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Case Study: A Model Interactive Qualifying Project

Energy Efficiency of the Worcester Friends Meetinghouse

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Abstract — **Every student at Worcester Polytechnic Institute is required to complete an interdisciplinary research project called an Interactive Qualifying Project (IQP). Student teams investigate issues at the intersection of technology and human needs, developing engineering solutions to societal problems. In 2013, a student team carried out an IQP project titled "Energy efficiency of Worcester Friends Meetinghouse" with the aim of reducing energy consumption in a building housing a number of non-profit agencies. The research, which focused on the buildings heating system, thermostat, windows, insulation, and usage behavior of the occupants, has produced a number of practical recommendations that can be implemented both in this building and others like it. It further serves as an excellent model of the IQP program, and can be used to illustrate the objectives of, challenges facing, and philosophy behind the WPI student project system.**

Keywords — Interdisciplinary research, student projects, architecture, energy efficiency

I. INTRODUCTION

The home at 901 Pleasant St. in Worcester was originally constructed in the mid 1800s as a country estate (Fig. 1). Today, the house is used as an office and meeting space by several different nonprofit organizations. The building is three stories, with an unfinished basement. The office of the Center for Nonviolent Solutions (an organization that works with at-risk youth) is on the third floor, while the second floor hosts the offices of the New England Yearly Meeting, a regional organization representing the Religious Society of Friends (Quakers) in the Northeast United States. The ground floor is composed of a large meeting room, kitchen, and library. This space is used primarily by the Worcester Friends Meeting, one branch of the New England Yearly Meeting. In addition to weekly services, the Worcester Friends Meeting hosts lectures, presentations, and activities for children. The space is also used occasionally for the meetings of external groups, including local political parties, activist groups, charities, and non-governmental organizations.

In 2013 a representative of the Worcester Friends Meeting, which is in charge of building maintenance, expressed an interest in working with WPI students to improve the energy efficiency of the building. Rising energy costs threaten to make the house impractically expensive for the groups that use it. Cooperation between the Worcester Friends meeting and WPI students was made possible by WPI's unique, project-based educational philosophy [1]. Each year, students must complete a major team research project [2]. The Interactive Qualifying Project (IQP) is a nine credit requirement comprised of "applied research that connects science or technology with social issues and human needs". Nine learning outcomes have been identified:

1. Demonstrate an understanding of the project's technical, social and humanistic context;
2. Define clear, achievable goals/objectives for the project;
3. Critically identify, utilize, and properly cite information sources, and integrate information from multiple sources to identify appropriate approaches to addressing the project goals;
4. Select and implement a sound methodology for solving an interdisciplinary problem;
5. Analyze and synthesize results from social, ethical, humanistic, technical or other perspectives, as appropriate;
6. Maintain effective working relationships within the project team and with the project advisor(s), recognizing and resolving problems that may arise;
7. Demonstrate the ability to write clearly, critically and persuasively;
8. Demonstrate strong oral communication skills, using appropriate, effective visual aids; and,
9. Demonstrate an awareness of the ethical dimensions of their project work.

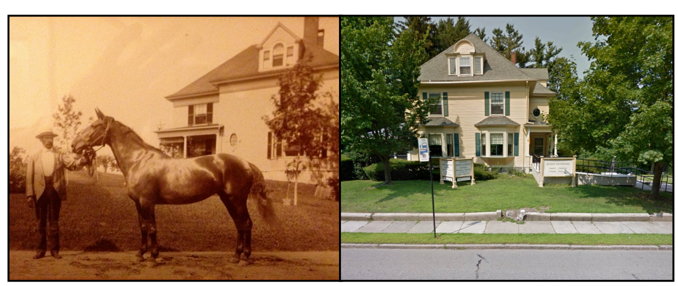

Fig. 1 – The Worcester meetinghouse shortly after construction (left) and today (right). Right image courtesy Google Maps.

In addition to researching a specific problem in its societal context and developing appropriate solutions, students deliver their findings through a final report and presentation, enabling WPI students to apply the scientific knowledge, skills, and technology that they learn in class to real-world problems [3].

A team of four students was assembled, and carried out research regarding the energy efficiency of the Pleasant St. Meetinghouse. Investigations focused on the windows, insulation, heating system, and thermostat of the house to identify the main technical issues at work. The project also investigated, through interviews and questionnaires, the behavior of the individuals and groups that use the meetinghouse. Practical recommendations regarding ways to improve the energy efficiency of the meetinghouse were made, and all of the learning outcomes of the IQP program were met.

