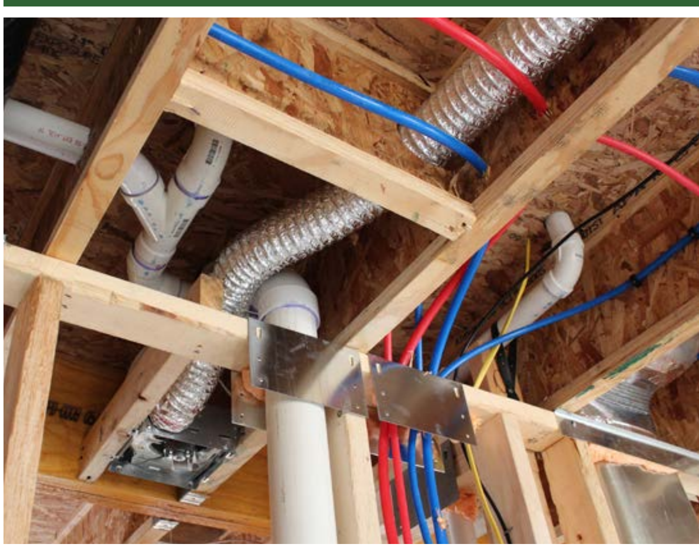
3RD Residential Building Design & Construction Conference

State College, PA | March 2-3, 2016

Conference Proceedings

Edited by Dr. Ali M. Memari & Sarah Klinetob Lowe



Proceedings of the 3rd Residential Building Design & Construction Conference

March 2-3, 2016

Penn Stater Conference Center Hotel, State College, PA USA

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Preface

Energy efficiency, sustainability, resiliency, and hazard mitigation have been some of the main drivers for many innovations in residential building materials and architectural, structural, mechanical, and electrical systems in recent years. There is also increasing demand for high performance, healthy, and affordable construction, and in particular those that employ renewable energy sources. These and other relevant issues have encouraged government, foundations, philanthropic organizations, investors, researchers, design professionals, product manufacturers, developers, and other stakeholders to support or seek advancements in the state-of-the-art and state of-the-practice in the field of residential construction. Significant efforts are being expended to develop new materials, products, processes, procedures, and guidelines to improve the state of existing residential buildings and to incorporate innovations in design and construction of new buildings as well as retrofit projects. Because of the need for timely knowledge sharing and dissemination of the results of extensive R&D activities and new advancements and developments in the field, the Pennsylvania Housing Research Center (PHRC) at the Pennsylvania State University is pleased to continue organizing the Residential Building Design and Construction conference series to serve the housing and residential construction industry for this purpose.

The 3rd Residential Building Design and Construction Conference was held on March 2-3, 2016 in State College, PA in conjunction with the 24th Annual Pennsylvania Housing & Land Development Conference. The latter event has been a successful PHRC program over the years with emphasis on topics of interest to developers, builders, remodelers, design professionals, planners, regulatory and code officials, modular and HUD code builders, and housing product manufacturers. As a relatively new PHRC program, the Residential Building Design and Construction Conference is intended to provide a forum for researchers and design professionals to discuss their latest findings, innovations and projects related to residential buildings. The Residential Building Design and Construction Conference invites papers and presentations on various issues related to residential buildings, which encompass single- and multi-family dwellings, mid-rise and high-rise structures, factory-built housing, dormitories, and hotels/motels.

