	**Min.**
Heating COP	Physical	Triangular	4.2	3.0
Cooling COP	Physical	Triangular	2.5	1.8
PV power coefficient	Physical	Triangular	0.20	0.18
Setpoint factor	Scenario	Uniform	1	-1

A setpoint factor is added to the weekday setpoint temperature schedule for heating and cooling to represent a uniform variation of $\pm 1°C$.

To limit the risk in the scenario uncertainties, fixed limitations are added to the boundary conditions [Hopfe et al. 2013]. A truncated normal distribution is added as a factor to the lighting, equipment, and occupancy schedules for the basement.

Table 3. Properties for Factors

Parameter	Distribution	μ	Max.	Min.
Setpoint factor	Uniform		-1	1
Occupancy factor	Truncated normal	1	0.8	1.2
Appliance factor	Truncated normal	1	0.8	1.2
Lighting factor	Truncated normal	1	0.8	1.2

To perform the analysis for year 25, the infiltration rate is increased from 1.08 ACH to 1.48 ACH at 50 Pa to

account for loss of air tightness. The fixed COP value for heating and cooling is lowered to account for degradation over time. The reduction in the energy generation due to deterioration of PV modules over time, is considered as 80% of the marked value as per the manufacturer's specification. The maximum and minimum for the triangular distributions for these adjusted values is shown in Table 4.

Table 4. Properties for Some Physical Parameters in Year 25

Parameter	Maximum	Minimum
Heating COP	3.6	3.0
Cooling COP	2.2	1.8
Photovoltaic power coefficient	2.2	2.0

Part II: Stress Testing

The second part focuses on the DesignBuilder model, which facilitates modeling of the HVAC system more accurately and in greater detail and accounts for complex zone interactions.

There are different modes of operation in the building: heating-only mode, cooling-only mode, and mixed heating and cooling mode. In winter when the building only needs heat, the heat pumps extract heat from the return side of the campus chilled water loop, and the hot water is provided to the building. The chilled water is exported back to the campus loop where it can be used. In swing months when the building needs both hot and chilled water, both the heat pump and the campus chilled water loop are utilized, and the excess chilled water that is not used by the building is exported back to the campus system. In summer when the building only needs chilled water, it will get it from the campus loop, and the heat pump system will remain off.

Ventilation to the building is provided by a DOAS, which also controls the moisture through a heat recovery wheel that contains a desiccant. The auditorium has its own air handling unit (AHU), which serves the ventilation and conditioning needs of the auditorium. The net cooling energy consumption for the building accounts for the chilled water that is sent back to the campus loop as well as the campus chilled water plant efficiency. The regularly occupied spaces use radiant slabs for heating and cooling and variable volume terminal units serve the conditioned air. This is represented in Figure 2.

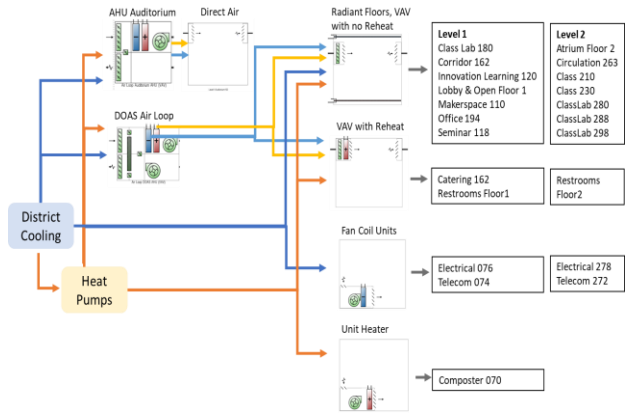

Figure 2. HVAC schematic

The variable volume terminal unit modulate the terminal unit damper to vary the airflow between its maximum and minimum in response to the space temperature, relative humidity, and CO_2 levels. During occupied hours, the CO_2 cutoff is 1,000 ppm, and during unoccupied hours it is 800 ppm. The maximum relative humidity cutoff is always 50%.