II. Methodology

A. Team demographics

The IQP is not a major-restricted project; team members and faculty advisors usually come from different disciplines. This is usually encouraged, in order to encourage interdisciplinary thinking among the students, and more fully investigate every aspect of the issue. In this case, after speaking with the representatives of Worcester Friends Meeting to define the specific issues to be investigated, a student team was assembled representing four different programs: Civil and Environmental Engineering, Architectural Engineering, Electrical and Computer Engineering, and Biomedical Engineering. The faculty advisors are both in the Department of Civil and Environmental Engineering, but focus on disparate areas (architecture and infrastructure material chemistry). A team composed of students with such a variety of backgrounds helps to meet the first four learning outcomes by enabling the holistic investigation of any particular topic.

The IQP is a three-term project (which, at WPI, amounts to roughly 15 hours per week for each student, over the course of seven weeks per term). During the first term, students develop a research proposal to be carried out during the second and third terms. Based on an initial walkthrough of the house, a literature review, and conversations with home energy specialists, the team decided to focus on five areas thought to be most likely to have a significant impact on energy usage: Windows, insulation, the heating system, the thermostat, and the behavior of the meetinghouse's users [4].

The primary difficulty in assembling an interdisciplinary team such as this is the difficulty in finding common times for group meetings. This is the primary reason for the inclusion of the sixth learning outcome (Maintain effective working relationships within the project team and with the project advisors, recognizing and resolving problems that may arise) in the WPI project-based education system.

B. Windows

Before research was carried out, a blueprint for the building was developed (Fig. 2). No blueprint had previously existed, and drawing this item up enabled the team to speak about the house in a standardized way (e.g. by giving each window a specific identifying number).

Due to the age of the house, traditional window styles are primarily used. There are 29 double-hung windows in the meetinghouse, a design that features two vertically sliding sashes. All of the windows are made of softwood, a design that requires regular maintenance to prevent wear. The windows located in the basement and staircases are fixed windows. These windows are not made to open and can be designed in any size or shape, though in this case they are generally small in size, and either round or rectangular. The house has 10 fixed windows. All windows, whether fixed or double-hung, are single-pane with wooden frames, installed in wooden casements.

In the meeting space, there are two large bay windows overlooking the road. The protruding designs of these

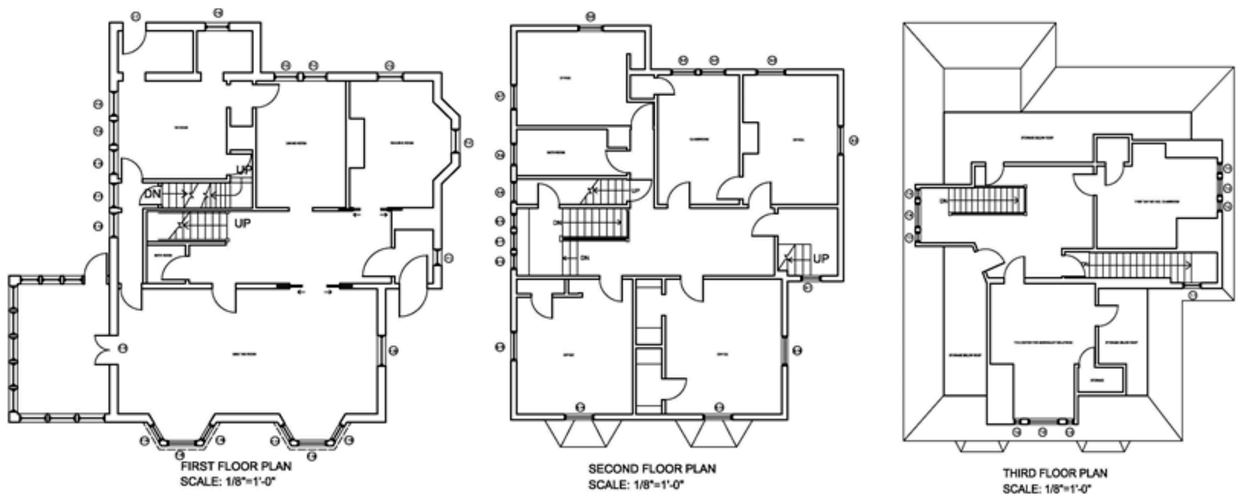

Fig. 2 – Layout of the meetinghouse. Left to right: First, second, and third floors. Not shown: Basement.

windows are intended to create greater interior space. Both are a combination of a middle stationary window with a double-hung window on either side (i.e. three individual windows in total per bay window).

