ORNL MAXLAB Flexible Research Platforms

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ABSTRACT

Oak Ridge National Laboratory (ORNL) was competitively awarded the “Maximum Energy Efficiency Building Research Laboratory” (MAXLAB) project under the American Recovery and Reinvestment Act (ARRA). As part of that project, the design and construction of two flexible research platforms (FRP) was included to provide new building test apparatus at ORNL. The two FRPs are designed to be capable of being outfitted as test buildings that are representative of typical construction methods, materials, and geometry used in the light commercial market. These test buildings will be heavily instrumented and will provide ORNL’s industry partners a means of assessing new HVAC, control, and envelope solutions under realistic conditions, in a low financial risk environment. The long-term data collected at the facility can be used to validate analytic models which can then be used by developers to refine their potential products and reduce delivery time to market. This paper outlines the FRP concept, long term research plan and the challenges in the design and construction of the base research apparatus and test buildings.

Introduction

In the U.S., light commercial buildings account for 95% of the nation’s commercial buildings and 50% of the nation’s commercial building floor space (EIA 2003, Table A1). These buildings, defined as those of 50,000 ft^2 or less, represent 47% of commercial building energy bills (EIA 2003, Table C2A),, or approximately $80 billion annually (DOE 2009, Table 3.3). There is a large market potential for significant energy savings if innovative energy-efficient retrofit solutions could be implemented on a large scale. Although standard system tests (such as climate chamber experiments) are well documented and understood by industry, extensive performance data is often not available on whole-building installations that were constructed using standard construction means and methods.

Currently new technologies are typically tested at the component level and then released to the marketplace for integration into buildings. This means that data for retrofit options have usually only been obtained for idealized conditions in the laboratory. The initial deployment of new retrofit options in effect acts as the field test condition and performance issues can then have an adverse effect on the building, occupants, maintenance staff and building owner.

Another issue with novel building retrofits is how to assess whether building energy modeling programs have been set up to properly model the performance of a new system. Determining the accuracy of an energy model (e.g. reconciling to measured data) can be very difficult and time consuming due to the large number of variables in the energy model, uncontrolled variation in equipment and lighting usage and occupancy fluctuations. Accuracy of the energy model is critical as the energy cost information output from the energy analysis software is in turn used by designers and owners in financial analysis. The system financials in turn play a large part in the retrofit decision making process. An inaccurate model can result in otherwise valid retrofit options being rejected.

Developers of new technologies need low-risk test apparatus where they can test their ideas under realistic conditions without the prohibitive capital cost of constructing a dedicated experimental facility. This test apparatus also needs to provide extensive system performance measurements in order to determine the accuracy of energy modeling software and to tune those energy models to better approximate actual as-installed conditions.

Vision for a Novel Research Facility to Study Future Retrofit Options

To address the lack of realistic building test apparatus for the study of entire building retrofit systems, it was proposed that a new test facility be developed that would allow installation of entire systems in a building with simulated occupancy. Data could be collected to study the system performance, but if the system were to not perform as expected there would be no occupants or building owner adversely affected. In addition the apparatus would be heavily instrumented and metered to allow extensive data collection for use in reconciling measured performance and performance as predicted by various energy models. The FRP test buildings will serve users to provide baseline system performance and to act as a realistic test bed which will permit measurement of retrofit performance data. A new ORNL user facility that would consist of two Flexible Research Platforms – each a building slab and superstructure capable of supporting a variety of test envelope and HVAC systems. The footprint area for the FRPs was selected to characterize the 53% of the nation's building stock that are less than 5,000 square feet (EIA, Table A1). The number of floors for the test buildings was determined after review of CBECS data for non-mall occupancies. For non-mall buildings less than 5,000 square feet, 76% were one-story construction and another 18% were two-story (EIA, Table B7). One of the FRPs was to accommodate one-story test buildings, while the second FRP would allow construction of two-story test buildings.

