Thermal Reconstruction of a Crime Scene Using Calibrated Simulation

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Abstract

This study utilized energy simulation in support of a forensic pathology time of death analysis for a corpse discovered in a single family residence two years prior to the study. In order to produce an accurate estimate of the interior temperature profile at the time of death, a thermal model was constructed using EnergyPlus and calibrated using environmental monitoring data from the site.

The thermal model was able to predict the temperature in the room of interest within 1.4°C (2.5°F) with 90% confidence. This model was then altered to account for known differences between the monitoring period and the period of interest, and used to predict what the temperature profile had been at the time of death.

This study adds to a small body of work that compares simulated to measured performance data for unconditioned spaces, which should have a growing relevance as building energy performance simulation (BEPS) tools are used to model passive strategies.

1. INTRODUCTION

This project began with an unlikely telephone call from an attorney seeking expert advice for a homicide trial. Two years prior, a body had been discovered in the closet of a two-story home in the greater Sacramento area (Figure 1), and a suspect had been arrested. With the trial imminent, the attorney's question to us was, would we be able to determine the temperature in the closet in the specific building during the few days prior to the discovery of the deceased? Crime scene photographs showed that the building's HVAC system was off at the time the corpse was discovered. The temperature of the environment was a critical component of the time of death analysis, the findings of which might help the jury determine the verdict.

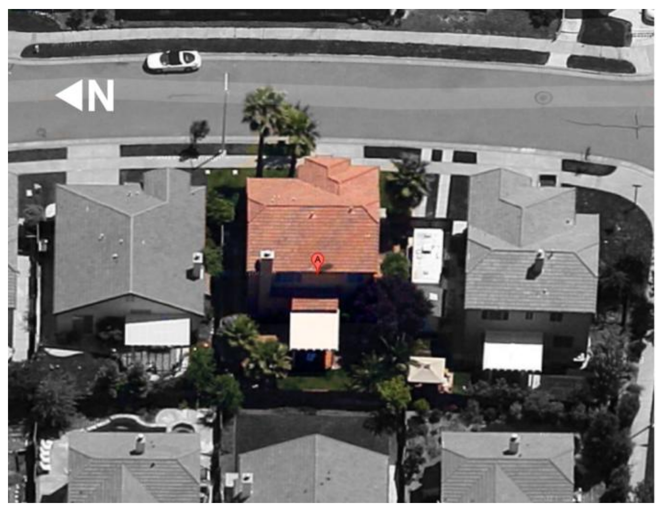

Figure 1. The two-story house in question.

Because the findings would need to withstand courtroom scrutiny, the accuracy and defensibility of this study were critical. While we did not find a precedent for such a forensic study in the literature, there is a body of work that seeks to accurately predict thermal conditions in buildings for design and operation using building energy performance simulation (BEPS).

In order to increase the accuracy of a BEPS model, studies have shown that a process of calibration can be used to "tune" a model. Many published calibration studies focus on HVAC system energy use; relatively few published studies show a process for calibrating a BEPS model of an unconditioned space or building. As an initial phase of a project to form a process for comparing measured and simulated building energy performance data, Maile and colleagues built a BEPS model of a typical zone of the San Francisco Federal Building, installed a series of environmental sensors, and then used the monitored data to adjust modeling assumptions so that simulated and measured temperatures were similar (Maile 2010b). Pereira and Ghisi built a calibrated model of a ventilated and otherwise unconditioned single-family house to investigate the impact of thermal envelope properties on occupant comfort (Pereira and Ghisi 2011).

However, even if a BEPS model of the house is calibrated with perfect accuracy for the current time period, there may have been conditions that existed immediately before and after the homicide that deviate from the assumptions in the calibrated model. The goal of this study was not only to create an accurate calibrated simulation of the house, but also to make assumptions explicit and meaningful in terms of their effect on the final predicted temperature profile.

Through a court order, we were able to gain access to the specific house in question, which had just been vacated by the previous tenant. We designed a thermal model and an environmental monitoring plan to address the goals of the study. We used monitored data gathered on site to calibrate the thermal model, and then adjusted assumptions to account for known differences between the calibration period and the period of interest at the time of the homicide.

