Applications and Validation of Building Performance Analysis for a Georgia Farmhouse

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Fig. 1. Main House, Hardman Farm, south facade, Sautee Nacoochee, Georgia, 2010. The deep porch overhangs and shutters help control solar gain. Photograph © Jonathan Hillyer.

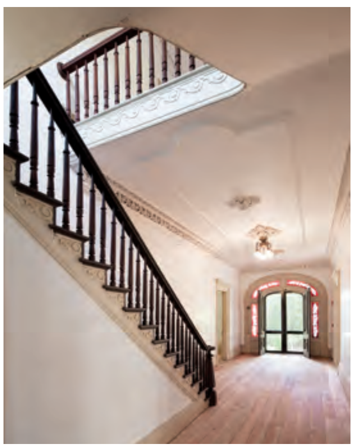


Fig. 2. Main House, Hardman Farm, central hall, 2010. The central hall provides cross ventilation and air exchange between floors. Photograph © Jonathan Hillyer.

Building performance analysis informed the design of a minimal mechanical approach for a historic farmhouse. Post-occupancy monitoring demonstrated whether the building performs as predicted.

The primary goal of this project was to preserve the Main House at Hardman Farm, which is located in the foothills of North Georgia, 80 miles northeast of Atlanta. Hardman Farm provided an opportunity to explore sustainable design within the context of a historic property. This project, which consisted of the conservation of a highly intact historic resource, was guided by building performance analysis to predict how the passive environment of a traditionally designed and constructed historic building might be utilized or supplemented. Computer simulation of building performance was used to better understand the historic interior (indoor) environmental conditions and to serve as a guide for future design decisions regarding climate control. This article describes the energy-modeling approach during design, its application, and the resulting minimal mechanical approach that was implemented. After construction was completed in 2010, a second project was launched to conduct post-occupancy monitoring, in order to validate the assumptions and applications of the energy-modeling results against actual building performance.

Preservationists are accustomed to performing assessments of building conditions and recommending treatments, but the assumptions made during the planning and design phases often are not revisited against the building's actual performance or post-occupancy use. However, with adaptive use and energy upgrades for historic buildings on the rise, research on post-occupancy evaluations is growing.[1]

Constructed in 1870, the Italianate-style Main House is the centerpiece of what was once a working dairy farm that was later converted into a summer retreat. Nestled in the historic Sautee Nacoochee Valley of the North Georgia mountains, the site has deep cultural and natural significance. Culturally, it is significant for its location along a primary Native American trading route, its subsequent use as a dairy farm, and its later use by Lamartine G. Hardman as a place of agricultural experimentation and as his summer residence during his tenure as Georgia's governor from 1927 to 1931. The area around the site is important for its natural and agricultural landscape. The house and other parts of the property are further distinguished for their pristine condition.[2]

Unlike most houses, which have been altered over the years to keep up with current styles and technologies, the Main House at Hardman Farm has been changed very little since 1870. It retains its original floor plan, construction materials, mechanical systems, and decorative features. Analysis of the interior finishes revealed that the original plaster, the paint on the wood trim, and the shellac on the wood doors are still exposed.[3] The house is exemplary for its examples of early turn-of-the-century adaptions of new technology. The original gasoliers, early twentieth-century electrical lighting fixtures, and early plumbing systems and fixtures also survive.

In the 1980s the property was donated by the Hardman family to the Georgia Department of Natural Resources (DNR) for use as a historic site. The DNR initially planned to use the building as a house museum. In order to preserve the collections, which consisted of furnishings and artworks, the DNR planned to create a museum-quality interior environment with tightly controlled temperature and humidity ranges. While this approach is typical for a collections conservation environment, it quickly became clear that achieving these goals would significantly impact the building envelope and interior spaces. Multiple systems approaches were considered, but they were rejected for the following reasons:

- the invasive nature of mechanical equipment and distribution and in-space devices, both physically and audibly
- the damaging effects of insulating the building envelope, both in terms of impact to interior finishes and potential for condensation within the exterior wall assembly
- the potential negative impact of a new environment on historic materials that had, over time, acclimated to the North Georgia environment.

The design team, in collaboration with the DNR, determined that the house was too valuable in its current pristine condition to move forward with such an intrusive approach. Instead, the DNR decided that building performance analysis should be undertaken to explore minimal, less invasive heating and cooling strategies. In studying alternative approaches for cooling the house, the design team and the DNR reviewed the existing thermal conditions of the house, while also distilling and prioritizing the goals for the interior thermal environment.

Based on experience, the team believed that continuing to use the inherently sustainable passive features of the house for cooling, rather than installing a mechanical cooling system, would be the best approach for preserving both the building and the collections, which after 140 years had acclimated to their environment (Figs. 1 and 2). The team also believed that this approach would result in a reasonable level of visitor comfort and would provide visitors with a more historically authentic experience, both visually and thermally. To verify this approach and provide a sound basis for decision-making, the design team utilized computer simulations to better understand the existing thermal environment of the house and to predict how these conditions would be perceived by the visitor. This understanding of the interior thermal environment would also provide the team with a predicted range of seasonal temperature swings, which if too broad, could negatively influence the performance and durability of repair materials and techniques.

Computer simulation of building performance has become a fairly standard practice for many project types, due in large part to the proliferation of the LEED green building rating system and other sustainable design initiatives. Unfortunately, just as the LEED system is tailored for the construction of new buildings or the extensive remodeling of existing structures, the modeling software available at the time of this project relied on assumptions based on the properties of modern construction materials. This article evaluates how well these design-phase models served to predict the performance of a particular historic building and how the data inputs were adjusted to represent the properties of historic construction assemblies.