Setpoint temperatures and relative humidity cutoffs maintained for different space types shown in Table 5.

Table 5. Setpoint and Setback Temperatures

Winter		Summer		Space Type
Setpoint	Setback	Setpoint	Setback	
72.5°F	60°F	78°F	85°F	Auditorium, Classroom, Class Labs, Makerspace, Innovation and Learning, Office
65°F	60°F	80°F	85°F	Corridor, Mechanical, Support

Defining Stress Tests

The stress tests considered are:

Stress Test 1: Peak occupancy for a day in the whole building, spread across zones for an artificially created weeklong heatwave: Tests whether the HVAC system can handle the increase in loads across the building. This is done for one week between July 8-14. The outdoor air temperature is 5°C higher than recorded actual weather and is substituted in the weather file. The occupancy for each zone is increased by 50% at the same time, keeping the schedules the same.

Stress Test 2: Peak occupancy for a hot day in a single zone: Tests whether the layout of the HVAC system can handle the imbalance in zonal loads. The occupancy is

assumed to increase by 50% and the analysis is carried out for July 12, with the outdoor air temperature 5°C higher than the actual temperature.

Stress Test 3: Power outage of 8 hours on a hot day with normal occupancy: Checks how fast the building can be cooled down after a period of no cooling and ventilation as the result of a power outage during occupied hours for a single day between 8 a.m. and 6 p.m. The simulation shows how fast the system responds to the rise in temperatures and how fast it can cool down the space after power is restored.

DISCUSSION AND RESULT ANALYSIS

Part I: Risk Analysis

The Monte Carlo simulation shows that the mean of the distribution for the resultant EUI increases to 33.1 kBtu/ft^2/year. This is more than the deterministic EUI of 32.1 kBtu/ft^2/year calculated earlier. Considering a risk appetite of 5%, the top 5% of the results from the distribution are assumed to be an acceptable risk. The maximum EUI within this risk margin is then found to be 35.91 kBtu/ft^2/year. In other words, to avoid a bigger risk of non-compliance than 5%, the renewable generation system should be designed to meet this load.

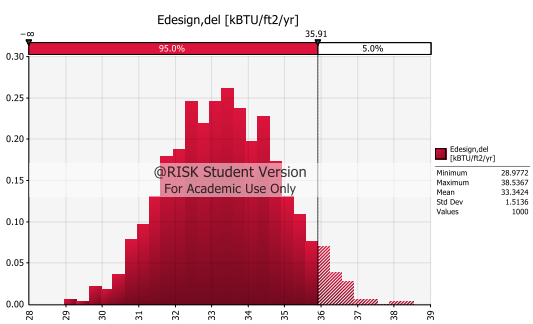

Figure 3. Distribution for EUI in year 1

The analysis is also done considering the energy generation from solar PV and accounting for uncertainty in the PV power coefficient.

Generating the distribution of net EUI by combining the UA of load and generation for year 1 indicate that the mean of net EUI increases from -12.1 kBtu/ft^2/year to -9.7 kBtu/ft^2/year, that is 29.1% net positive, seen in Figure 4. Assuming again an allowable risk margin of 5%, the maximum net EUI obtained from the distribution is -3.7 kBtu/ft^2/year. The net energy consumption by the building is in this case is -68.87 MWh, which is net positive by 18.9%.

Results for year 25 show that the mean of the distribution for EUI increases to -1.5 kBtu/ft^2/year, which is more

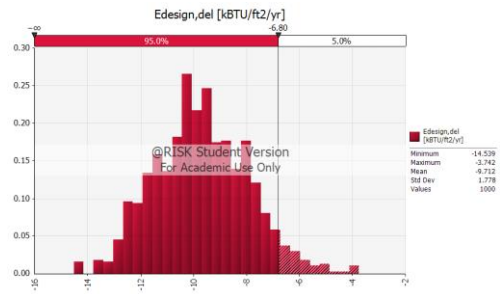

Figure 4. Distribution of net EUI in year 1

than the deterministic EUI of -4.4 kBtu/ft^2/year, seen in Figure 5. The building is only 4% net positive in this case. Accepting a risk margin of 5%, the maximum EUI as shown in the distribution is 2.3 kBtu/ft^2/year. The building is in fact no longer guaranteed to be net positive in year 25 if one accepts a 5% risk margin.

