THERMAL DECAY

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Introduction to Thermal Decay Project

The goal of this project is to develop a simple and scalable procedure to collect and analyze time-series temperature data inside and near residential buildings to determine their thermal mass. This will allow us to accurately recommend retrofits for individual houses. Further, publically available and homeowner-sourced home attribute characteristics can be used to build a model that predicts the thermal mass of homes that cannot be measured. This semester, we focused on creating a robust design for data collection and developing sample proof-of-concept analyses with legacy data.

Key Use Cases and Originating Requirements

A subset of this project's high-visibility use cases and originating requirements are as follows:

1. The system shall analyze existing data from the previous iteration of this project.
2. The system shall use the thermal decay equation to determine the thermal mass of individual houses based solely on indoor and outdoor temperature readings.
3. The system shall compare the heating and electricity bills to the thermal mass of the individual houses to determine the energy-efficiency.
4. The system shall collect temperature data in houses with varying location and building material characteristics.
5. The system shall use a log tag outside of each home to gather localized temperature data.
6. The system shall calculate H (house heat coefficient) as a measure of efficiency.
7. The system shall build a model to predict H based on home characteristics easily accessible in public records.
8. The system shall foster collaboration between the ICN 2030 Modeling and Policy Teams.

Initial Research Phase

The initial research phase was split into three sections: the measurement devices (LogTags), factors that could affect heat loss in buildings, and publically available data.

LogTags

At the onset of the project, we received several HAXO-8 and TRIX-8 LogTag temperature recorders. According to the product specifications, these loggers measure and store up to 8,000 humidity and temperature readings between -40℉ to 185℉, which encompasses the temperature range of Ithaca winters with cushioning. The sensors are encased in polycarbonate and can be connected to a USB Cradle Interface. This hardware can be connected to a Windows-based computer and upload the temperature and humidity data to an online software.

Initially, we faced issues with the software as both members of our team owned computers that operated on MacOS. The LogTag company has not yet put out a software that is compatible with MacOS systems. We attempted to use the online version of the software, but this required a Wifi Cradle Interface as opposed to the USB versions that were available to us. After leaving campus, however, we were able to borrow a computer from a family member that ran on a compatible operating system. For this project to continue, the team will need reliable access to a communal PC.

Another concern we had about the LogTags from the onset was their longevity. Since these recorders had been used several years prior, it was unclear how long the batteries of the LogTags would last. Therefore, we looked into possible battery replacement procedures. The HAXO-8 and TRIX-8 LogTags contain fixed CR2450 3V $LiMnO_2$ batteries. Because they are fixed, there is no compartment that allows us to easily replace the batteries. Using battery replacement tutorials for other types of temperature sensors, however, we have determined that it is possible to open the LogTags and resolder a new battery to the existing motherboards. It is worth exploring the time/cost tradeoff between replacing batteries and purchasing new LogTags.

Heat Loss in Buildings

The next set of research we conducted was learning about heat loss in buildings. Before starting work on the project, we were given several powerpoints and reports that outlined general heat loss concepts, including different parameters of heat flow and potential sources of heat loss.

The aforementioned parameters were helpful for discussions regarding well-mixed and streamlined air. These include Grashof's number, Reynold's Number, Prandtl's Number, and Rayleigh's Number. Though they were not directly applicable to the project, they highlighted the fact that placement of LogTags in various rooms would affect the results, so we had to account for error in our measurements when analyzing the thermal mass of the houses. Grashof's number could be utilized in predictions of the transition from laminar to turbulent flow, as it involves ratios of buoyancy and viscous forces. Reynold's Number is a measure of how well-mixed the air in a room is, where larger values indicate well-mixed air. Prandtle's Number is an indication of insulations, as it highlights the relative thickness of thermal boundary layers with respect to the velocity of the air flow. Finally, Rayleigh's Number helps differentiate between laminar flow and turbulence depending on given critical values. The formulas for these parameters were also discussed, but we decided not to include them because of their lack of relevance to the calculations in this project.