2. THERMAL MODEL

In order to build an accurate thermal model of the house, we selected EnergyPlus as the BEPS platform. EnergyPlus provided a few key advantages for this study:

- subhourly calculation and explicit zone temperature reporting, allowing direct comparison to high-resolution monitored temperature data.
- accurate representation of thermal mass effects
- ability to explicitly control model geometry through Open Studio, and assumptions through a text editor

The published validation reports for EnergyPlus (version 7.0.0.036) include a suite of tests described by the BESTEST methodology. For this study, a series of four envelope tests was especially relevant. As with most of the tests published, each test result is compared with results of other BEPS models of the same zone. The report then identifies if the EnergyPlus results are within the approved range (defined by Min and Max in Table 1 below). We note that EnergyPlus (E+) simulation results are within the acceptable range for all cases. However, we also note that the EnergyPlus value is an average of 1.4°C (2.4°F) above the minimum, and an average of 1.2°C (2.2°F) below the maximum. The range indicates acceptance of some internal error in BEPS in general. Since the report is not an empirical validation, it may or may not indicate how closely EnergyPlus might simulate actual measured results.

	Average Hourly Zone Temperature (°C)			
	BESTEST			
Test case	Min	Ave	Max	E+
Low mass building	24.2	25.3	27.4	26.2
High mass building	24.5	25.5	27.5	26.4
Low mass, ventilated	18.0	18.9	20.8	18.9
High mass, ventilated	14.0	14.5	15.3	14.6

Table 1: EnergyPlus BESTEST validation results for free floating zone temperature models (Henniger and Witte 2011)

In order to recreate the crime scene of the past using BEPS and also describe our confidence in the result, an accounting of the potential errors was required. In general, we grouped these errors into problems with

- the accuracy of the BEPS platform algorithms,
- the ability of the BEPS platform to accurately represent site conditions, or
- the accuracy of BEPS user inputs (weather, shading, building envelope properties, internal gains, incorrect simulation settings, etc).

The first and last were described as internal vs external error types, respectively, by NREL researchers who completed research to systematically test for internal error types (Judkoff and Neymark 1999). The Building Energy Simulation Test (BESTEST) methodology that they developed formed the basis for the current ANSI/ASHRAE 140-2007 standard for testing for BEPS accuracy. ANSI/ASHRAE 140-2007, Standard Method of Test for the Evaluation of Building Energy Analysis Computer

Programs (ANSI/ASHRAE 2007), specifies a series of analytical tests to determine if a BEPS platform produces results in line with theoretical results as well as with other BEPS platforms.

The ANSI/ASHRAE 140-2007 standard tests for accuracy using a simplified, geometrically pure model. Errors may also be introduced due to the approximations, assumptions, and simplifications required for building a BEPS model of an actual building, such as simplification of geometry, the assumption that zone air is perfectly mixed, or the simplification of foliage shading (Maile 2010a).

2.1. Input Model

We designed the input model with particular attention to the downstairs closet (the space of interest) and zones adjacent (see Figure 2 below). All zones in the house were modeled, although we grouped rooms into a single zone for spaces that were not adjacent to the downstairs closet. While we constructed the initial model carefully, we did not spend too much time working out fine details, since we were working with initial instincts about what parameters might be critical. We anticipated that the calibration process would reveal any critical, inaccurate assumptions.

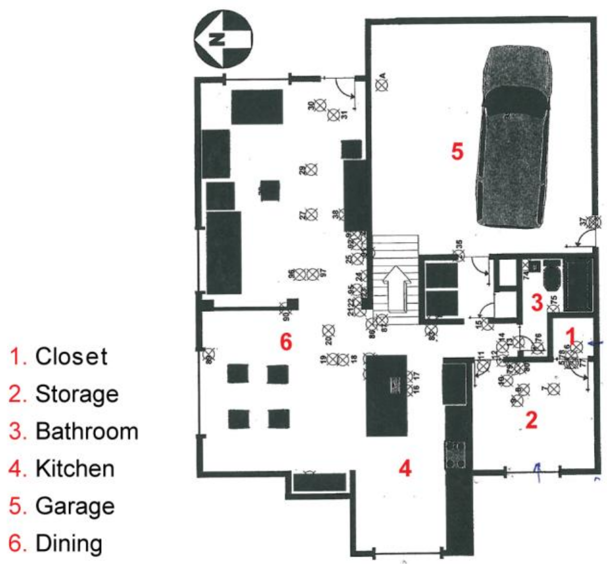

Figure 2. First floor plan of house, showing spaces referenced. The body was discovered in the closet.