Perhaps the most aesthetically pleasing window in the house is the large, custom casement-screened window on the landing of the main staircase. Metal grilles are used to separate the window into divided lites, similar to stained glass, adding a significant historic feel to the meetinghouse.

The investigation of the windows will take place in two parts: a visual inspection and analysis of each individual window using a thermal imaging camera. These images, along with the results of the visual inspection, will enable the grouping of the various windows into specific categories, depending on their structure, function, and quality.

C. *Insulation*

In warm climates, insulation is used to prevent heat from entering a space, while in cool climates it is used to retain as much heat as possible. Insulation is found in all parts of a building; inside the walls, lining the attic or roof, under the floor, and near the foundation of the house. The ventilation and heating systems are also insulated (e.g. with mat insulation wrapping pipes or ducts). There is a wide variety of insulation types, and each section of the house may use different materials depending on location and specific conditions. Outdated, damaged, or inefficient insulation can contribute to heat loss, and increase energy costs.

Different types of insulation are normally compared using the “Resistance-value” (R-value). The higher the R-value, the better the insulating ability. For example, a common brick has an R-value of 0.20 per inch, while fiberglass batt insulation has an R-value of 3.17 per inch. Both materials can be used to insulate a home, but fiberglass does a much better job, as it is roughly 16 times more effective at containing heat.

As it is a well-known physics principle that hot air rises above cold air, the highest point of a given structure is generally considered the most critical area for insulation. As the partially renovated attic (the third story of this structure) was easily accessible, and other insulation (such as that in the walls) could not be investigated without causing damage to the structure, the student team focused on a visual inspection of the attic insulation.

D. *Heating System*

The main heating system in the Worcester meetinghouse is made up of a gas-fired steam boiler, metal pipes, and steam radiators. Natural gas is combusted to heat water; steam is then distributed to radiators throughout the house by metal pipes. (Many of the radiators are original to the house; the boiler, located in the unfinished basement, is not.) In addition to the main heating system, electric baseboard heaters are installed in some rooms on the third floor.

In this project, the current heating methods in U.S. were analyzed and compared, and the heating systems in the meetinghouse were analyzed based on the gas usage, boiler efficiency, and building energy codes (both state and national).

E. *Thermostat*

While the boiler or heating system produces the heat, the thermostat is the brain of the operation: Its purpose is to control the temperature of a space. Programmable thermostats are becoming more and more popular as they allow people to have control over the temperature of their home or work environment. This increases both the comfort of the consumer and the energy efficiency of the structure. Most residential thermostats have four setpoint temperatures per day, at which the thermostat attempts to keep the building. Setpoints are usually programmable for morning (wake up), day (when at work or out of the house), evening (returning home), and night (sleep).

WiFi programmable thermostats are the newest type of thermostat and are gaining popularity. A WiFi thermostat provides all of the same features as a programmable thermostat, with the addition of being able to change settings from any location via the internet.

The investigation of the thermostat was carried out in two main phases: First, the thermostat currently installed in the meetinghouse was investigated to determine whether or not it should be upgraded or replaced. Secondly, a new heating program was developed, based on the behavior of the building’s occupants and users.

F. *User Behavior*

Developing an efficient program for the thermostat required a thorough understanding of who uses the building, and how they use it. A list of the different groups that use this space was provided by the Corresponding Clerk of Worcester Friends Meeting (the primary users of the space). A set of questions was developed, to be asked during one-on-one interviews with the head of each group, focusing on the frequency with which each group uses the meetinghouse, and what areas they use; what appliances they use when they are there; if they use the current thermostat, and their attitudes towards possible installation of a Wi-Fi thermostat; and general concerns that they may have regarding the building. Although the building is not a formally-designated “Historic Building”, due to its age, the users were still asked about their opinions regarding potential improvements of the building, and whether or not they should be carried out under the guidelines used for historic structures [5].