The conference series intends to provide opportunities for contributors from academia, A/E design firms, builders, developers, product and system manufacturers, and government and code officials to submit papers and/or make presentations on most aspects of residential buildings including the following areas and topics:

- Aging-in-Place, Assisted Living, and Senior Living
- Alternative Energy Generating Systems
- Building Integrated Photovoltaic Systems
- Building Performance Metrics/Verification Methods and Occupant Behavior

- Building Science and Building Enclosures
- Energy Efficient Building Components
- Fire Damage and Protection
- High Performance Residential Buildings
- Indoor Air Quality
- Innovations in Residential Architecture and Design
- Innovations in Modular and Manufactured Housing
- Innovative and Emerging Housing Construction Methods/Systems
- Innovative Wall, Floor, Roof, Window, & Siding Systems
- Learning from the Performance of Residential Buildings under Natural Disasters
- Low-Income and Affordable Housing
- Panelized Building Components
- Resilient New Design and Retrofit of Existing Buildings under Natural Disasters
- Retrofit of Existing Buildings for Energy Efficiency
- Rural and American Indian Housing
- Serviceability and Life Safety Damage Aspects
- Smart Home Technologies
- Sustainable Housing Construction Materials & Methods
- Temporary Housing for Disaster Situations
- Whole Building Design Approach
- Zero-Net Energy Homes

The presentations at the 3rd Residential Building Design and Construction Conference have covered many of the above topics, including the following: building envelope sustainability and retrofit, cross-laminated timber, energy audits, energy efficiency and high performance buildings, fire safety, hygrothermal modeling, indoor air quality and natural ventilation, modular construction, passive house design, phase-change materials, post-disaster housing, resilient design and retrofit, senior living, and wind loading effects on roofs.

Two Keynote Speakers were invited for the conference: Tedd Benson, President of Bensonwood, and Dr. John Straube, Principal at RDH Building Science and RDH Building Science Labs and Associate Professor in the Faculty of Engineering at the University of Waterloo. Tedd Benson focused on the next generation of homebuilding in his presentation "*The 21st Century Craft of Sustainable Homebuilding: Culture, Technology, and Methods Toward a Better Way to Design & Build.*" Dr. John Straube focused on the importance of building science in his presentation "*Building Science: The Foundation of Future Residential Building Design and Practice.*"

The conference included presentations by university professors, researchers, graduate students, architects, consulting engineers, product manufacturers, and product related associations/councils. For this conference we also organized a special session on Innovations in Senior Living by three leading senior living housing developers.

We wish to thank the members of the Steering Committee and the Scientific Committee of the conference for their contributions. The support of the PHRC staff for logistics is gratefully acknowledged.

Proceedings Editors:

Ali M. Memari and Sarah Klinetob Lowe

March 2016

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An Approach to Analytically Modeling Modular Vertical Expansions

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Abstract: Multi-story modular construction methods may offer advantages over site-intensive construction methods for some vertical expansion projects. Vertical expansions can be design-intensive depending on the condition of the existing building and the availability of design documentation. Feasibility of a modular vertical expansion is highly dependent on a variety of factors such as local ordinance and code, the building construction type and use, as well as the site and existing building conditions.

Identifying those factors that can adversely affect feasibility on complex projects, such as vertical expansion, can often be difficult in the preliminary design stages. Front-end planning tools can be used to help identify those factors early on in the preliminary design stages to help eliminate costly design errors. In modular projects, design errors could have an amplified effect due to the inability to make design changes after module production has begun.

In this paper, some of the factors that can affect the feasibility of a modular vertical expansion are explored, and the benefits of using a coarse finite-element modeling approach to help identify those factors are discussed. A case study is used to demonstrate this approach and provide project-specific factors, some of which can be generalized to other modular applications. The results of the case study show the important planning information that can be obtained by studying generalized structure behavior in the front-end portion of the design.

1. Introduction

Prefabrication and modular construction methods have been identified by the National Institute of Standards and Technology (NIST) as a potential way to improve productivity in the U.S. construction industry (MBI, 2010). Multi-story modular construction is a subset of modular construction.

Multi-story modular construction methods, as shown in Figure 1, are currently being utilized by the construction industry for the purposes of quickly constructing cost-effective, multi-family housing. In the U.S., the merits, effectiveness and applicability of these methods are currently topics of interest and debate within the construction community, and research shows that projects currently employing multi-story modular construction methods are experiencing varying degrees of success (Jellen, 2015).