The energy model consists of 9 thermal zones, representing the downstairs closet, adjacent storage room, bathroom, kitchen, garage, dining room/foyer, the southwest bedroom, its closet, the rest of the upstairs, and the attic. Site shading objects were modeled for buildings and trees adjacent to the house (Figure 3).

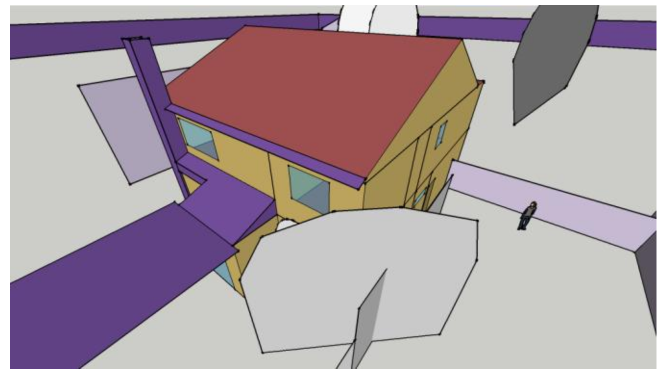

Figure 3. Screen capture of the energy model geometry. Note that two-dimensional purple and white objects are providing shade, while orange and red objects define thermal zones.

The thermal model was built using building materials and processes most likely to be used at the time of the house construction (1999). This was further informed by regulatory research regarding the Title 24 (California Energy Code) requirements in effect at the time. In addition we performed thorough non-invasive observations at the building at the time of the monitoring equipment installation.

To estimate internal loads, we considered possible ways that energy can be added to the house other than through the building enclosure or through the HVAC system. These included the presence of people, the use of lights, the use of electronics, and heat from miscellaneous installed equipment. Up until the last 36 hours, it was assumed the house energy use was typical as indicated by monthly energy bills. Energy usage for the month prior was an average of 18.1 kWh/day, which increased to an average of 18.8 kWh/day for the period of interest. While this use would not in reality be constant, we started this analysis with the assumption that the energy use was consistent, or about 765 W on average. While this may have introduced errors associated with daily patterns (ie, day vs night), it should accurately represent heat balance due to electric loads over the course of a multiple day period as long as daily patterns did not vary significantly.

In order to assign these electrical loads to appropriate thermal zones in the house, we referenced police photographs. These indicated a variety of appliances in the kitchen and adjacent laundry area. On the second floor, each bedroom contained some electrical devices, but the main electric load upstairs was the home entertainment system in the living area. This would be a significant draw on electricity: our research on the model of television in the second floor living area indicated that it would have been drawing over 200W when it was on. Electricity use for lighting would also have been distributed throughout the house. Lastly, the HVAC system energy for operating the heat pump would be present in the attic space. Our rough approximation is that the power was distributed as follows: 50W in the attic, 500 W upstairs (of which 100W was placed in the southwest bedroom), and 200W in the kitchen.

The use of natural gas would also have contributed to internal loads through hot water heating and cooking. For an unoccupied time period, we estimated the hot water heater energy use to be about 80W on average (ie, the rate at which energy dissipates from the system to the space regardless of the actual use of hot water).

The model contained no interzonal airflow. This was a characteristic we initially expected to change in the calibration process, but did not for two reasons. First, the closet and its adjacent storage room were connected to the rest of the house through a door that the police report described being approximately 1 inch open. Since infiltration was the only other potential source of air movement, we did not expect to find significant interzonal airflow in these two critical spaces. Second, the calibration process yielded effective ventilation areas far smaller than our initial assumptions, as well as closely matching temperature profiles without assuming interzonal airflow.

3. ENVIRONMENTAL MONITORING

For the site monitoring, we deployed a series of sensors throughout the house to track temperature conditions in the first floor closet, as well as in the adjacent zones: the adjacent storage room, bathroom, kitchen, dining room, garage, southwest bedroom, and southwest bedroom closet.

We studied the police photographs from the crime scene and police reports in order to configure components of the house as close as possible to how they were found when the body was discovered. The door between the downstairs closet and storage room was approximately 7 inches ajar, and the door between the storage room and kitchen was about 1 inch ajar. The downstairs bathroom window was partially open, as was the window to the bedroom above the storage room. The storage room window was closed. Interior blinds on upstairs windows were also adjusted. The HVAC system was turned off.