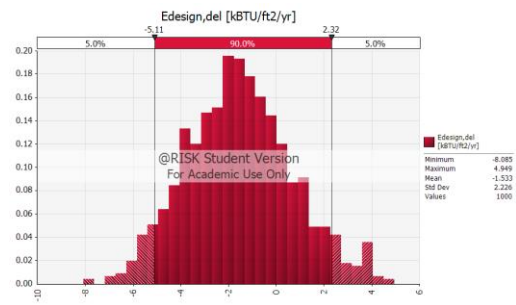

Figure 5. Distribution for net EUI in year 25

Part II: Stress Test

The indoor temperature and CO_2 levels are checked for various zones when subjected to the stress tests.

Stress Test 1

Because the auditorium has its own AHU for ventilation and conditioning the space, the internal conditions are checked for this zone to determine whether the system can handle the additional loads.

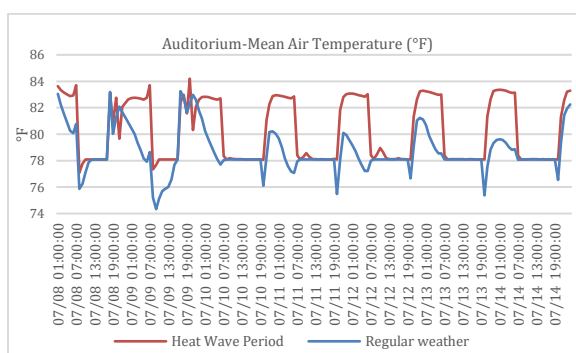

Figure 6. Mean air temperature in auditorium—Stress Test 1

As seen from the results from Figure 6, the setpoint temperature is well maintained at 78°F during virtually all occupied hours, even during the heatwave period. During the unoccupied hours, the temperature in the heatwave period rises faster during the heatwave days but is easily maintained below the setback temperature of 85°F.

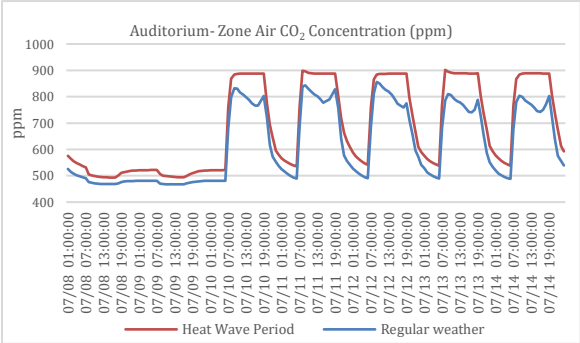

Figure 7. CO_2 concentration in auditorium—Stress Test 1

Figure 7 shows the CO_2 concentration during the weekdays, from July 10–14 is within the 1000 ppm cutoff level during the occupied hours, despite the increase in occupancy.

The indoor space temperatures are also checked for other zones in the building served by the DOAS unit for ventilation and radiant slab for cooling the space. As per discussions with the facilities management team, the exact use of the makerspace has not been laid out clearly. The zone temperatures are checked specifically for this variable use space during increased occupancy for Stress Tests 1 and 2.