As the number of groups using the building was relatively small, the responses to these questions did not require rigorous statistical analysis; instead, the results were simply compared in a table, and a schedule for the programmable thermostat was proposed.

III. Results and Discussion

A. Windows

Four different options for improving the insulation of a window were identified by the team: Complete replacement of the window (the most expensive but potentially most effective option); The installation of a custom Plexiglas frame, transforming a single-pane window into a double- or triple-pane window (inexpensive and effective, although it may be difficult to cut an attractive piece of Plexiglas with the correct dimensions); Covering the window with a thin plastic film (inexpensive and extremely easy, but generally unattractive and unprofessional looking); and finally, completely barricading the window space with bricks, wood, or insulation (extremely effective, extremely easy, and extremely aesthetically unpleasant).

Visual inspection and analysis using the thermal camera revealed that almost every window in the meetinghouse is damaged in some way (Fig. 3). This was not particularly surprising, as all of the windows were installed in the mid-19th century. Generally speaking, windows fell into one (or more) of three categories: those with damaged frames, those with damaged casements (primarily warped wood), and those that lost significant amounts of heat due to the fact that they are thin, single-paned windows.

Many of issues regarding the damage can be easily fixed at a low cost. Small changes and modifications to the current windows could save a significant amount of energy. First, it was recommended that the fixed windows in the basement (long, thin windows located at the top of the basement walls, which corresponds to ground level) be completely barricaded. The wooden frames and casements of the windows are severely warped, presumably due to the action of ground water, and several of the windowpanes are cracked. It is not clear, however, if local codes would allow this.

The second recommendation was counter the thin panes and wooden frames, through use of thin plastic films. To test this recommendation, thin plastic film was actually applied to one of the windows. This method was cheap, easy to install, and thermal camera images from shortly before and shortly after insulation suggest that heat flow through the window was significantly decreased. This method is recommended for all other windows throughout the house, dependent on aesthetic concerns (e.g. the thin films may be appropriate in offices and the kitchen, but not in the main meeting space).

B. Insulation

The meetinghouse attic space is composed of three eaves (the central area has been renovated and used as a third story). None of the areas inspected have appropriate, modern insulation. The existing insulation is an Owen's Corning fiberglass insulation with an aluminum reflective wrapper, installed in the 1970s. Portions of the insulation are installed backwards (with the aluminum wrapper facing the wrong side) while other portions are severely damaged, including a large hole through which roofing shingles can be directly accessed.

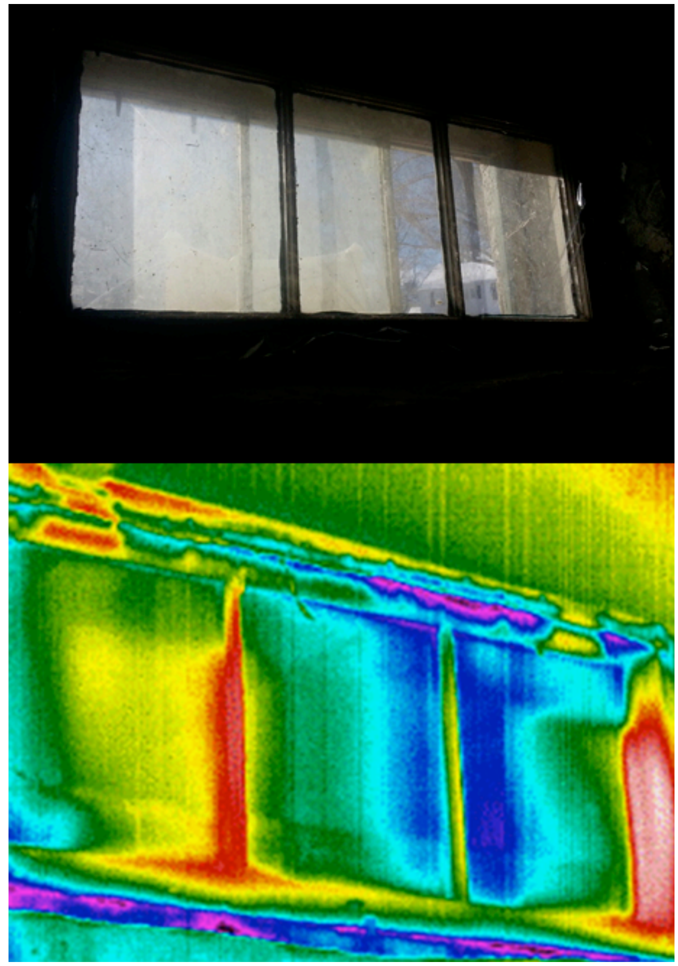

Fig. 3 – A typical fixed window in the meetinghouse basement. Above: photograph. Below: Thermal camera image, in which colors reflect temperature. In the thermal camera image, heat loss through the thin single pane (blue area on right) can be identified, as well as heat loss due to warped casement (purple/blue line, bottom).