The sensors used were HOBO U12-012 dataloggers. These dataloggers were configured to record simultaneous measurements at 10-minute intervals for a period of approximately 5 weeks, starting February 8, 2012. We monitored air temperature in all rooms and also monitored globe temperature and insulated surface temperatures in the downstairs closet and adjacent storage room.

3.1. Weather Data

We identified two sources of weather data in the general area: Sacramento International Airport (KSMF) and the Sacramento Municipal Utility District Rotating Shadowband Radiometer (SMUD RSR). We found that these stations would have data available for the calibration period as well as at the time of the homicide.

To ensure that the data from the nearby weather stations was comparable, we also collected weather data on site to confirm that the weather data collected from the nearby stations would accurately represent the conditions on site. We used an industry-standard weather station (a HOBO H21 weather station) to monitor temperature, humidity, wind speed and direction, and solar radiation.

The outdoor temperature profile at the site was very similar to the temperature profile recorded at the airport. The solar radiation was a very close match between the global horizontal radiation measured on site compared with the global horizontal radiation measured at the SMUD RSR (Figure 4). Clear days show a nearly identical profile, while

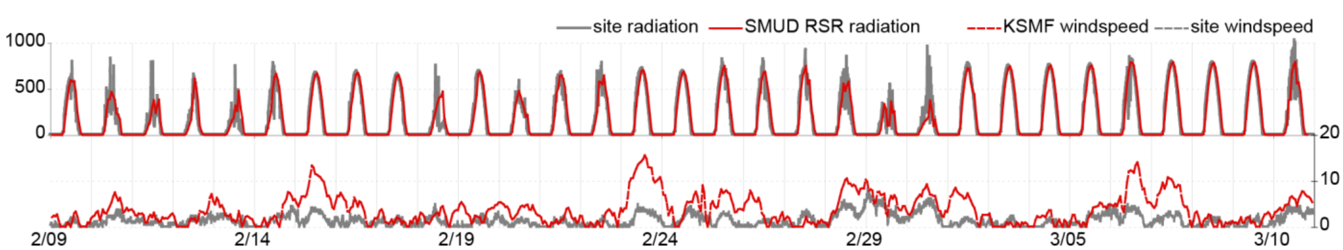

Figure 4. Comparison of solar radiation (left axis, W/m2) and wind speed (right axis, mph) between local and site weather stations.

cloudy days show a similar overall pattern despite discrepancies due to passing clouds. The comparison of wind speed shows the most variation between site and KSMF data (Figure 4). This is due in part to differences in the boundary layer profile between the open, unobstructed airport site and site monitoring station surrounded by obstacles such as houses and trees. Note that while the magnitude of the wind speed does not match, the variation is similar. This means that the speed of wind at the site can be approximated by applying a boundary layer correction factor to the airport wind speed, a correction that is taken into account in EnergyPlus.

Finally, the frequency distribution of wind direction shows a similar general trend: winds tended to come from either the north or the S/SE. During southerly wind patterns, the airport has a tendency to show winds more from due south, while the site winds veer slightly to the east. The weather stations report a wind direction of 0, or North, when wind is calm.

In preparation for the use of weather data in an EnergyPlus simulation, the EnergyPlus weather file (EPW) for Sacramento Metropolitan Airport was modified. For the weather file dates that corresponded to the monitoring period, the temperature, humidity, dewpoint, wind speed, and wind direction were replaced with data from KSMF, and the global horizontal radiation, diffuse horizontal radiation, and direct normal radiation were replaced with data gathered from SMUD RSR.

4. MODEL CALIBRATION

The process of model calibration was iterative. Each iteration was configured to generate subhourly air temperatures for each zone. Data visualization was utilized to graph all simulated zone temperatures with the monitored data, which initially did not match well (Figures 5 and 6). We began the process by exercising parameters to assess the effect on overall results (insulation, ground temperature calculation parameters, thermal mass, and ventilation) and performing elimination parametrics where major thermal drivers were eliminated in turn (no solar gain through