The factors contributing to heat loss were invaluable aspects of our research, as they helped us determine what information should be requested of potential volunteers in the project. Essentially, all of these factors contribute to infiltration of outdoor air into the home or leakage of indoor air to the outside. These factors can be split into two categories, summarized below:

Air Pressure Differences	Thermal Boundary Holes
Wind Fans Doors Windows Stack effect	Insulation voids Unconditioned spaces Windows Doors Gaps in Walls

For the purposes of our project, the most measurable factors are those in the "Thermal Boundary Holes" category. These aspects of a house are essentially voids in the otherwise insulated house. The goal of insulation is to provide a continuous thermal boundary, but there are three types of instances in which the insulation is not necessarily up to standard. First, objects such as studs and locations such as balconies and porches can create "thermal bridges" in the insulation. Gaps that occur in spaces around windows and doors, the floors of attics, ceilings of garages, and unconditioned stairways are considered "voids." Furthermore, compressed insulation in older homes tends to do a worse job at keeping heat inside of homes.

Unconditioned spaces include stairwells, attics, basements, and garages. Because they are typically not insulated, heat is pulled from the rest of the house and leaked to the outside via these areas (stack effect). If a house has multiple unconditioned spaces, the most economical approach to avoiding heat loss is to insulate the inner envelope of these spaces in order to prevent said stack effect. Ceilings and roofs come into play if they are pitched, as pitched roofs generally lack insulation as well. One possible retrofit to these structural components is the addition of radiant barriers to ceilings and attic floors, as this removes the need for insulation in these types of areas. Windows and doors are analogous to holes in walls. Windows can be rated according to U-factor, solar heat gain coefficients, visible transmittance, and air leakage, all of which are indicators of a material's ability to transmit heat. Exterior doors are not rated in this manner, but they can be tested for insulation by measuring the temperature of the inside and outside surfaces of the door.

From this information, we have determined that the biggest causes of heat loss in the typical residence are unconditioned spaces, insulation, and windows and doors. This conclusion is reflected in the procedure outline below.

Publically Available Data

Before deciding to request house-specific information from the volunteers, we completed the research phase by looking into publically available data. This included square footage, elevation, past damage by fires and/or floods, and primary building materials. While the first two could be determined from public records and maps, the latter factors were affected by privacy and online availability. We determined that publically available data may not be the best source of information, but we will be noting this information in the preliminary survey and housing inspection processes outlined below.

Final Procedure

The results of the semester's research have been outlined in the procedure below, which will be implemented and adapted as necessary beginning in the Fall 2020 semester.

Outreach to Volunteers

After discussing the goals of the thermal decay project with our supervisor, Al George, we determined that the best results of LogTag data collection would occur during the winter months (as there is a higher gradient between indoor and outdoor temperatures). Therefore, the first month of the Fall 2020 semester will be dedicated to outreach. In this vein, we need to gather potential volunteers who will check out the LogTags and use them to gather temperature measurements in their homes. Due to the COVID-19 outbreak, we decided to develop a outreach email draft that can be sent to potential contacts as soon as state lockdowns are no longer in place. These cold emails will be sent to members of the sustainability organizations in Ithaca and Tompkins County, such as EcoVillage, TCCPI, and Sustainable Tompkins. The draft below will, of course, be adapted to the specific institutions as they are being sent out.

Outreach Email Draft
Dear [Community/Organization Leader],

My name is [Team Member], and I am a member of Cornell University Sustainable Design. The Ithaca Carbon Neutrality Team is pursuing a project studying thermal decay in residential buildings. Using LogTag temperature sensors, we are tracking temperature changes in homes to determine the rate at which heat is lost. We are reaching out to ask for potential volunteers for this project.

After filling out a brief survey and allowing team members to take notes of windows and doors in the house (though this is not required), volunteers will check out LogTags from [Name of Location] and place one on each story of their house and one outdoors. For approximately two weeks, volunteers will turn on the LogTags, which will passively take temperature measurements. Specific instructions regarding mounting procedures and measurement conditions will be given out upon request. We hope to determine the rate of heat loss from this data and deliver an assessment of how well-insulated your house is in comparison to other houses of similar sizes. This can help you understand if your home could benefit from a retrofit (endorsed by the Ithaca Green New Deal).