Initially baseline test buildings would be constructed on each FRP, with envelope characteristics (e.g. insulating properties) similar to the 79% of existing light commercial building stock that was initially constructed before 1989 (EIA, Table B7). As complete test buildings, the full envelope would be exposed to natural weather. The internal HVAC systems would operate in response to weather conditions (heat gain through the envelope and outside air temperature/humidity) and to internal heat gains approximating office equipment. Data would then be collected from hundreds of sensors in the building envelope and HVAC systems. This data would be analyzed and compared to energy modeling calculations. The baseline performance data would be used to evaluate how the energy modeling software addresses building energy use and identify sources of error in the energy modeling code. Following the baseline building evaluation, energy-saving tune-ups or retrofits to the test buildings will be implemented and exposed to natural weather. Measured data will then be used to evaluate the effectiveness of the tune-up or retrofit energy-savings and how well the energy modeling calculation methods predict actual performance.

The permanent research platforms will be available as a Department of Energy designated user facility, to be administered by the ORNL Building Technologies Research and Integration Center (BTRIC). The platforms would add to the existing building user facilities that include: laboratory environmental chambers for both HVAC equipment and building envelope systems, the Roof Thermal Research Apparatus (RTRA) and the Envelope Systems Research Apparatus (ESRA). The existing user facilities allow industry users to test individual HVAC system components or samples of envelope system components, whereas the FRPs would allow evaluation of a complete and operating system or envelope in a working test building.

Industry Input and Potential Research Facility Users

ORNL conducted public meetings in 2010 and 2011 for the development of the Light Commercial Building Roadmap for the Department of Energy (DOE). Building component suppliers and owners/operators identified technical barriers they believe exist to improving energy efficiency in a cost-effective and timely manner. During the roadmapping process problems were identified by building performance area, possible research actions identified and efficiency targets were proposed. Care was taken to formulate the target goals in such a way to be aggressive yet identify that retrofit payback periods must be fairly short for the commercial market to bear the first cost of such building retrofits.

As user input was obtained, a group of industry leaders began to suggest retrofit studies that interested them and could be conducted on the Flexible Research Platforms. These industry participants each developed a research agenda and then proposed it to the BTRIC staff for review as a potential industry user test on the future user facility. The BTRIC user facility administrators reviewed the various proposals, suggested modifications where necessary and assisted the potential users in finalizing their research proposals. At the conclusion of this process, either a user agreement or a Cooperative Research and Development Agreement (CRADA) were put in place with each industry participant.

Envelope. Multiple envelope industry partners proposed research on either of the two research platforms. The research included investigations into both roof and wall systems and windows. In particular the prospective users identified their interest in participating in research subjects including:

- Enhanced wall cladding and innovative continuous exterior insulation systems
- Cost effective wall cavity or exterior wall surface retrofit packages
- Retrofit packages for low slope roofs
- Whole-building air sealing materials and installation techniques
- Validation of energy modeling for systems utilizing Phase Change Materials (PCMs) for insulation
- Developing envelope retrofit packages incorporating PCMs
- Applying the results from the data measurement and energy modeling in the development of Web-based tools to assist users in estimating retrofit installed costs and annual cost savings

Equipment. In the area of heating, ventilating, and air-conditioning (HVAC) equipment, a group of industry leaders also prepared extensive lists of potential research applications on the platforms once test buildings had been prepared. These manufacturers produce a wide variety of HVAC equipment types for commercial applications. The potential research areas suggested by these users included:

- Developing more cost effective means of delivering higher-efficiency HVAC equipment
- Prioritizing equipment categories to be enhanced for high efficiency

- Devising a process to assist owner/operators create energy efficiency challenge specifications to drive competition amongst manufacturers to develop higher efficiency equipment
- Developing a tool for users to quickly assess how cost effective various retrofit options might be in a given setting (use and climate) and at various equipment sizes

Controls. Building automation systems and controls is another area with the potential to achieve significant energy savings in the commercial market. Multiple industry participants noted several emerging technologies for research, among them:

- Low-cost wireless sensors
- Applying wireless sensor systems to identify HVAC system tune-up opportunities, costs and energy savings
- Developing a smart monitoring diagnostic system (SMDS) for packaged unitary HVAC systems
- Develop a tool for contractors to quickly estimate the costs for system tune-ups, SMDS installation and potential cost savings to the owner

Modeling. Current practices in building design are evolving to more seamlessly allow fully integrated building design. This includes energy analysis throughout the building development to allow optimal configuration of the building layout and systems for enhanced energy efficiency. Several industry partners in the areas Building Energy Modeling (BEM) and Building Information Modeling (BIM) suggested research into developing a variety of capabilities including:

- Autonomous data correction in energy models
- Auto-tune the building energy models using measured data
- Automated estimating of building energy savings based on data from a limited suite of sensors
- Demonstrating a cost reduction in the process of improving energy efficiency through the interoperability of BIM and BEM
- Web based tools with graphical user interface (GUI) for estimating costs and savings potential for retrofits

Research Apparatus/Infrastructure

The user facility consists of two permanent building frames and their slabs, and the necessary utility infrastructure (water, electricity, natural gas) to support a variety of test building configurations that might be applied to each platform superstructure. The test building envelopes and interiors could be modified or completely removed following a user’s series of research tests. The permanent structure and slab would however remain and be available for fit-up to another user’s specifications. The test slab and superstructure (designated as the platform) would function as an apparatus to facilitate the user’s research.

As part of the utility infrastructure system, pulse meters were specified on the equipment natural gas lines and on the central domestic water line to document natural gas and water consumption. Electrical systems for the general receptacles, mechanical equipment and lighting were arranged to facilitate submetering by a central data acquisition system.

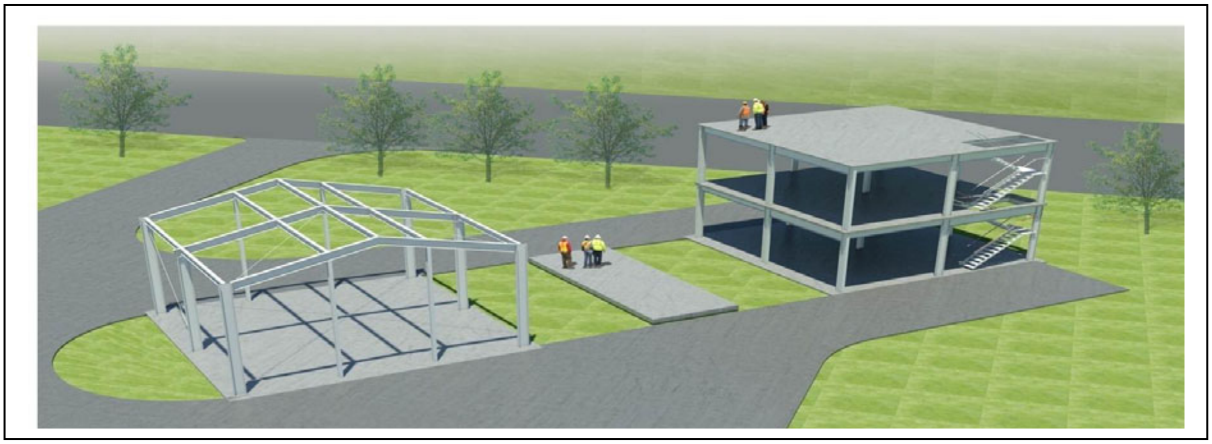
Installed on the permanent FRPs, the test buildings would be unoccupied, with research equipment used to simulate internal loads that would otherwise be imposed by occupants and office equipment. The lighting and equipment would be electronically controlled based on usage and scheduling determined by the users and the research team. In this way the research could be conducted in a low-risk fashion. There would be no building occupants that could possibly be adversely affected by the varying lighting and HVAC operations or the novel envelope and HVAC retrofits dictated by the research team and the industry partners.