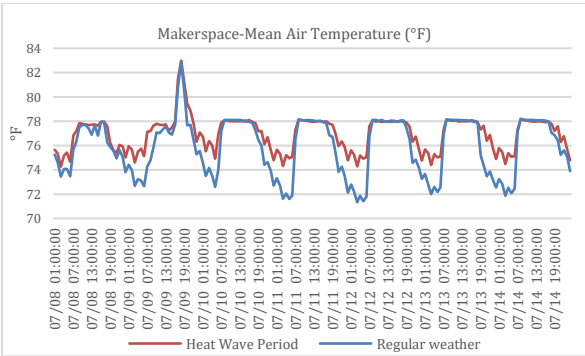

Figure 8. Mean air temperature in makerspace—Stress Test 1

As seen from Figure 8, the cooling setpoint temperatures are maintained at 78°F during the heatwave period, indicating that the system can handle the excess loads.

Stress Test 2:

Since the occupancy for the auditorium may exceed beyond the designed capacity of the space during events, the stress test is simulated for such an extreme situation. The simulation is also carried out for the main building served by the radiant slabs for cooling.

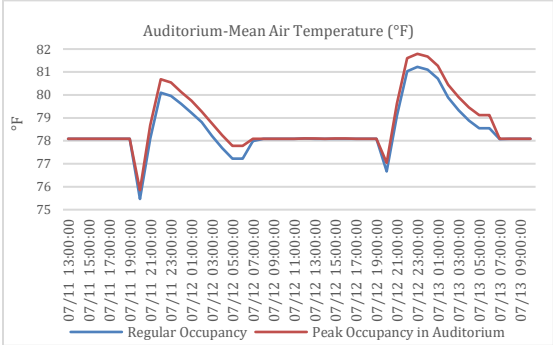

Figure 9. Mean air temperature in auditorium—Stress Test 2

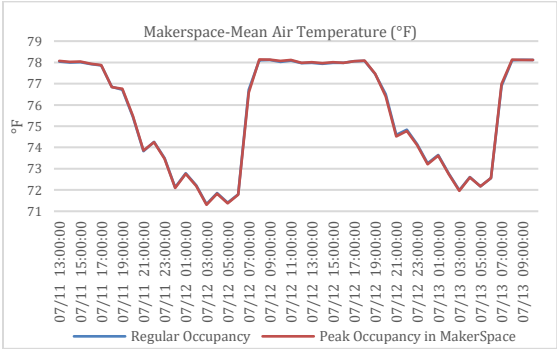

Figure 10. Mean air temperature in makerspace—Stress Test 2

As seen from the results for both cases in Figure 9 and Figure 10, the system for both the auditorium and main building is able to maintain setpoint temperature at 78°F despite zonal imbalances due to increased load in one space.

Stress Test 3:

The analysis is done for the auditorium for zones in the main building. The peak in the space temperature during the outage between 8 a.m. and 6 p.m. is at 93°F for the auditorium as seen in Figure 11 and at 90°F for the Innovation and Learning zone, taken as an example of a zone in the main building, as seen in Figure 12. The lower spike in temperature in Innovation and Learning is due to the thermal storage potential of the radiant slabs. The thermal mass of the slabs cools down the space by a small amount even after the outage. The results indicate that the HVAC system is able to cool down the space

after the outage since the space temperatures are restored for both zones.