If anyone in your organization is interested and would like to learn more about the project and/or participating in the experiment, please have them contact us at [Team Member's Email]. We look forward to hearing from you!

Thanks!
[Team Member]

Institutional Review Board for Human Participation

Because this project requires potentially private data from volunteers, we will require permission from the Cornell Institutional Review Board to proceed with this experiment in the fall. We have looked into the process and determined that the application should be very similar to that of the previous iteration of this project. We have also obtained access to the previous application, so we can simply adapt it and submit for review. Given the extended time period over which the IRB reviews these applications, we intend to submit the application well before the start of the project in September (i.e. over the summer).

LogTag Procedure

Before performing the actual experiment, volunteers will complete a preliminary survey, check out the LogTags from (most likely) the Tompkins County Public Library, and receive instructions regarding mounting and measurement procedures.

Preliminary Survey

The intent of the preliminary survey is to collect information about the heat loss factors we found in our initial research phase. Though it is not required to actually carry out the experiment, the information provided in this survey will assist us in sorting the houses into groups based on size and structure. Furthermore, these factors will help us determine whether recommending retrofits to the homeowner will be worth the cost. The following information is requested in the preliminary survey:

1. Name, Email, Address
2. Number of Stories
3. Approximate Square Footage
4. Number of External Doors
5. Whether or not doors are insulated
6. Number of Windows on Each Floor
7. Number of Unconditioned Spaces
8. Number of Rooms on Each Floor
9. Whether or not the roof is pitched
10. Type of Insulation
11. Type of Windows (Single/Double Paned)

Checkout Procedure

The checkout procedure has not yet been fully developed. We intend for the LogTags to be borrowed and returned from the Tompkins County Public Library. They will most likely be kept in a separate storage space and only brought out if requested by volunteers. In addition to the LogTags, the volunteers will be given Ziploc bags and push pins for mounting. The library will also request a waiver that allows us to access their LogTag data and use it for our thermal decay analysis. We have not yet been able to reach out to the library as it has temporarily closed due to the COVID-19 outbreak. As lockdowns begin to dissipate and social distancing measures become less necessary, we hope to establish the checkout procedure in full detail prior to October of 2020.

Measurement Instructions

The volunteers will receive these instructions via email once they have submitted the preliminary survey and checked out their LogTags:

1. Place a LogTag in a corner room on each floor out of sunlight. The locations should be approximately ⅔ up the wall. Use the pushpin to mount the Ziploc bag on the wall. Ideally the LogTags should not touch furniture or be near windows and/or doors.

2. One LogTag should be placed outside by mounting the Ziploc bag on a tree or post with a pushpin. This LogTag should also be in the shade to maintain average temperatures.
3. Turn on all the mounted LogTags by pressing the Start button. If the button blinks green, it is working correctly and can be left alone. If not, please email [Team Members' Emails] in order to troubleshoot and/or checkout new LogTags.
4. For the next two weeks, turn the heating down each night to (ideally) 64℉ from 7:00 PM to 7:00 AM. (Of course, if this does not match your general routine, turn the heat down whenever you go to sleep.) This will provide the best results for analysis while still keeping the house relatively warm. During this time, avoid opening doors and windows unless absolutely necessary, as these structures are potential losses of significant heat.

House Inspection

While the preliminary survey must be filled out, it does not necessarily provide all the relevant heat loss information of a house. We decided that the most optimal collection of data could be determined via house inspection. Due to potential privacy concerns and the logistics of traveling from Cornell's campus to Ithacan homes, this part of the thermal decay procedure is completely optional. However, volunteers who *do* agree to have the house inspection will allow us to confirm/complete the information in the preliminary survey as well as look for potential gaps in the thermal boundary.