Design-Phase Analysis Methodology

Once the design team committed to using energy modeling to analyze the existing interior thermal environment of the Main House, the best methodology needed to be established. Relying on their past experience with simulation-analysis tools, the architect and the mechanical engineer identified computational fluid dynamics (CFD) as the appropriate technology to understand the passive airflow within the house. CFD is a technique used to model the behavior of fluids. In buildings, it can be used to model the movement and temperature of air within spaces. This dynamic is important to understand as it allows designers to investigate the temperature distribution and air movement within buildings before they are built, allowing them to test options and select the most effective solutions.[4] The mechanical engineer performed CFD studies of how the house responds passively to ambient conditions during the warmer summer months. The team conducted the analysis using CHAM PHOENICS/FLAIR software.[5] These analyses were run at increments of five degrees from an outdoor ambient temperature of 90°F down to 70°F with an assumed occupant load of three people and 100 watts of lighting per room. These studies revealed that while the internal and external gains did increase the temperatures of the spaces, these higher temperatures stratified near the ceiling, leaving the occupied zone, roughly 6 feet 8 inches above the floor, reasonably comfortable at 78°F in most rooms with 10-foot ceiling heights.

While promising, these results were valid only for the specific conditions that had been input and did not capture any dynamic response of the house to changing conditions throughout the day. To better understand this behavior, a whole-building energy model in eQUEST, developed for LEED certification, was set up to produce an hourly report of temperatures in each space without the use of mechanical systems (usually referred to as a free-running model). The methodical and iterative practice of whole-building energy modeling is physics-based and computer-aided. It helps to predict energy use and also helps evaluate energy-efficiency strategies for their potential to improve building performance.[6] eQUEST was selected because it is user-friendly, incorporating a wizard mode to walk the user through the modeling process, and it was free. It was responsible primarily for the proliferation of the whole-building energy-modeling practice. Today, it is widely considered to have been overtaken in capabilities by more advanced tools.

A free-running model of the Main House at Hardman Farm with no systems installed showed an encouraging summer trend: the interior of the house cooled overnight to near the nighttime outdoor low temperature with the interior maintaining this temperature throughout much of the day, despite the steady increase of the outdoor temperature. The interior temperatures did not begin to climb until the late afternoon sun began to hit the house, at which point the temperature shot up quickly to above the ambient temperature, then began the cycle of cooling to the nighttime low.

An important aspect of the evaluation process was achieving an interior environment that limited the seasonal swing in interior temperatures and humidity, which would cause repetitive cycles of expansion and contraction. Because the materials had acclimated to the existing environment, the team believed that by maintaining the upper range of typical temperatures in the warmer months, there would be no deleterious effect on the existing historic fabric of the building. However, allowing temperatures to drop below freezing could have a deleterious effect on some of the proposed repair and conservation materials to be used during the restoration work. For example, the plaster repairs are prone to expansion and contraction during seasonal temperature swings.

While the building performance analysis was used to verify an approach of not using mechanical cooling, it was also used to evaluate multiple heating scenarios. The traditional method of using the wood-burning fireplaces for heating was ruled out due to operational concerns and the potential of introducing soot and other pollutants into the conserved interior spaces. The eQUEST energy model was used to evaluate several relatively noninvasive heating systems, including baseboard heaters, hydronic radiant floor systems, and hybrid systems. Each system under consideration was modeled and evaluated in terms of initial cost, operating cost, energy efficiency, ability to achieve the LEED prerequisite, physical impact on historic fabric, impact on historic settings, maintenance considerations, and human comfort. Additionally, scenarios where no system was installed at the second level were also explored, further minimizing the impact to historic materials from the installation and distribution of such systems. This evaluation led to the selection of an underfloor hydronic radiant system to heat the first floor and the decision not to heat the second floor, which would benefit from heat naturally rising from the first floor.

In setting up the eQUEST model, the team understood that a number of assumptions would need to be made. The first variable that required an informed assumption was the lack of localized or site-specific weather data; ideally, a local weather station would have been in place to provide site-specific weather data for input into the model. In the absence of a local weather station, the design team evaluated the surrounding weather-station information available online through the National Solar Radiation Database (NSR Database), which had weather data available for the following surrounding locations: Watkinsville, Georgia (75 miles south of site); Chattanooga, Tennessee (126 miles west); Greenville, South Carolina (100 miles east); and Asheville, North Carolina (121 miles northeast). Greenville was selected as the geographic location that might best approximate the microclimate of the Sautee Nacoochee Valley due to its similar elevation and some other minor geographic similarities. The information available on the NSR Database is formatted by Typical Meteorological Year (TMY2). The TMY2 is a 30-year (1961–1990)