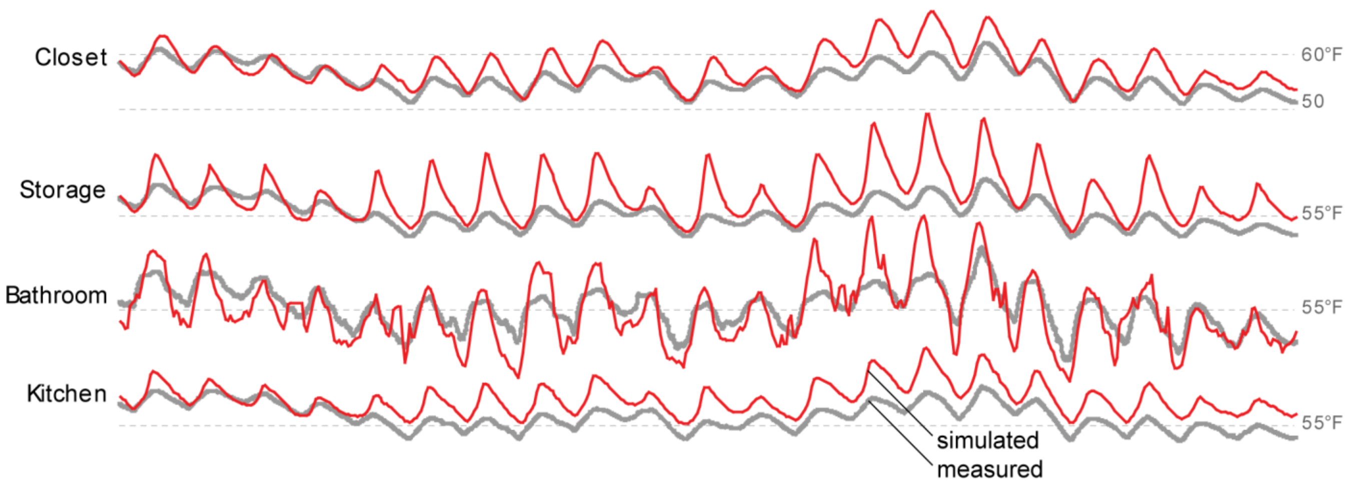

Figure 5. Before calibration: time series visualization of simulated and measured zone air temperatures for first 3 weeks of monitoring period.

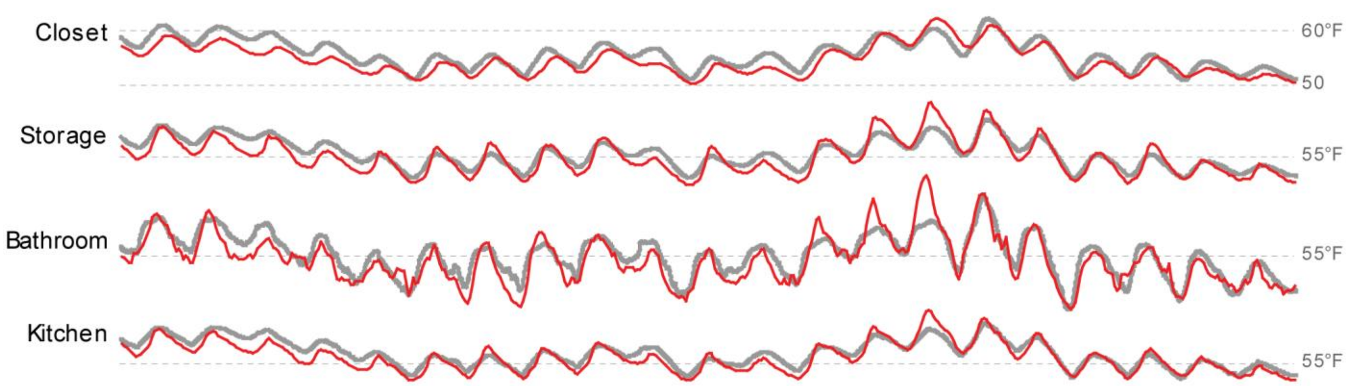

Figure 6. After calibration: time series visualization of simulated and measured zone air temperatures for first 3 weeks of monitoring period.

windows, no solar gain on opaque surfaces, no wind). This helped us develop intuition about which parameters were driving the system.

Then, the model was tuned to produce results that matched the measured temperatures more closely. For each iteration, a hypothesis was developed for differences observed between simulated and actual results, and how differences varied across different zones. Ultimately, measured and simulated results matched closely (Figure 6).