The team also looked into digital imaging as a potential method by which these gaps could be found. This process involves thermography cameras that can spot insulation gaps via infrared cameras, and it is commonly used by architecture firms to determine whether or not a design has been carried out correctly. While this information would be helpful when analyzing the LogTag measurement results, initial searches showed the cameras to be expensive, with primary searches showing prices ranging from $350 to $500. Therefore, digital camera imaging will most likely not be part of the house inspections.

Data Collection

Collection Procedure

As previously mentioned, the exact logistics of returning LogTags to the Tompkins County Public Library have yet to be determined. After LogTags are returned however, Thermal Decay subteam members will collect the LogTags from the library on a biweekly basis and upload the data to the LogTag software for analysis.

Data Analysis

Summary of Relevant Equations

To quantify a home's ability to retain heat, we need to calculate its thermal mass. To achieve this, we can use the following equations:

$$mC_p(\frac{dT}{dt})_{on} = Q - \frac{(\Delta T)_{on}}{R}$$
$$mC_p(\frac{dT}{dt})_{off} = \; - \frac{(\Delta T)_{off}}{R}$$

In this context, mC_p represents the thermal mass of the home, $\frac{dT}{dt}$ is the change in temperature inside the home with respect to time, Q is added heat, Δ T is the difference in temperature between the inside and outside of the house, and R is the thermal resistance of the house.

$$mC_p(R) = \; - \frac{(\Delta T)_{off}}{\frac{dT}{dt}_{off}}$$

Currently, we are focusing on quantifying the product of mC_p and R, since we only require study participants to lower (turn off) their heat at night. In future iterations of this project, it would be optimal to conduct experiments with added heat to utilize the first equation to separate thermal mass and thermal resistance.

Data Sources

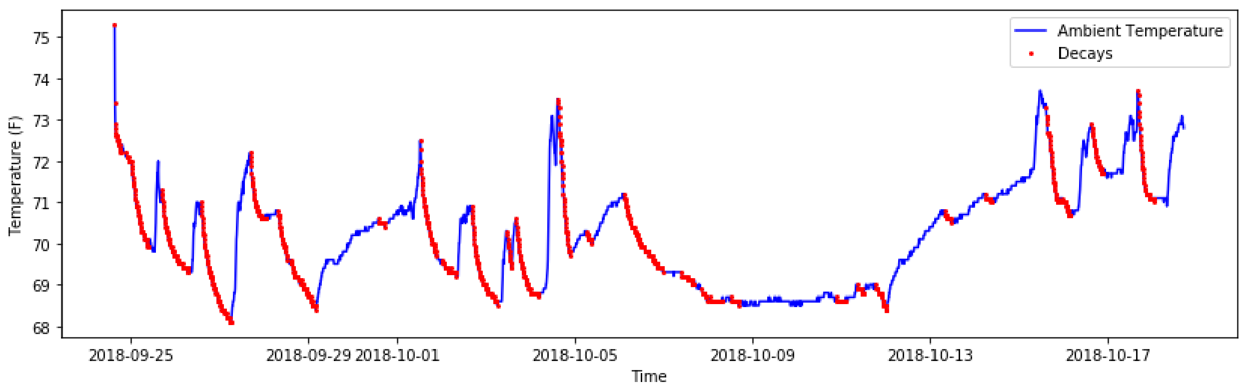
We were not able to collect new data in the Spring 2020 semester due to the COVID-19 Pandemic. Therefore, we completed a sample analysis based on a legacy dataset from a previous iteration of this project. This dataset contains indoor temperature data for one house during the months of September and October of 2018. Temperatures are recorded every ten minutes, to the 0.1 degree.