Table 1. Summary of Assumptions across Different Design and Validation Models

	CFD Design-Phase Model	eQUEST Design-Phase Model	eQUEST Validation Model	DesignBuilder Validation Model
Roof assembly U-value BTU/(hr °F ft²)		0.385	0.385	0.385
Wall assembly U-value BTU/(hr °F ft²)		0.274	0.274	0.274
Window assembly U-value BTU/(hr °F ft²)		0.89	0.89	0.89
Floor Assembly U-Value BTU/(hr °F ft²)		0.85	0.85	0.85
Infiltration rate (ACH@50Pa)		1.8	3.39	3.39
Occupancy number		21 (assumed)	2–12 (daily tours)	2–12 (daily tours)
Occupancy hours		Weekdays, 6:00 a.m. to 4:00 p.m. (assumed)	Thursday–Sunday, 10:00 a.m. to 4:00 p.m. (daily tours)	Thursday–Sunday, 10:00 a.m. to 4:00 p.m. (daily tours)
Weather file source		TMY2 Greenville bin	On-site weather station	On-site weather station
Lighting description	100 watts/room	100 watts/room	100 watts/room	100 watts/room
HVAC description	N/A	Hydronic radiant heating, first-floor only	Hydronic radiant heating, first-floor only	Hydronic radiant heating, first-floor only

survey of "typical" hourly weather conditions including temperature, humidity, solar radiation, cloud cover, and wind speed and is intended for use in building-systems analysis.

The eQUEST model also required assumptions about the performance of the existing construction. The wall construction of the Main House consisted of interior plaster on wood lath, wood studs, and exterior wood siding applied directly to the studs with no sheathing. The walls are uninsulated, and due to the significance of the historic materials, there was no consideration of adding insulation. The large, single-glazed windows were also to be conserved, with no alterations for improved thermal performance. Similarly, the wood-framed roof structure with metal standing-seam roofing was uninsulated. The only building component scheduled to receive insulation during the preservation work was the floor system. The flooring of the first story was a wood-framed structure over a high, ventilated crawl space. A graph showing assumed U-values for these assemblies is included in Table 1.

The infiltration rate used in the eQUEST model was 1.8 air changes per hour (ACH) at a pressurization of 50 pascals, which was determined by doing a single-point blower-door test during the design phase.

Another unknown variable during the design phase was occupant load. At the time of the design, it was not known how the house would be operated. The initial design-phase energy model divided the house into eight zones and assumed occupant loads at varying square-footage rates. Maximum occupant load within the model was 21 people. It was assumed that the house would be occupied during the daytime only, Monday through Friday, from 6:00 a.m. to 4:00 p.m.

After setting up the model with the Greenville weather data and the U-values derived from each individual material within an assembly, virtual sensors were located within the eQUEST model. The model predicted that if the first floor were maintained at 68°F during the winter months, the stack effect would result in keeping the second story above 32°F even on the coldest day. Based upon this analysis, the design team decided to install a hydronic radiant floor-heating system on the first floor only, with no heating system installed on the second floor. As a component of the planned hydronic radiant heating system, the underside of the flooring of the first story would receive additional insulation in the form of 3 inches of foil-faced, rock-wool insulation finished with a layer of 1/2-inch DensGlass sheathing, which was incorporated into the model as part of the analysis.

To evaluate the effects that the modeled conditions would have on visitor comfort, the concept of adaptive thermal comfort was used. Per the adaptive comfort model in ASHRAE *Standard 55*, the thermal response of occupants in naturally ventilated spaces (where the windows can be opened and closed) will depend in part on the outdoor climate, and they may offer a wider comfort range than in buildings with centralized HVAC systems.[7] This comfort model assumes that occupants adapt their clothing to thermal conditions and are sedentary. For the adaptive thermal comfort model to be fully applicable, there must not be a mechanical cooling system or heating system in operation. Since the Hardman Farm project would have a radiant heating system on the first floor operating during winter, the adaptive model was not literally applied, but the concept served to guide the project's analytical and decision-making processes. This concept gave the client and the team some justification for providing a more authentic thermal experience for visitors. Given that the house is part of a larger site with outbuildings and adjacent trails, it was reasonable to assume that visitors would come appropriately dressed for seasonal conditions.

To get to the core concern regarding how high the interior temperature might rise during peak summer months, the energy model was used to predict the interior temperatures during the hottest days of the year. The energy model showed that the existing passive shading and ventilation features of the house, combined with the wood-framed building envelope, were sufficient to minimize direct solar gain during the proposed hours of visitation. The energy model predicted that for only a few days in August, the interior temperature in upper-level rooms would exceed 90°F during the last two hours of the site's operation. This predicted outcome was considered a small inconvenience when compared to the invasive nature of a mechanical cooling system and the interpretive opportunities of an authentic thermal environment.

The design-phase analysis demonstrated effective temperature stratification and thermal lag to justify the use of passive cooling with minimal heating. However, as stated above, the team recognized that the available tools did have limitations and that the process had required several assumptions, which, if not fully accurate, could impact the value of the predictive modeling. These uncertainties led the design team to pursue a grant to implement post-construction monitoring and evaluation to better understand the accuracy of the design-phase analysis. Outlined below is the methodology used to validate the results of the design-phase modeling and to demonstrate the effectiveness of the tools used for evaluating passive-design strategies inherent in historic buildings.

Validation Methodology

The National Center for Preservation Training and Technology (NCPTT) provided a grant to monitor the existing weather and interior conditions. The goal was to gather site-specific weather data, as well as data on interior temperatures and relative humidity, to compare to the assumed weather conditions and the interior temperature predictions from a recalibrated design-phase eQuest model.