Figure 1. SoMa Studios, a 23-unit apartment building in San Francisco's trendy South Market district (image by Modular Building Institute (MBI)).

To capitalize on the construction methods' available productivity benefits, it is important to understand how to best implement this prefabricated method and recognize the factors that can adversely affect feasibility. The research discussed here was initiated to study how to optimally maximize the benefits of multi-story modular methods in construction projects. It was discovered early on in the research that the pairing of the method to a suitable application and the proper execution of the front-end design process can increase feasibility for complex projects involving higher levels of prefabricated components.

To develop a deeper understanding of the design process and study feasibility factors, a multi-story modular construction application was selected and the design process was mapped. A case study was then used to verify the mapped design process and to identify factors that could potentially affect feasibility (Jellen 2015). The case study helped to identify additional factors that were more easily recognized during the engineering design process.

The scope of the research was limited to studying the construction of multi-family residential facilities. Multi-family residential structures such as apartments, student housing and social housing units were identified in the research as good candidates for modular construction methods because of their often simple, repetitious floor plan and geometry. These aspects make the module templating process for production more efficient.

2. Modular Construction Study and Application Selection

Initially, an in-depth state-of-the-art review was conducted to determine specific benefits available to users of multi-story modular construction methods, barriers to implementation, appropriate applications for the construction method, and opportunities for expanded use of the construction method. The review pointed to two primary advantages over the competing site-intensive construction methods: 1) the significant construction schedule reductions available through off-site production and 2) the reductions in community/business disturbance associated with just-in-time delivery of the modules.

Notable barriers identified include the social stigmas that exist regarding prefabricated housing and the term "modular", the geometric limitations (transportation and production) of the method, redundancy of assemblies that exist due to the six-sided nature of a module, varying break-even points associated with the economical production of the modules, the significant amount of pre-planning necessary to successfully implement a prefabricated component into a construction project, and the difficult nature of making design modifications once production of the modules has begun.

The review highlighted vertical expansion as an appropriate use for multi-story modular construction methods and one that might be used more frequently in the United States (U.S.). A vertical expansion project can benefit, in some situations, from both the time saving aspects and the reduced community disturbance available to users of this construction method. However, in order to determine whether modular construction methods are appropriate for any particular project, preliminary planning and feasibility analysis should be conducted.

2. The importance of Pre-planning effort

Users of prefabrication and modular construction techniques can be rewarded with productivity improvements in their construction projects, but misapplication and poor planning or implementation can produce just the opposite effect. Fully modular projects require a significant amount of pre-planning effort, and design changes are difficult to implement once the production of the modules has begun. Because of these aspects, it is necessary for designers to ensure that all factors that affect project feasibility are investigated in the front-end of the design. Any missed items in the planning stages could result in project inefficiencies. A vertical expansion would be considered a fully modular project. Mostly complete modules would be delivered to the construction project and installed. Once the modules are set, the majority of the construction effort is complete.

To elaborate on the importance of the planning stage of projects involving higher levels of pre-fabrication, the design process for the conceptual modular vertical expansion case-study building, shown in Figure 2a, will be discussed. The decision to modularize a project does not necessarily have bearing on all aspects of the design process, but there are particular parts of the process that can be impacted by the decision and will be further discussed.

3. Vertical Expansion Design Process

Vertical expansion of an existing building can be daunting engineering task. There are processes, decisions and inputs within the design process, many of which are not directly related to modular construction, that require detailed consideration. The engineering problem involves mating a new structure to an in-service structure. Among other considerations, the design team must ensure that 1) the existing structure is adequate to accept the new loading, 2) the aesthetics and enclosure integrity are maintained on the exterior, and 3) access/egress routes to and from the new expansions are provided.