Single story research platform. One of the platforms would be a 40’x60’ (12.1 m x 18.3 m) single story, pre-engineered metal building frame. A conventional metal building design process was followed for the development of the frame. However the standard performance specification for the metal building frame was modified to require the frame be completely self-supporting without wall or roof panels installed to act as a diaphragm. The floor area was to be a clear-span area with no intermediate structural members permitted. This maximized the available floor space for research apparatus. In addition one end wall of the building was specified to be framed to allow the installation of a large overhead door later in the project. This in turn defined the column placement on that end wall of the frame.

Two story research platform. The second research platform would be a 44’ x 44’ (13.4 m x 13.4 m) two story, steel structure designed to accommodate a variety of envelope systems such as masonry, insulated precast concrete panels, or metal studs with sheathing and an Exterior Insulating Foam System (EIFS). The two story platform would also feature access to the roof to facilitate working with various mechanical systems or to access sensors placed to measure roofing system performance.

Platform slabs and foundations. Both research platforms were designed as slab-on-grade construction. To provide information related to slab heat gain or loss and how EnergyPlus (EnergyPlus, 2011) calculates that effect, a system was designed to minimize heat transfer effects at the perimeter of the slab. A deep foundation was constructed, then a concrete sub-slab was installed. Next layers of lightweight Expanded Polystyrene (EPS) insulation were added to a thickness of twelve inches (0.3 m). A second steel-reinforced top slab was then installed on top of the insulation later. The polystyrene insulation was added to turn up at the edge of the upper slab along the full perimeter of the slab. The upper slab design included loop piping to be secured to the rebar at the perimeter of the slab. The loop piping was designed to connect to a central system at a service pad to be located between the two research platforms. The service pad was designed to accommodate a small loop water pump system, a research chiller and heater. Temperature sensors were to be installed at the slab interior and perimeter. A central data acquisition system would monitor the input from the temperature sensors and then signal the loop system pump and heat transfer equipment to operate as needed to offset the temperature difference measured between the slab perimeter and interior. Figure 1 shows an artist’s concept of the permanent research platforms, ready to receive test building envelopes and interior systems.

Figure 1



Oak Ridge National Laboratory, Artist's Concept of the Flexible Research Platforms

Test Buildings

Based on input from the initial user group, the ORNL BTRIC research team developed a research plan for test buildings to be constructed on both research platforms. Figure 2 indicates an artist's rendering of an initial concept for two finished test buildings as installed on the underlying permanent platforms.

Figure 2

Oak Ridge National Laboratory, Artist's Rendering of Test Buildings

Single story test building. The baseline single story test building is designed to approximate early 1990s typical construction with an open floorplan. The envelope performance was selected accordingly from ASHRAE 90.1-1989. Interior lighting was selected to be conventional T-12 fluorescent fixtures that were to be suspended from the roof structure. The lighting density was chosen to be typical for open office usage in the early 1990s. Electrical power provisions were made to accommodate research equipment that would be used to simulate the electrical consumption (and resulting heat generation) typical of office occupancy. To facilitate a quick change from a baseline HVAC system to a retrofit system, two independent HVAC systems were designed to share common distribution ductwork. The baseline HVAC system selected was a conventional packaged air-conditioner with natural gas heat. The second HVAC system, which would function as the first retrofit option, was a prototype gas-engine driven split system heat pump. That system configuration included a ground mounted exterior module and two ceiling mounted air handlers. An in-line exhaust fan was included in the mechanical system to approximate the function of a general exhaust fan as would typically serve a core restroom group. Outside air was ducted from wall mounted intake louvers into the test building and directly connected to the central return ductwork. Domestic water was designed to serve humidifiers to be located within the test building. Both HVAC systems were to be controlled from local thermostats, although provisions were made to facilitate installation of a central building automation system at a later date.