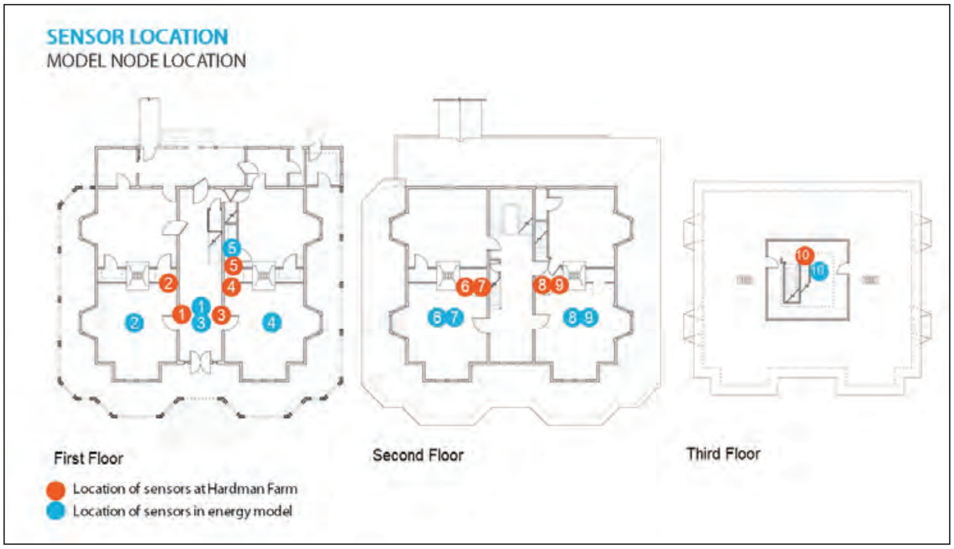
Another goal of the grant was to build a new model using the more sophisticated modeling engine, EnergyPlus.[8] At the time of the validation analysis, which came several years after the design-phase analysis, EnergyPlus-based modeling software was overtaking the market and perceived to be more accurate. There was an opportunity to compare and contrast the capabilities of each software as applied to a historic structure. eQUEST was chosen due to its ready availability and ease of use; however, this choice was made with an understanding that the program had limitations that could have a bearing on the resulting data. For example, eQUEST does not have the capacity to represent the effects of air transfer and stratification from room to room, while those effects are incorporated into the EnergyPlus engine. The design-phase analysis had extrapolated that information from the CFD analysis. With regard to representing the effects of thermal lag, eQUEST uses a transfer-function method with custom weighting factors that leads to errors in approximating the performance of thermal mass, whereas the EnergyPlus engine uses the heat-balance method, which models thermal-mass effects more accurately.

Monitoring

The approach to recalibrating the design-phase analysis and calibrating the validation analysis was to incorporate weather data collected from an on-site station so that the actual weather conditions of the specific site could be used in lieu of the TMY2 Greenville weather data assumed during the design phase. The design team worked with Campbell Scientific to assemble a weather station to gather site-specific readings on temperature, humidity, wind speed, solar radiation, and rainfall. Using the measured weather data and a software called Elements, weather data was logged hourly and a data file was created.[9]

The data for interior conditions was gathered using wall-mounted wireless moisture/temperature/relative humidity monitors (WMTR) made by Protimeter Hygrotrac, Model BLD9000, in various locations of the house; they transmitted data on an hourly basis to a data logger. The monitoring approach was informed by a 2001 climate-monitoring project proposed for Drayton Hall in Charleston, South Carolina.[10] A primary goal for that project was to assess the interior conditions as they related to conserved finishes.

The one-year monitoring period began on June 1, 2015, and ended on May 31, 2016. Ten sensors were located throughout the house. They were positioned on both floors in a deliberate manner in order to gauge a range of thermal conditions (Fig. 3). Sensors 1 through 5 were located on the first floor; sensors 6 through 9 were located on the second floor; and sensor 10 was located in the cupola to get a sense of the overall temperature stratification of the house. Additionally, sensors 2, 6, and 7 were located on the sunnier side of the house, while sensors 4, 8, and 9 were located in more shaded rooms. Sensors 1 and 3 were placed on opposite walls of the central hall to determine whether there was any perceptible difference within the central space where air was circulating through to the upper level.



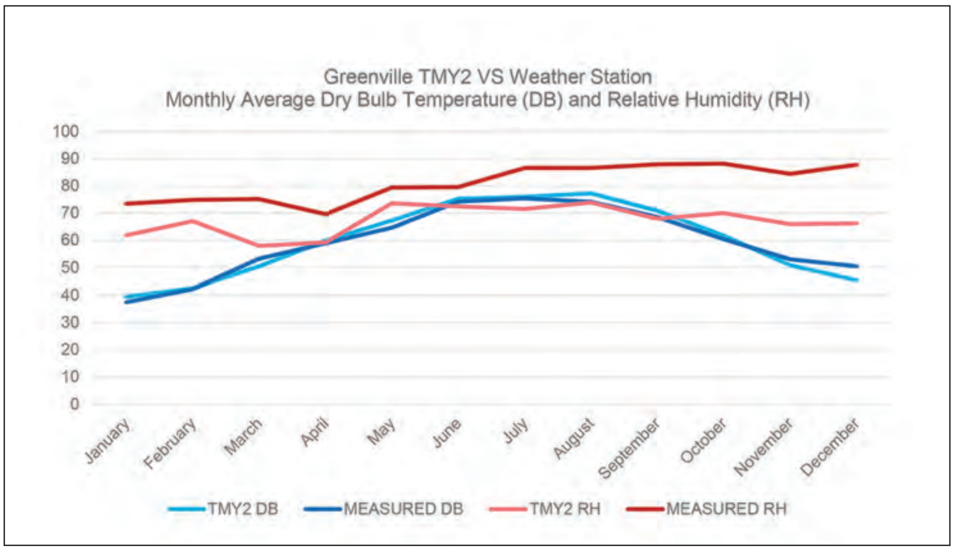


Fig. 3. Main House, Hardman Farm, floor plans showing sensor locations. The red circles display the locations of the physical sensors, and the blue circles indicate the location of the same sensor as assumed by the validation energy model. Figures by Sandeep Ahuja unless otherwise noted.