The R-value of the material was calculated using the thickness method to be 3.02; however, the insulation is severely damaged and torn, so the actual value is substantially less, albeit difficult to quantify. The only possible recommendation is to switch out the old insulation, replacing it with a modern, correctly-installed material. In this way, the amount of energy saved will be considerable; but whether this would offset the moderate cost of such a replacement is unclear.

C. Heating System

In the current heating system, the meetinghouse has two heating zones. One is the classroom on the third floor, where electrical baseboards are installed on the window side, controlled by an adjustable switch near the door. The other zone is the rest of the house, heated by steam radiators controlled by a thermostat on the first floor. The meetinghouse is not occupied every day and not all of the space is used when people have an event there. Thus, installing only one zone in most of the spaces in the meetinghouse leads to overuse of energy. Single zone heating may also lead to significant comfort issues, as the thermostat in the first floor atrium tells the boiler when to turn on or off, and the boiler may shut off when the first floor is warm but other areas of the building are still cold.

To deal with this problem, the main zone could be split into several heating zones in order to reduce the use of gas. There are two options: To divide the house into three zones, with each floor as a zone. Usually, only one floor is occupied when events are going on in the meetinghouse. The second option would be to supply a number of portable heating units (i.e. space heaters). The advantage of this is that only the heating units in the occupied rooms would be turned on, significantly reducing gas consumption and slightly increasing electricity consumption. However, people may feel uncomfortable because of the temperature difference in each area. The initial cost of buying and installing equipment of either option is likely to be fairly high, and not something that Worcester Friends Meeting would be able to move forward with in the near future.

In terms of the heating system itself, the gas-fired steam has been already used for at least 18 years. Due to the age of the system, the Annual Fuel Utilization Efficiency (AFUE - the ratio of annual heat output to the total annual fossil fuel energy consumed by a boiler) is difficult to estimate, but it is likely to be significantly lower than 90%. Nationally, the minimum AFUE value for a gas-fired steam boiler is 80%; The Massachusetts State Building Energy Code specifies a minimum efficiency of at least 89%. Raising the efficiency of the heating system itself is difficult short of completely replacing the system, and option that is too expensive for the users of the meetinghouse.

D. *Thermostat*

The meetinghouse thermostat had once been partially programmable, but upon inspection, it was found to be irreparably damaged. The thermostat displays 69 °F regardless of the interior temperature, which was usually several degrees higher. The programming was also inoperable; Rather than cooling or heating the building to a selected temperature, the thermostat attempted to keep the house at a constant, fairly high temperature. Replacing this thermostat would be a simple, low-expense step to effecting a significant improvement in the energy efficiency of the building.

Discussions with local energy professionals led to the identification of certain minimum qualities for a replacement thermostat: WiFi capability, a touch screen (preferably with very large numbers), and a warranty. Satisfying these requirements has the added benefit of making the meetinghouse eligible for energy efficiency rebates from local utility companies.

As with the sealing of the windows, the research into the thermostat afforded an opportunity for hands-on work. A thermostat that met all of the above requirements, a Honeywell VisionPRO, was identified by the group and purchased by the Worcester Friends Meeting. This thermostat is a relatively expensive ($~300) high end model compatible for up to three heating and two cooling zones. The major obstacle with implementing the thermostat in the meetinghouse dealt with the outdated heating system. The broken digital thermostat only used R and W wires. The R wire was a 24V AC input that provided power to the thermostat. The W wire went from the thermostat to the relay switch to control the heat: When the relay closes the circuit completes and the boiler turns on. The more modern WiFi thermostat required a third wire (called a “C” wire) for returning energy to the device and powering the electronics. The C wire was not easy to implement as the boiler did not have a printed circuit board with labeled terminals. Instead, one end of the C wire was connected to the back of the thermostat and the other to the 24V AC ground from the ignition circuit using a two-to-one wire connector. The new thermostat is fully operational, and initial experience shows that the temperature in the building corresponds much more closely to the thermostat’s set point than before.