To approximate the outside temperature, we used archived Ithaca weather data from Weather Underground. Unfortunately, these temperature readings are less granular than our indoor logtag data, measuring degrees fahrenheit every hour in whole numbers. They are also less accurate; in order to calculate the thermal mass of the house, it is critical to have highly precise readings from directly outside. Due to wind, shade, and geographic variation, general Ithaca weather readings can be up to a few degrees different from localized temperatures. As shown by our initial analysis, this will not yield readings that will allow us to accurately calculate $mC_p(R)$ .Further, for this project to scale, we must collect coinciding temperature data with an outdoor LogTag, since archived weather data is only available in day-long datasets (making downloading weather data extremely manual and tedious). Next semester, we will solve this issue by providing each home with three logtags: two for inside (to measure variability within the house), and one for outside.

Parsing Time Series Data and Fitting Curves

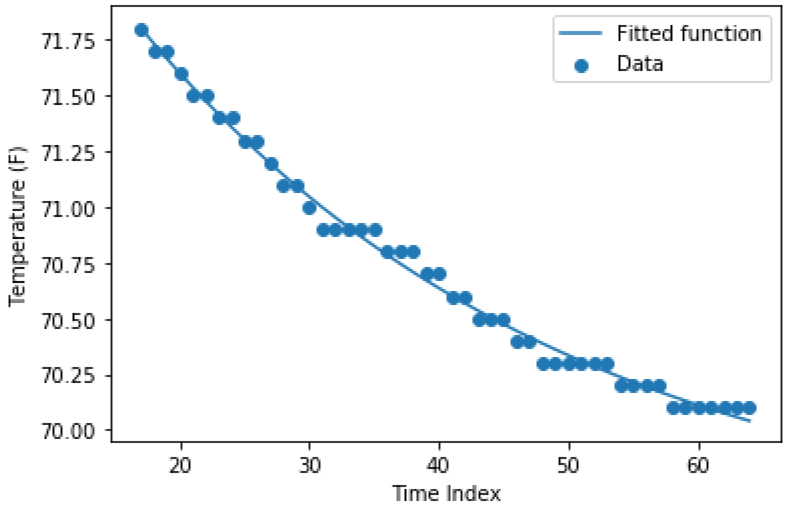
In order to fit exponential decay equations to heat loss events, we must first identify when the temperature in the house is decreasing. We wrote a simple parsing algorithm that loops through the temperature readings, and creates a list of decays lasting more than 2 hours and 30 minutes. Each event contains the timestamps and individual temperature readings during the decay.

When run on our test dataset, the algorithm identified the following decay events:



This algorithm is a start, but many improvements can be made. Currently, if the temperature increases in the home during one time step by as little as 0.1 degrees, it ends the decay "run" and begins a new one when the temperature drops again, potentially parcing one decay event into two or three. Likewise, it does not specifically identify exponencial sections within a decay, which may allow initial instability in temperature to alter our curve's fit.

A potential fix for this problem could be to update the algorithm to only add a value to an existing run if the decrease in temperature between T and T-1 is less than the change in temperature between T-1 and T-2. The only issue that may arise here is that it can take multiple timesteps for the temperature to fall 0.1 degree, even at the steepest section of the curve (shown below). This issue could be solved by taking the average temperature over 30 minutes and fitting a curve to those averages. This could also smooth out any small temperature increases.



Once the decay events are identified, we can find the best fit exponential equation and take its derivative at each timestep to calculate slope ($\frac{dT}{dt}$). Using this along with ΔT, we can calculate $mC_p * R$ at each interval. Ideally, this would yield a similar result at each timestep during each decay. Then, we could find the average thermal mass, and build a confidence interval for it based on the variability between events.

In our example analysis, we identified and fitted one decay event because we did not have access to a complete Ithaca weather dataset. Our calculated $mC_p * R$ was not the constant value that we expected. As the decay progressed, our $mC_p * R$ value grew. We think this is due to inaccurate outdoor weather data, resulting in inaccurate ΔT values, and the fact that the data was taken in relatively warm-weather.

Next Steps

As mentioned above, we need to complete an analysis with accurate outdoor data taken in cool weather months to truly prove that this method works. This will allow us to understand how accurate these models can be under optimal conditions. Once this is complete, we can also develop a completely automated method of exporting LogTag Data directly from reader software into an application that automates the analysis and provides customized reports with results to homeowners.