Fig. 4. Difference in the TMY2 Greenville weather data and the measured site-specific weather-station data at Sautee Nacoochee for dry-bulb temperature and relative humidity.

Modeling and Calibration

The methodology for modeling entailed recalibrating the existing design-phase eQUEST model with the site-collected weather data and then comparing the predicted results from eQUEST to those from the newly calibrated EnergyPlus-based software. There are other user interfaces to EnergyPlus, but due to its ease of use and focus on comfort-related metrics, DesignBuilder was selected as the program for the validation analysis.

In order to set a comparative baseline between the two modeling programs, various data points were updated to reflect the actual conditions that would impact the results, such as occupancy. During the design-phase analysis, an occupant load of 21 was estimated. For the validation analysis, visitation numbers were updated to reflect a daily visitor count, generally between 2 and 12 visitors during each of the three scheduled daily tours. In addition to the daily tour visitors, other groups and school tours visited approximately once or twice a week; they ranged in size from 15 to 42 visitors. The house was closed to the public in January and February 2016. When operations resumed in March 2016, visitation hours were between 10:00 a.m. and 4:00 p.m.

Table 1 shows the various parameters used for each phase of the modeling process and what assumptions were confirmed or changed after occupancy. Values associated with the U-value of the building envelope remained constant throughout, while other parameters were updated using the verified data collected over the life of the project. The revised infiltration rate was determined by a multi-point blower-door test done post-renovation.

As mentioned above, the data from the weather station helped create an accurate weather file. The difference between the weather-station data and the Greenville TMY2 weather file can be seen in Figure 4. When comparing the differences in the temperature, the TMY2 and the weather-station data (light and dark blue curves, respectively, in Fig. 4) are on average 2°F apart. The graph also shows that the temperature difference between measured data and TMY2 is higher in the months of December and August. The relative humidity, on the other hand, shows a greater difference between the measured data and the TMY2 weather file, approaching a 13.8 percent difference on average. Generally, however, the selection of the Greenville weather-data file was a good match climatically to the microclimate of the Hardman Farm site.[11]

Results and Discussion

Validation methodology. Two key metrics—temperature and relative humidity—were collected by the interior sensors for the validation analysis of both models. The software available at the time of the design-phase analysis allowed for the output of temperature and relative humidity averaged for the whole room as measured from the exact center of the room. The sensors, however, were placed with the intent to record the differences between areas within the same room. Due to the similarity between locations of actual versus modeled sensors, some of the sensors have identical data in the energy model and can be condensed to one, such as sensors 1 and 3, which were located in the central hall.

Condensing the locations of the two sensors allowed the design team to correlate the data measured by the interior sensor, the existing eQUEST model, the recalibrated eQUEST model, and the DesignBuilder model. A graph displaying results for sensors 1 and 3, shown in Figure 5, illustrates the four curves for temperature throughout the year. However, for relative humidity, shown in Figure 6, the graph shows only the measured data and the data from DesignBuilder. The existing and updated eQUEST data is not plotted for relative humidity since eQUEST does not output relative humidity.

During the calibration process, it was evident that the measured data and the DesignBuilder data aligned closely throughout the year. Interestingly, the eQUEST model showed bigger differences in the winter months. Although the data from DesignBuilder and the actual measured data appeared to be close in a monthly analysis, the team decided to investigate it at daily intervals to confirm the calibration of the energy model shown in Figure 7.

The DesignBuilder model and the measured data show a daily average temperature difference of 1.89°F as shown in Figure 7 and a relative humidity difference of 7.3 percent as shown in Figure 8. After noting that the energy model was closely aligned to the measured data on a monthly and daily level for sensors 1 and 3, the same was done for the remaining six sensors, and the findings were consistent.

eQUEST and DesignBuilder. The differences between the design-phase eQUEST model and the validation-phase recalibrated eQUEST model resulted from updating the weather file to the newly created file from the weather station, updating the occupancy schedules to reflect tour visitation logs for the year, and improving the accuracy of the geometry in the model. Despite these