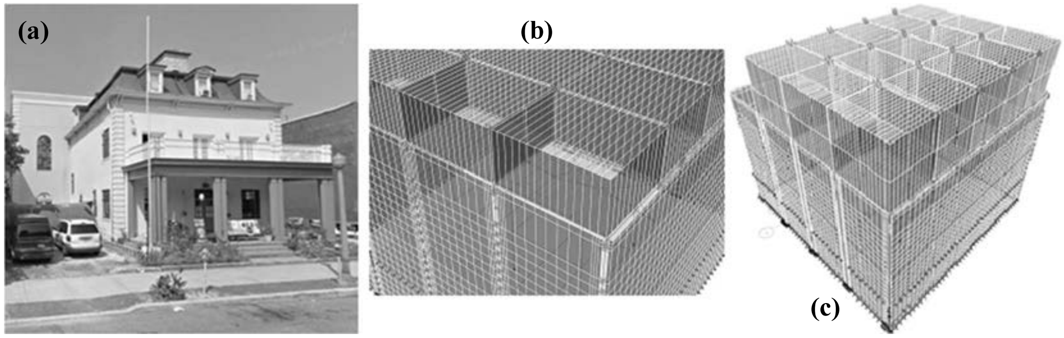

Figure 2. (a) Case study building used to conceptualize and investigate feasibility factors. (b) Analytical model of the expanded case study building shown in Figure 2a. (c) Two-story expansion.

In the research, the design process for a modular vertical expansion was studied to evaluate factors related to modular construction that could have an effect on project feasibility. The case study building, shown in Figure 2a, was identified in the research as a good candidate for vertical expansion. The design process was mapped for the expansion of this building, and the analytical model, shown in both Figure 2b and 2c, was used to validate the process and extract factors more easily recognizable during engineering design.

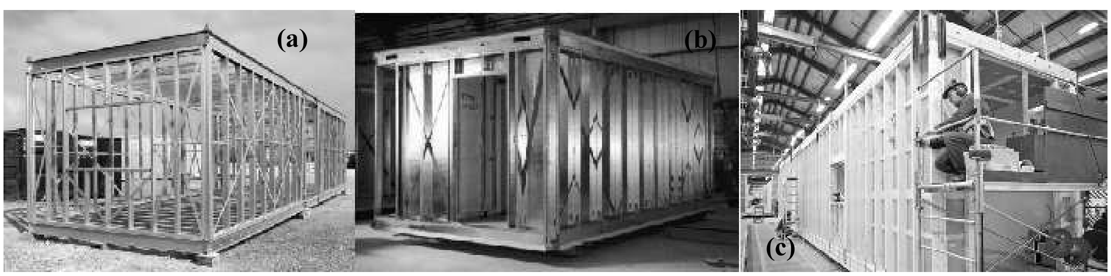

Figure 3. (a) Corner-post bearing module (image by Lawson and Ogden, 2008), (b) CFS wall-bearing module (image by Lawson and Ogden, 2008) (c) Wood wall-bearing module (image by MBI)

During the course of the research, typical structural modules used in modern modular construction were identified. The two dominant structural module types discovered were wall-bearing types and Corner-post bearing types. An example of each is shown in Figure 3. A simplified computer model of the existing building was created, and one- and two-story expansions were successively added to the model to explore the effects of each. Wood-framed wall bearing and cold-formed steel wall bearing modules had similar structural systems and weights (Table 1), so a generic wall-bearing expansion was explored rather than creating individual representations of each.

Table 1. Estimated weights of modules in comparison with steel framing. The module weights include framing and gypsum coverings

Construction Type	Weight (lb/ft^2)
Corner-Post Bearing	57.5
CFS Wall-Bearing	36.8
Wood Wall-Bearing	37.7
Structural Steel Framing	61.2

In order to document the design process and identify factors influenced by the decision to use modular construction, a series of seven process maps were created to describe in general terms the engineering design process. The majority of the focus was placed on the structural engineering and building codes assessment aspects. The engineering design process for the modular expansion was divided into four pre-construction phases; the pre-planning phase, structural evaluation of existing building phase, expansion conception phase, and expansion analysis phase.