Two story test building. The second research platform would be a two story, steel frame building to allow the installation of various types of common commercial envelope systems. The initial baseline building program was developed as part of a research grant awarded to Bayer Material Sciences and ORNL by the Energy Efficient Buildings Hub (EEB Hub). The EEB Hub is a DOE Energy Innovation Hub led by Penn State University and is located at The Navy Yard in Philadelphia (http://www.eebhub.org/). The baseline two story test building was designed to approximate construction at The Navy Yard. Much of the construction is unreinforced masonry with minimal insulation. Therefore the two story test building was designed to have 8” nominal concrete masonry units with exterior brick. This masonry exterior would however not be a load bearing wall, as the structural steel frame of the FRP serves that purpose. The window area for the test building was selected based on typical percent areas for commercial buildings in the ten county metropolitan area surrounding The Navy Yard. The interior of the building was designed to have four perimeter rooms and a core room on each floor. A central stair enclosure would extend from the ground floor to the roof. Electrical power was designed to accommodate research equipment that would be similar to light office occupancy in each of the spaces. Lighting was chosen similarly to that used on the single story test building, with T-12 fixtures and a density typical for 1990s construction. The lights would however be installed in an acoustical (lay-in) ceiling. The baseline HVAC for the test building would be a rooftop Variable Air Volume (VAV) with electric reheat shut-off terminal boxes. Two retrofit systems would also be installed. Those systems would be a water loop heat pump system with fluid cooler and natural gas boiler and a Variable Refrigerant Flow (VRF) system. The HVAC system also included an inline exhaust fan for general exhaust and a roof mounted Dedicated Outdoor Air System (DOAS) to provide tempered fresh air to the return plenum when the WSHP or the VRF system were to operate. The HVAC systems were designed to be alternated so that measurements could be taken for the three different systems and then compared with projected results from the energy models. A central building automation system would allow control of the multiple HVAC systems.

Data Acquisition System

The baseline test buildings were designed to function as unoccupied research apparatus. A central data acquisition system (DAS) was designed to allow monitoring of the building performance as well as control of various building systems. Experience gained from similar residential building research conducted by ORNL was used in the development of the sensor list and the DAS equipment. The DAS was designed to allow the test building lighting, research equipment, and HVAC systems to be controlled in accordance with a schedule that was to be maintained in a database. This was to allow the research team to carefully control building HVAC setpoints/schedules, humidifier operation, lighting loads and scheduled usage, and heat loads/schedules in a manner to approximate occupancy similar to a conventional office building. Using a scheduled system for internal building loads would allow the researchers to repeat those conditions as the various HVAC systems were cycled in each test building. In addition, the DAS would record data from a weather station located at the site. This weather data would then be used during the energy modeling process to help reduce modeling errors that might occur due to using standard hourly weather data files. With the DAS acting as a controller for internal loads and building HVAC systems, the conditions will be closely controlled such that the actual internal loads would align as closely as possible with the data input for the various energy models.

The DAS sensor package includes sensors for monitoring: temperature, humidity, airflow, CO2 concentration, and heat flux. Envelope performance will be monitored by thermistors, temperature, relative humidity sensors, and heat flux differential thermopiles located at a variety of predetermined locations along the walls and interior roof. Power usage at mechanical equipment would be monitored by small commercial current transducers. The DAS setup was designed to include a data acquisition panel dedicated for the devices at the North, South, East and West exposures on each test building (typical for two floors at the two story test building). Each of the zone DAS panels would then transmit data back to a central DAS panel for the test building, which in turn would send data to a server to be located in the MAXLAB. The modular design with the multiple DAS zone panels were intended to facilitate easy disconnection and relocation devices for whenever retrofit envelope cases or retrofit HVAC systems were to be installed by the users.

Current Project Status

Design

Building program documents were developed for each test building based on the individual user's various research plans. The program documents were used to guide the team of ORNL architects and engineers in the development of construction documents for both test buildings.

The test buildings were designed using an integrated design approach and were developed using two different BIM platforms (Autodesk Revit and Bentley BIM). The BIM designs were necessary for the construction of the test buildings themselves, but also were part of the research. The BIM/BEM research group used the native BIM models to test the BIM to BEM data transfer methods currently available to streamline data input from the building design to various energy modeling software products.