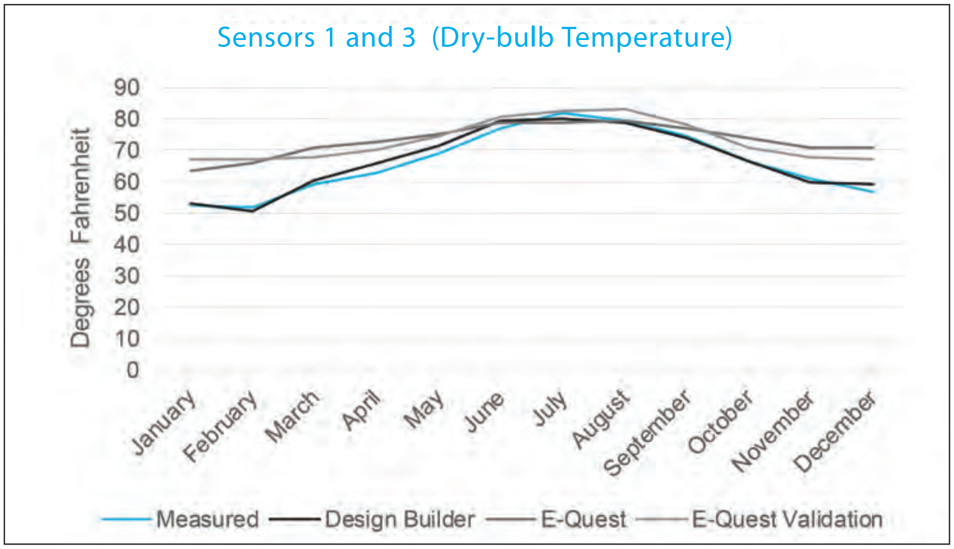


Fig. 5. This graph marks four different curves on a monthly basis: measured interior temperature data collected by sensors; DesignBuilder: data output by DesignBuilder; eQUEST: design model; and eQUEST validation: modified eQUEST model.

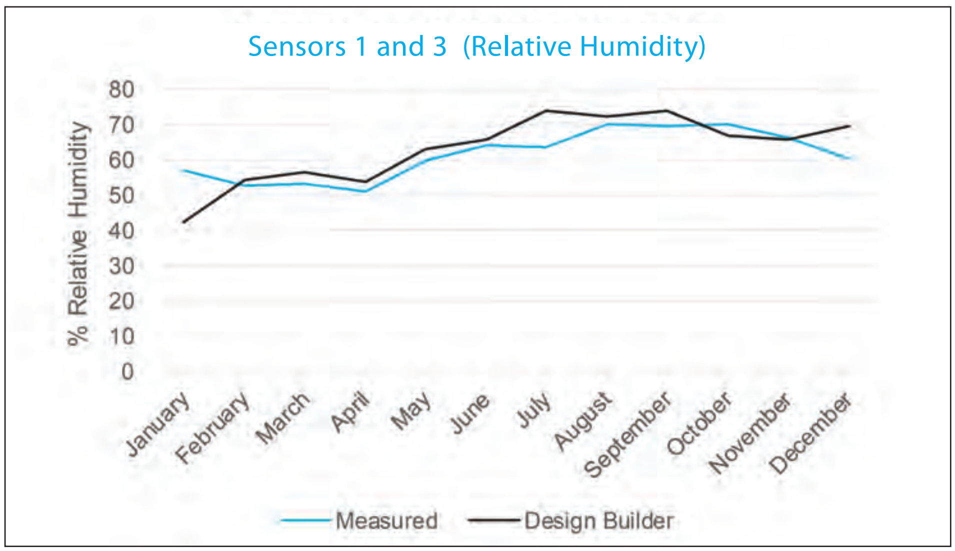
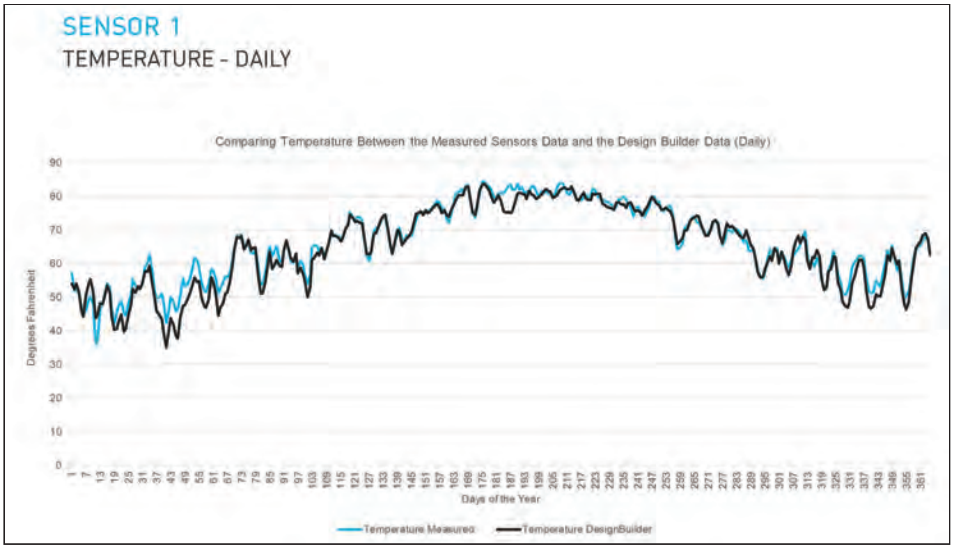


Fig. 6. This graph marks two different curves on a monthly basis: measured relative humidity; data collected by sensors and DesignBuilder; data output by DesignBuilder.

changes, no significant differences pertaining to thermal-comfort outputs emerged.

One of the key outcomes from the validation process was the ability to compare the accuracy, ease of use, and applicability of two energy-modeling platforms. Analyzing both the recalibrated eQUEST model and the calibrated DesignBuilder model revealed that the eQUEST model does not recognize the severity of the temperatures in the winter months; however, it matches closely to the measured data for the summer months. Also, eQUEST does not output an hourly report of relative humidity, which is a major factor in determining the thermal comfort.