In the pre-planning phase, the existing building was evaluated for candidacy. The candidacy evaluation process had two sub-processes, which were the project conceptual evaluation and the modular application evaluation. During the conceptual evaluation process, the validity of the concept is explored. Client motivations, constructability-related considerations, interfaces, and safety and access questions are all inputs to the process. During the modular application evaluation portion of this phase, the design/client must evaluate initially whether modular construction would benefit the project. If it is not appropriate, the owner can choose at this point, early on in the design process, to evaluate site-intensive construction methods or terminate the process. There are many decisions that occur during this phase that can have an effect on feasibility.

The structural evaluation of the existing building would occur shortly after or concurrent with the pre-planning phase. In this stage, the design team must assemble all available documentation and make a decision on the extent of investigation required to assess the condition of the building, the likelihood of expansion, regulatory environment, excess structural capacity of the building, strong connection points for the new expansion, and determine load reduction opportunities to increase feasibility of expansion. There is little in this phase that is influenced by the decision to modularize, although it is critical to project success and safety that this step is diligently executed.

After the existing building has been evaluated and the decision has been made to move ahead, the expansion conception phase can begin. The decision to modularize a project can have significant impact on project feasibility during this phase. It is in this stage where the appropriate module/manufacturer are selected for the project as well as the expansion height. This phase involves an iterative loop where different module types are investigated for use in the expansion. The method of load transfer and connection methodology should be defined after this stage. Building code evaluation as well as preliminary structural analysis is conducted to estimate expansion height and the effect of the expansion on surrounding elements.

Following the conception phase is the analysis phase. A sound concept should be delivered from the expansion conception phase. During the analysis phase the concept is proofed with further structural analysis and regulatory review. If necessary, changes can be made here to improve feasibility. If significant changes are involved it may be necessary to re-evaluate the concept. If no significant changes are needed and the design looks feasible, the analytical model will be ready to be delivered for final detailed design upon completion of this phase. At this point the model/concept can most likely be released for use in bid documents.

4. Lessons Learned From Design Process Validation

As mentioned previously, the case study was used to validate the design process map. While the state-of-the-art review and creation of the design process map were helpful in identifying the more obvious factors that could affect project feasibility, the case study was helpful in revealing the more subtle factors. In this part of the research, the mapped process was used to implement four expansions on the case study building. During the design of these conceptual expansions, factors that could affect project feasibility for this particular expansion were observed and documented.

An initial lesson learned was the importance of selecting an appropriate modeling technique to efficiently obtain the information required for the task. In this instance the information required for the research was primarily front-end planning related, similar to the information that would be required for an actual project. It was decided that a coarser model, in this case, was better suited to the needs of the research.

4.1 Modeling Lessons Learned

Initially, it was attempted to model the modules in their entirety with individual beam elements for the framing components and finite-element shells used for the gypsum wall sheathing and floor sheathing (Figure 4a). Modules modeled in this manner were overly complicated for the intended use. The many elements necessary to construct one module slowed computation time down and the modules became overly rigid without the use of multi-dimensional springs attaching the wall- and floor-sheathing to the structural framing.