We ran the energy model simulation using the weather file modified for the calibration period. We then compared the conditions predicted by the energy model with the actual conditions measured on site. The iterative calibration process resulted in simulated data that much more closely matched the measured data (calibrated assumptions are shown in Table 2). The following are a number of notable alterations made to the model in the calibration process:

- removed scheduled occupancy that was erroneously included in the model
- fine tuned interior space temperature parameter of slab temperature pre-processor
- reduced ventilation opening areas by an average of 73%
- fine tuned foliage shading objects
- slightly increased thermal mass in walls
- increase shading coefficient of storage room window screen based on photograph of weave

In addition, we noted that Energy Plus reported a spike of transmitted solar radiation entering the storage room when the sun was at a very large angle of incidence upon the storage room window. Our back of the envelope calculations of transmitted solar radiation for that moment in time indicated that this was likely an internal EnergyPlus error that could not be completely corrected in the calibration process.

Ultimately, we found that a model with the parameters listed in Table 2 generated the closest fit for all zones, and the downstairs closet in particular. These assumptions constitute the calibrated model. Comparing the modeled results to the actual conditions measured results in predicted temperatures that vary from the actual recorded by less than 2.5°F (1.4°C) 90% of the time; the average difference was 1.1°F (0.6°C). The quality of fit for the model is shown in Figure 6 above.

Lights and Equipment	Lights off; 80W from water heater in garage	
Site Shading	Buildings, 8 palm trees, a tall hedge to the south, a deciduous tree to the southwest, and an orange tree near the storage room window (as shown in Figure 3 above)	
Building Shading	Various overhangs	
Infiltration	Effective Leakage Area calculation as described by Title 24 legacy building calculation methods	
Ventilation	Effective open areas for airflow due to wind and stack effect for the bathroom (0.04 m^2), garage (0.04 m^2), southwest bedroom (0.03 m^2), and attic (0.186 m^2) zones	
Internal Mass	Closet, Storage, Bedroom, Bedroom Closet : none Kitchen : counter tops, millwork, interior walls	Bathroom : fixtures Dining, upstairs : interior walls
Exterior Roof	U-Factor with film = 1.965 W/m^2-°K	
Attic Walls	U-Factor with film = 0.851 W/m^2-°K	
Exterior Walls	U-Factor with film = 0.472 W/m^2-°K	Thermal Mass = 32mm gypsum inside insulation
Exterior Windows	U-Factor = 3.979 W/m^2-°K	Solar Heat Gain Coefficient (SHGC) = 0.70
Attic Floor	U-Factor with film = 0.162 W/m^2-°K	
Ground Floor	Uninsulated concrete slab, with wood finish in closet and storage	
HVAC System	Off during calibration period, but set to heating mode at 68°F prior to calibration period	

Table 2: Calibrated model settings

5. TEMPERATURE PROFILE PREDICTION

Even though the BEPS model and the monitoring configuration were designed to match the configuration of the house at the time of the homicide, there were differences that could not be recreated and therefore could not be calibrated. During our study of crime scene photographs and police reports, we maintained a list of differences between the calibrated model and the model that would be used to simulate the time period around the homicide (Table 3).

The model was changed to take these assumptions into account, and then it was run with a weather file constructed from the time period of the homicide. We ran two predictive models to assess a range of potential scenarios for HVAC system use, since there was some uncertainty regarding when the HVAC system was switched off. While police photographs indicated that the system was off when the body was discovered, the client indicated that the system could have been on or off prior to Saturday at 1:30 PM. We therefore ran two models to simulate each scenario.

The energy model run with calibrated parameters and the addition of the assumptions described above showed that the temperature in the closet varied during the time period of interest as shown in Figure 7, for each HVAC scenario. A 90% prediction interval is shown, based on the error observed in the calibration process.

5.1. Potential Sources of Error

We acknowledge three potential types of error: inaccurate simulation, non-representative sampling for calibration boundary conditions, and inaccurate assumptions regarding conditions in the prior period. The inaccuracy of the simulation is evidenced by the error between modeled temperatures and measured temperatures. Our selection of a 90% prediction interval accounts for this error.

Lights and Equipment	attic: 50W, kitchen:200W, upstairs:400W, bedroom:100W
Site Shading	Include foliage of deciduous tree to the southwest
Internal Mass	Addition of objects in various zones: furniture, boxes, etc
People	1 person with a typical residential occupancy for all spaces except closets and attic, up to Saturday, at 1:30 pm, and 0 people after that
HVAC System	Unconditioned: System set to 68°F up until two weeks before the body was found
HVAC System	Partially conditioned: System set to 68°F up until Saturday at 1:30 pm

Table 3: Additional assumptions for prediction.