The record drawings for the two test platforms (the slabs and superstructures) were used to form the basis for the test building BIM files. The final BIM files included the civil, structural, architectural, electrical and mechanical designs for the test buildings. Students from the University of Tennessee prepared the various BIM models under the supervision of ORNL architects and engineers.

Figure 3

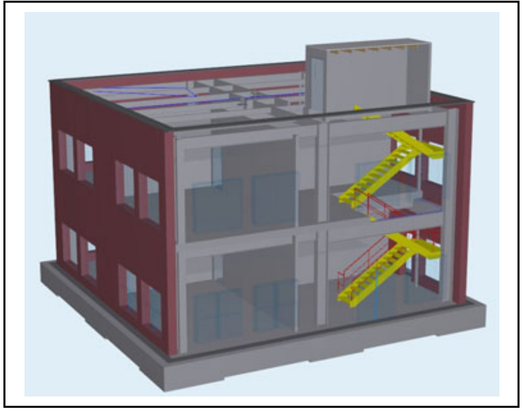
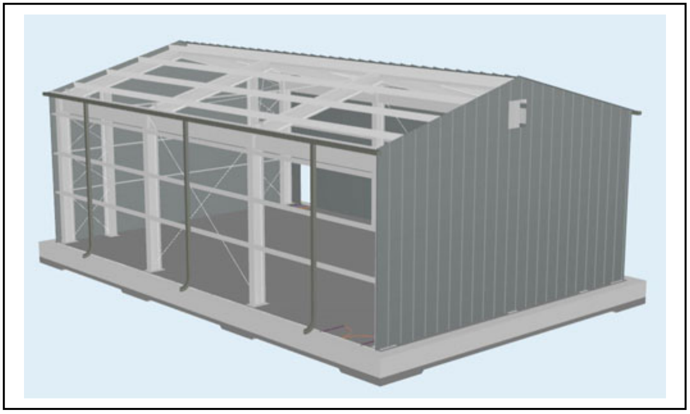


Figure 4



Oak Ridge National Laboratory, Building Information Models of Test Buildings

The BIM development for the test buildings proceeded in the same manners as a typical BIM project would. During the BIM process the team encountered several common issues found in building design/modeling and construction. For the single story building, BIM software products do not offer a library of shapes for pre-engineered metal building structural members. The steel design is very much dependent on the individual building manufacturer. To closely model the actual building steel used in the construction, the architectural students had to devise custom steel shapes for the various structural members using the metal building shop drawings submittal as a guide. Later another it was discovered the metal building components that had been erected were actually somewhat different from the original metal building submittal documents. The student then had to rework the structural elements to conform to the final record documents submitted for the test building. Similarly during the two story test building modeling the student had to accommodate changes that were made to the platform design, in particular changes made to the final stairwell design and a safety railing at the roof.

Another common issue in BIM modeling that was experienced during the test building design was that of equipment BIM models not being available. Most of the light commercial HVAC equipment selected for both test buildings was not available in BIM file format from the various manufacturers. This meant the students had to devise equipment models for the various systems using the manufacturer’s equipment data sheets as references.

The intent of developing full BIM models for each test building was to allow seamless transfer of building geometry data to various energy modeling programs via a green building extensible markup language (gbXML) schema. This would allow the energy modeling researchers to compare energy modeling processes using a direct data transfer versus manual calculations and input. The BIM/BEM researchers could then seek to identify The BIM model would also allow the research team to easily identify building construction elements, equipment and the location of data acquisition system devices. Figures 3 and 4 depict partial BIM models for the two test buildings.

Construction

Both permanent platforms were constructed as part of the overall MAXLAB construction process. Site work and foundation construction (complete with heat transfer piping loops) were completed in mid-2011. Figure 5 shows the rebar installation for the two story building slab along with the 12” of perimeter insulation and the orange slab loop piping at the edge of the reinforcing cage. The structural steel for the two story building was erected in November 2011 (reference Figure 6) and the slab for the second floor was poured in January 2012.