E. *Occupant Behavior*

The original plan was to schedule face-to-face interviews with a member of each organization regarding that organization’s use of the meetinghouse. However, scheduling these interviews was more surprisingly difficult, and many of the interviews were done by phone.

The interviews revealed that the organizations using the meetinghouse considered the thermostat to be the most important single issue (Table 1). The users of the meetinghouse were frustrated with the low capabilities of the original thermostat, but also did not have a very high comfort level with technology. As such, a programmable thermostat, which could be altered by someone off-site (e.g., by someone with access to the thermostat over the internet) was extremely appealing to the various groups. After the actual installation of the thermostat, a heating schedule was developed and programmed based on the usage of the meeting house. As most users of the meetinghouse are somewhat older, the thermostat was set for a relatively high 72 °F during use. It was suggested that the Center for Nonviolent Solutions invest in a space heater, and the building remain unheated when their office is being used. This is due to the fact that the CNS

TABLE I. INTERVIEW SUMMARIES

Organization	Center for nonviolent solutions	Yearly Meeting	Monthly Meeting
Meeting frequency	3 times/week	1/week	2/week
Appliances used	Microwave, rarely	Microwave, rarely	Stove/dishwasher, frequently
Thermostat use	Never	Rarely	Rarely
Opinions on Wi-Fi thermostat	Interested	Very enthusiastic	Very enthusiastic
Rooms used	Library, 3rd Floor office	Library, 2nd floor	Entire 1st , 2nd floors
Storage space	Poorly insulated closet	Basement	No storage
Other concerns	Not all floors need to be heated all day	Needs not high	Difficult to turn off thermostat when leaving

office is relatively small (a single room) and relatively rarely used (a few hours per week) by one or two staffers. This suggestion was not taken up for the convenience of the CNS staffers.

It should also be noted that, despite the age of the building, the users displayed essentially no concern for carrying out any potential renovations using the guidelines or methodologies recommended for the rehabilitation of historic properties.

IV. CONCLUSIONS AND RECOMMENDATIONS

This meetinghouse is one of the many historic buildings that can be found throughout the Worcester area. It started life as a country estate, and then the city grew in around it, to the extent that today it looks like any other home on a fairly nondescript street. Although the outer appearance remains aesthetically pleasing, the energy efficiency of the building has failed to keep pace with technology.

Some initial work has been carried out, specifically the installation and programming of a new thermostat, and the low-cost improvement of one of the many windows. The team has several recommendations regarding how the Worcester Friends Meeting can quantify the effects of these improvements, as well as ways that the building can be improved in the future:

1. The programming of the thermostat should be revisited on a regular basis, to ensure that the selected schedule is appropriate to the usage of the building.
2. Users of the building should consider using space heaters, rather than heating the whole building, depending on the exact logistics of their use of the house (group size, etc.).
3. The users of the meetinghouse should consider upgrading and modernizing the boiler system, should their funding permit.
4. The non-trivial technical challenge of dividing the meetinghouse into more than one heating zone, which could be handled by the new thermostat but not necessarily by the boiler equipment, should be considered.
5. The attic insulation should be completely replaced at the earliest possible time by modern, undamaged, correctly installed insulation.
6. Where not a matter of great aesthetic concern, windows should be treated with the inexpensive, easy-to-install plastic sheeting. At some later date, replacement of the windows should be considered.
7. The Worcester Friends Meeting should contact appropriate professionals, to determine if the basement windows, which are generally in the worst shape, can be barricaded without violating various safety codes.

These recommendations can be applied both to the meetinghouse, and to the many similar buildings throughout the northeast that are addressing similar challenges.

In addition the particular conclusions drawn from this project, this project serves as a model of the WPI project-based educational philosophy. The interdisciplinary student team met each of the nine learning outcomes expected of an Interactive Qualifying Project. Technical solutions to technical issues were developed, but they were developed in full understanding of the social and societal contexts of those issues. These solutions were developed with input from both stakeholders in the particular issue (in this case, the users of the meetinghouse) and industry experts.

ACKNOWLEDGMENTS

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