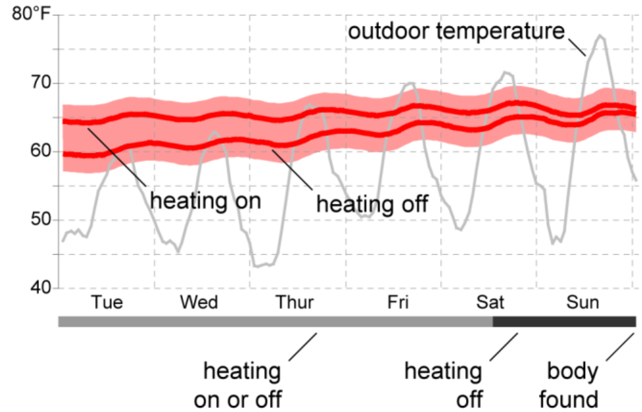

Figure 7. Projected temperature variation in the downstairs closet during the time period of interest.

Because the study occurred during a slightly different season, the boundary conditions present in the calibration period differed from those during the time period of interest. Ideally, the study would have been conducted during the same dates to obtain a more representative sample of boundary conditions, but even this approach will not generate a perfectly representative sample.

Finally, our list of assumptions for differences in the thermal model may have contained inaccuracies. Rather than exhaustively study the impacts of varying these assumptions, we instead provided the list of potential errors. For each, we made a preliminary, directional estimate about the effect that the potential error would have on the results. For instance, Table 4 shows the effect of two potential errors in estimating the Lights and Equipment load (a complete list was provided to the client). We proposed further analysis to study sensitivity to any of these assumptions if any became points of contention in the trial.

Error: Energy use for Lights and Equipment was much higher than typical during or prior to the period of interest. *Effect:* Reduce system energy use during system operation, and slightly increase temperatures when system was off.
Error: Energy use for Lights and Equipment was much lower than typical during or prior to the period of interest. *Effect:* Increase system energy use during system operation, and slightly decrease temperatures when system was off.

Table 4: Example of two potential errors between calibration period and period of interest.

6. DISCUSSION

This study presents a framework for calibrating a BEPS model to address a specific question relating to interior environmental quality. If the question had changed, the method of calibrating the model would also likely have changed. For instance, the zoning and detail in the energy model would have been distributed quite differently had the deceased been discovered in a different room. Similarly, the particular set of data available to us influenced the course of the study. With available data from SMUD RSR, we did not have to estimate the three components of solar radiation used in the EPW files. Had we less information about the crime scene or about the house, our confidence interval would have been larger, or our potential sources for error between the time periods would have become more problematic.

A number of findings may be significant relative to the field. First, we note that just as ventilation has been a significant calibration adjustment in prior EnergyPlus calibration studies (Pereira and Ghisi 2011, and Maile et al 2010b), so too was it a significant adjustment in this study. Our finding that we needed to reduce ventilation area by 73% is consistent with a finding that a 75% reduction in airflow was needed to achieve calibrated results for an unconditioned San Francisco Federal Building (Maile et al 2010b). This may indicate a tendency for the theoretical airflow models in EnergyPlus to not account for the complexity of dynamic airflow in actual buildings.

Second, the ability of EnergyPlus to closely match measured data in unconditioned buildings is not represented well in the literature. This study indicates that EnergyPlus is able to reproduce such conditions within a reasonable tolerance. As BEPS is used to study passive conditioning strategies, this finding should be pertinent.

7. CONCLUSION

We were ultimately able to provide an estimate for the temperature profile in the space of interest, along with quantitative and qualitative assessments of potential error. This was due to the availability of BEPS software capable of representing space at a sufficient level of detail, the availability of data, access to the property for monitoring and the process of calibrating the model.

In future studies, one significant tool that could be brought to bear to potentially improve the accuracy of the result is automated parametric optimization. Rather than tuning variables by eye, a parametric search algorithm could be employed to search for a set of parameters that minimizes the error between simulated trend lines and measured trend lines. We believe that optimization tools can complement the framework presented in this paper, but that they could not replace the prioritization or sequence of comparisons. Parametric analysis can only help identify issues with the handful of initially selected parameters; knowing which parameters to study and change was a result of studying subsequent iterations.

Finally, we note that the findings of our study were in the end not presented in court, for reasons not known to us. However, the importance of the accuracy of this study is underscored when considering that the accused has been convicted and is currently serving a life sentence for the homicide.

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