Figure 5

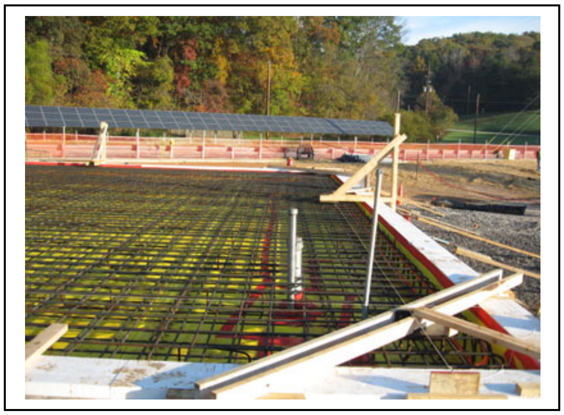


Figure 6

The single story pre-engineered metal building frame was erected in January 2012 (reference Figure 7).

Figure 7

Oak Ridge National Laboratory, Single Story Platform Frame with Two Story Platform in Background

Following the erection of the platform superstructures, construction continued with site piping and electrical for the central service pad area and each of the two platforms. In addition fire alarm, communications and data wiring were pulled through the conduits previously installed up through each platform slab.

Final site grading was scheduled for early March 2012 and the site readied for the first installation of a test building envelope on the single story test platform.

Energy Modeling

As part of the research project, energy modeling was to be conducted for baseline and retrofit test building cases on each of the research platforms. The modeling was to use several different programs including DOE's EnergyPlus and multiple programs provided by various industry participants. The energy modeling process sought to better predict baseline building energy performance for buildings with various envelope and mechanical systems, to determine the critical inputs that influence the quality of modeling results, and to more accurately model the performance of multiple retrofit options for envelope and HVAC systems.

Retrofit Design with Users and the Research Team

As testing of the baseline envelope and HVAC systems is conducted, the intent is for the research team to assist the individual users as they begin the design of the first retrofits for their various systems on the test buildings. The baseline BIM models can be provided to the users as they plan their retrofit cases.

The research team can also evaluate the various energy models for the baseline buildings and assess whether the DAS measurements are appropriate for use in reconciling the energy models to the measured data. The DAS sensor list and locations can be modified in the BIM models and relocated in the field as required.

Analysis and Outcomes for Users

Once data has been collected for the baseline buildings during late 2012, the actual building performance will be compared to the energy models. The intent is to identify key areas in the energy models for which input errors can significantly affect the quality of the output data. The research also seeks to identify whether using BIM as a data input method to the energy analysis helps to produce more accurate modeling results in a cost effective manner for the designer/modeler. The BIM demonstration will explore the benefit of a direct connection between BIM and energy analysis software. With regard to energy modeling research, the modeling of the test buildings, measurement and verifications and further calibration of models will be investigated. For the first year, the research program will focus on: EnergyPlus modeling using BIM inputs to simulate energy use, construction of the flexible research platform, deployment of the instrumentation and digital acquisition system, data collection and analysis/comparison between model results and measurement, and validation analysis efforts for Energy Plus. Following the acquisition of data for the baseline building, the program will then focus on retrofit construction document preparation, additional energy modeling, retrofitting the building shell, data collection on the retrofitted platform and analysis of the data. The calibration capability envisaged in this project will serve to generate confidence in the use of energy modeling tools and their predicted energy savings for small commercial buildings.

The baseline analysis will also serve as a reference point for the various users to provide them better information as to how the baseline systems actually perform in a building exposed to natural weather conditions as opposed to an individual system or equipment test in a climate chamber. It is projected the first set of retrofit cases will be designed during early 2013, with energy modeling, installation and monitoring occurring in mid to late 2013. The flexible research platforms will then begin to serve as research apparatus for a steady stream of users and their potential building retrofit systems. Ultimately one of the many goals of the research is to identify products and systems which the users may offer to the building construction industry as cost-effective retrofit options that offer sustained energy savings.

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Disclaimers

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