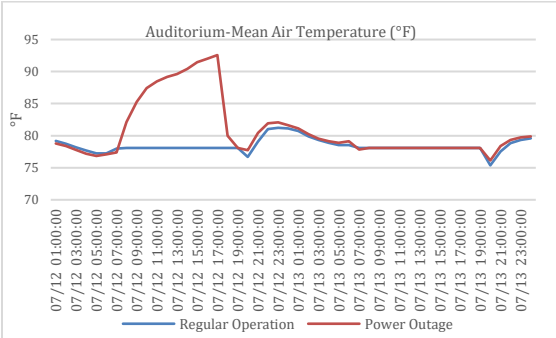

Figure 11. Mean air temperature in auditorium—Stress Test 3

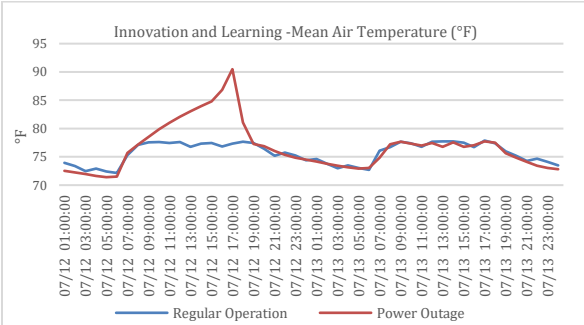

Figure 12. Mean air temperature in Innovation and Learning—Stress Test 3

The CO_2 concentrations are also analyzed during the power outage. As seen from Figure 13 and 14 the CO_2 concentration rises significantly leading to poor quality air during the outage period. This is due to the high occupancy in this zone; however, these levels are restored below the 1,000 ppm CO_2 concentration in both the auditorium and Innovation and Learning after the outage in less than 1 hour, indicating that the AHU and DOAS unit are able to supply sufficient fresh air to the building.

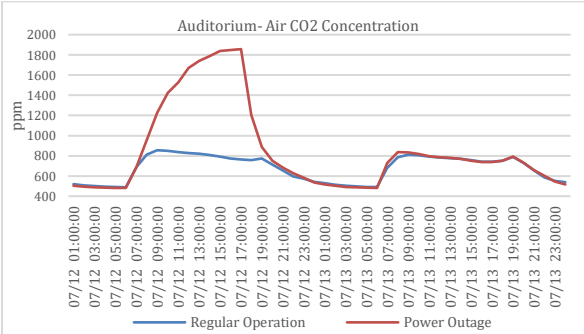

Figure 13. CO_2 concentration in auditorium—Stress Test 3

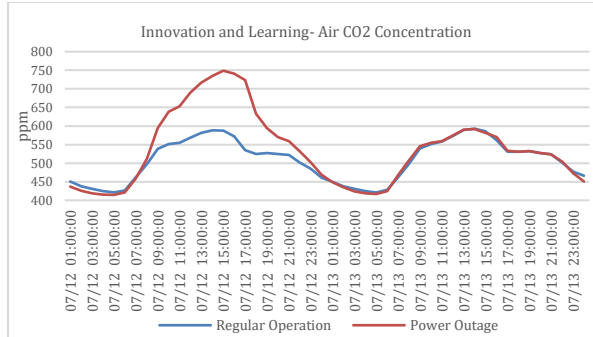

Figure 14. CO_2 concentration in Innovation and Learning—Stress Test 3

CONCLUSION

In this study, a low-resolution model-based risk analysis is conducted by considering uncertainty in physical and scenario parameters to determine whether the building is net positive in year 1 as well as year 25 of operation. The analysis shows that the building remains net positive for year 1 of operation; however, it is no longer net positive in year 25 if one accepts a 5% risk of failure. Building retrofits may need to be done to make up for the increase in infiltration rate, and the solar panels may need to be replaced for the building to remain net positive up to and beyond year 25.

The study is an example of how uncertainty in building parameters can be incorporated in building energy simulation to aid in the decision-making process. In this case, the result is useful for the building owners to justify the investment in building design and installed features to obtain the Living Building certification in the first year and to ensure future investment to support the building operations in the coming years.

The results from the high-resolution stress tests indicate that installed capacity of the HVAC system is capable of maintaining the setpoint temperature and CO_2 levels below the cutoff despite extremely high occupancy and severe weather. They also indicate that the layout of the HVAC system is suitable to handle imbalance in zonal loads and cool down the building in case of a power outage. These results are an assurance that the HVAC system can maintain comfortable indoor conditions in case the occupancy is more than anticipated during events.

FUTURE WORK

The building energy model can be adjusted based on the actual building operation and can be calibrated against the building energy consumption once it is occupied. It can be used for space programming and optimizing the

space utilization keeping the energy goals of the building in mind.

NOMENCLATURE

DOAS	Dedicated outdoor air system
EUI	Energy use intensity
UA	Uncertainty analysis
UQ	Uncertainty quantification
EPC	Energy performance calculator
PV	Photovoltaic

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