DesignBuilder incorporates the CFD capability to test the effect of air movement through different rooms and the stratification of interior temperatures within the two occupied levels of the house. It is a well-known fact that warm air rises in rooms with high ceilings and through central halls, but this exercise allowed for quantification. To utilize DesignBuilder's capability for doing so, a simple analysis was undertaken to compare the results in the validation DesignBuilder model to the design-phase CFD model. The actual measured interior temperature on the first level of the house was approximately 82°F when the outdoor temperature was 90°F. The actual measured interior temperature for the second floor on that same day was 87°F, a 5°F spread between the two floors. The DesignBuilder validation model similarly predicted a 5°F spread between the two floors but also predicted interior temperatures that were 5°F to 7°F higher than the actual measured interior temperatures. The design-phase CFD model predicted a tighter 3.6°F spread between the two floors and much higher temperatures than what the actual measured data confirmed. While DesignBuilder was closer in predicting the actual conditions, both models had a margin of error between 2 percent and 8 percent.



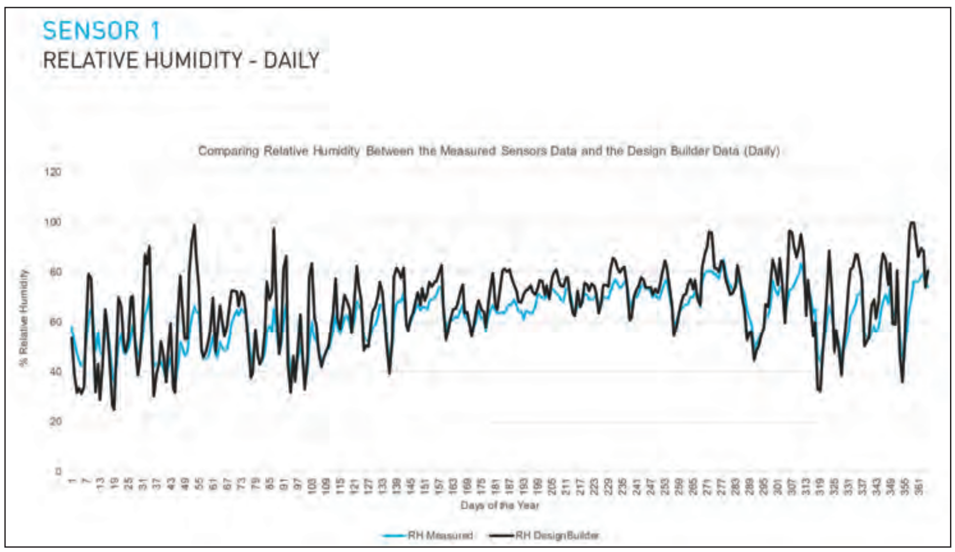
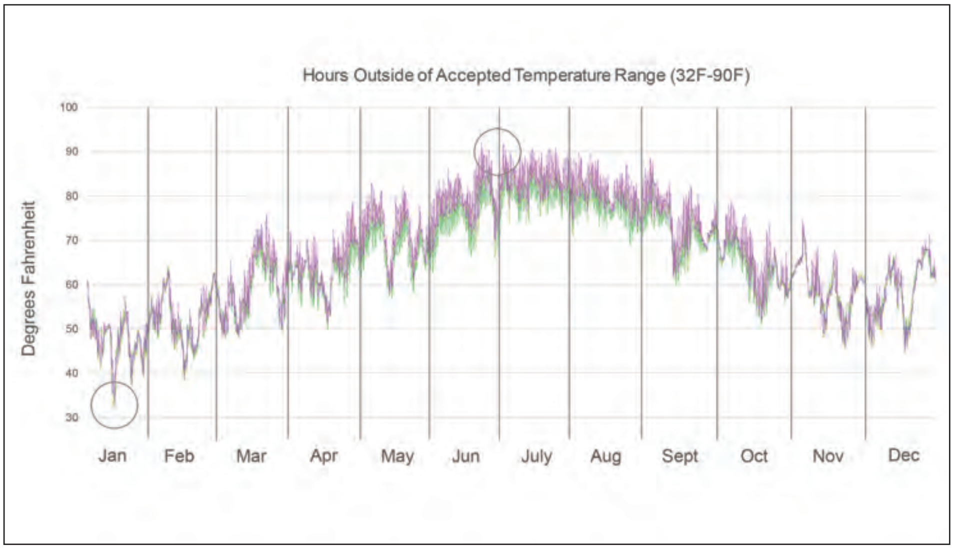


Fig. 7. This graph marks two different curves on a daily basis for sensor 1 on the first floor: measured; data collected by sensor 1 and DesignBuilder; data output by DesignBuilder (temperature depicted is daily average).

Fig. 8. This graph marks two different curves on a daily basis for sensor 1: measured; data collected by sensor 1 and DesignBuilder; data output by DesignBuilder (relative humidity depicted is daily average).

Comfort. After seeing the accuracy of the DesignBuilder model in predicting temperature and relative humidity, the design team focused on its outputs when trying to understand more about comfort within the building. The building had been designed without any mechanical cooling system and with no heating system for the second floor. Keeping this in mind, the DNR determined that 32°F to 90°F would be a suitable temperature range using the adaptive comfort model. To understand whether any days had temperatures outside of this range, the graph shown in Figure 9 was created from DesignBuilder.



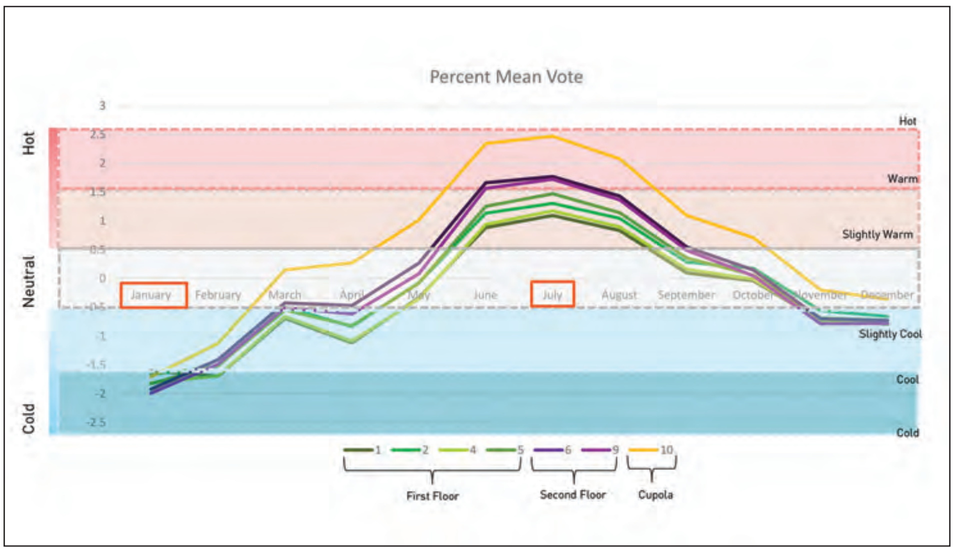


Fig. 9. The monthly breakdown of temperature measured by each of the sensors helps identify times when the temperature within the space is outside the acceptable range of 32°F to 90°F.

Fig. 10. Illustration of thermal comfort on a monthly basis using the metric predicted mean vote. The green curves represent sensors 1 through 5 on the first floor; the purple curves represent sensors 6 through 9 on the second floor; and the yellow curve represents sensor 10 at the cupola.

Thermal-comfort analysis based on the DesignBuilder validation model shows that there is a maximum of three hours annually during the occupied time when the building is "uncomfortable." In addition to the expanded comfort ranges for the project, the building was also tested using an industry-standard thermal-comfort metric, the predicted mean vote (PMV), which refers to a thermal scale that runs from cold (-3) to hot (+3).[12] It takes into account six metrics that affect thermal comfort, including metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity, and relative humidity. The graph above shows how the different spaces perform under this holistic comfort metric (Fig. 10).

The key reason for using the Fanger model is to observe graphically how the accepted thermal-comfort range in this building compares to the thermal-comfort range in an air-conditioned atmosphere. In the latter case, only values 0.5 to -0.5 (warm to cool) would be acceptable. However, given the historic-preservation focus of this project and the transient nature of the touring occupants, higher comfort ranges from 1.5 to -1.5 should be acceptable. In cases where the spaces are naturally ventilated and the occupants have the ability to alter their environment by opening a window, higher ranges of thermal comfort are acceptable. Figure 10 illustrates that only the month of January dips into the dark blue (cool-cold) band, and only the month of July rises into the deep red (warm-hot) band. Aligning closely with the comfort hypothesis made by the team, this model reveals that the building spaces will be thermally comfortable almost year-round.

Conclusions

If the design-phase analysis were performed today, it would be logical to avoid the two models that used eQUEST and CFD. DesignBuilder or an equivalent sophisticated platform with built-in CFD capability would be a straightforward choice. However, given the tight budget constraints and ease of use, eQUEST did provide reasonable data to guide the decision-making process and could be an option for those who cannot afford a building-analysis consultant on their design team. DesignBuilder's use of the heat-balance method to model thermal-mass effects and its functionality for approximating the thermal stratification of air resulted in a far more accurate prediction of building performance and would be the modeling platform of choice. It does, however, require a building performance analysis background to utilize.

The interior-temperature data, measured by sensors on site, further validates the design team's hypothesis that interior temperatures in the Main House will remain within the range of 32°F to 90°F, especially during operating hours.

This monitoring and validation exercise has proven the value of the design-phase analysis to provide reasonably accurate guidance for design decisions. The resulting data allowed the design team to rely on the building's original passive systems, avoid the installation of cooling systems, and restrict the installation of a heating system to the first floor. This minimal approach to systems installation reduced the impact on the building's historic fabric, spaces, and setting. The remarkably intact interior finishes can be protected from a damaging cycle of freeze-thaw, which was a primary concern for the project team. Interpretively, this minimal approach will allow visitors to experience this significant setting in a manner beyond the visual, capturing a true sense of how it felt to live on this historic rural Georgia farm. The design team hopes that this case study can offer some precedent for others to consider less invasive means of dealing with interior environments and to opt to utilize the features that historically controlled the thermal environment, in order to broaden the interpretive possibilities of historic structures.

Acknowledgements

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Notes

1. See, for example, Antonio Martinez-Molina, José-Luis Vivancos, and Isabel Ausina, "Thermal Comfort in Historic Buildings: The Case of Study of the Museum of History of Valencia" (case study, World Heritage and Degradation Conference, Capri, Italy, 2016).

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9. "Elements," Building Energy Software Tools, accessed 2015, http://www.buildingenergysoftwaretools.com/software/elements.

10. Watson & Henry Associates, "Climate Monitoring and Management System for Drayton Hall, Charleston, South Carolina," report prepared for the National Trust for Historic Preservation, June 2001, 1–9.

11. Wind data from the TMY2 file for June through August 2015 was substituted for actual wind data due to a temporary equipment malfunction.

12. Predicted Mean Vote (PMV) was originally developed by P. O. Fanger, an expert in the field of thermal comfort, and later adopted as an ISO standard.

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