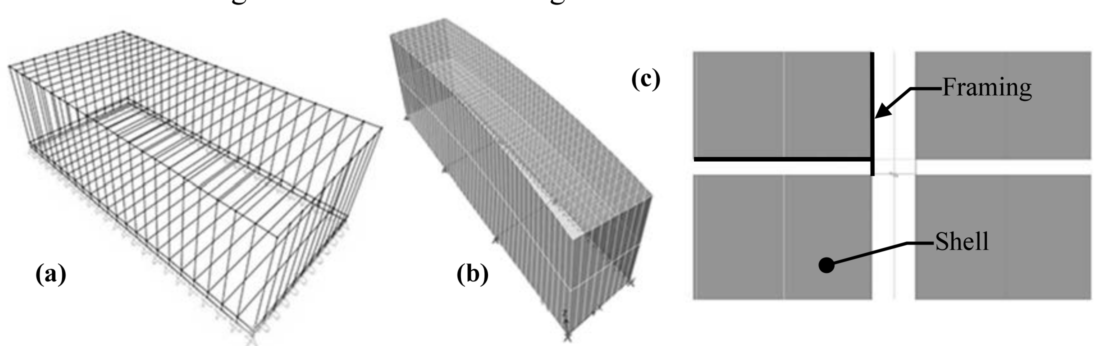

Figure 4. (a) Initial detailed version of a single wall-bearing module (b) Simplified shell version of stacked wall-bearing modules, shown in deflected form (wind load) (c) Intersection of four corner-post bearing modules.

The interaction of wall- and floor-sheathing with the structural framing (studs and joists) is complicated and difficult to model properly. Attachment of sheathing to stud or joist is typically accomplished with nails or screws and sometimes involves the use of an adhesives to strengthen the connection. Deformation of sheathed light-framed assemblies occurs due to rotation caused by nail slip, lateral translation due to bearing of fastener failure, and direct shear deflection of the sheathing. The summation of these three actions produces the total lateral translation of the sheathed wall assembly (Vieira and Shafer 2012). In order to model the three translation actions accurately, Vieira and Shafer (2012) used springs to represent the stiffness in each of these directions. Their method was not appropriate for this research.

The initial detailed finite element model of a wall-bearing module, shown in Figure 4a, was overly complicated for the goals of the project and it was decided to pursue an alternative approach. In the revised finite element model, the walls and floor system in their entirety were represented by the thin-shell finite-elements shown in Figure 4b. A 5/8 in. thick shell wall and a 23/32 in. thick shell floor system were defined in SAP2000 for use in the final ETABS model. Empirical formulas and test data from Intertek and HUD ("5/8" Dense-Glass Gold" 2003), (NAHB Research Center 1999) were used to calculate the mechanical properties necessary to represent the stud-wall assembly and framed floor system of the wall bearing module using isotropic finite elements.

The Modulus of Elasticity (E) developed for the wall system and floor system are shown in Table 2. The Modulus of Elasticity was defined as behaving linearly for the wall and floor system. In actuality, the behavior of both the sheathed wall- and floor-system was non-linear in both the Intertek and HUD tests. The linear modulus for both assemblies was estimated using a secant modulus in the expected stress range.

For the purposes of the research, it was only necessary to develop the mechanical properties for one wall and one floor system. Wall Type A, listed in Table 2, was used to resist/transfer both gravity and lateral loads for the wall-bearing modules and lateral loads only for the corner-post bearing modules. The test-coupon for the Intertek tests on Wall A was constructed from wood framing. It was assumed that the stiffness of a similar wall constructed from cold-formed steel elements would behave comparably to the wood-constructed coupon. Figure 4c shows how the area elements were utilized as infill for the corner-post bearing modules. A gap was left between top and bottom modules to ensure gravity load was transferred through corner posts only. The floor system for the corner-post bearing modules consisted of structural steel framing and a composite concrete floor slab, which were easily modeled using predefined properties in the software packages.

Table 2. Module wall and floor assembly mechanical properties

Assembly	Description of tested assembly	E (KSI)	Wt. (PSF)
Wall A	2x4 studs @ 16" O.C. , 5/8" Dense-Glass Gold gypsum sheathing nailed @ 4" on the perimeter and 8" in the field (1 ¾" Galvanized Roofing Nails).	31,300	7
Floor A	2x8x43 mil CFS joists @ 24" O.C. ; 23/32 OSB Sheathing attached with #8 Tek screws spaced @ 6" at the perimeter and @ joints and 12" in the field.; panels staggered.	60,000	10

4.2 Lessons Learned During the Design Process Validation

To determine the factors that could potentially affect the feasibility of a modular vertical expansion, the developed modules were added to the existing building finite-element model. The study suggested that feasibility was most affected by the quality of execution of the front-end design effort.

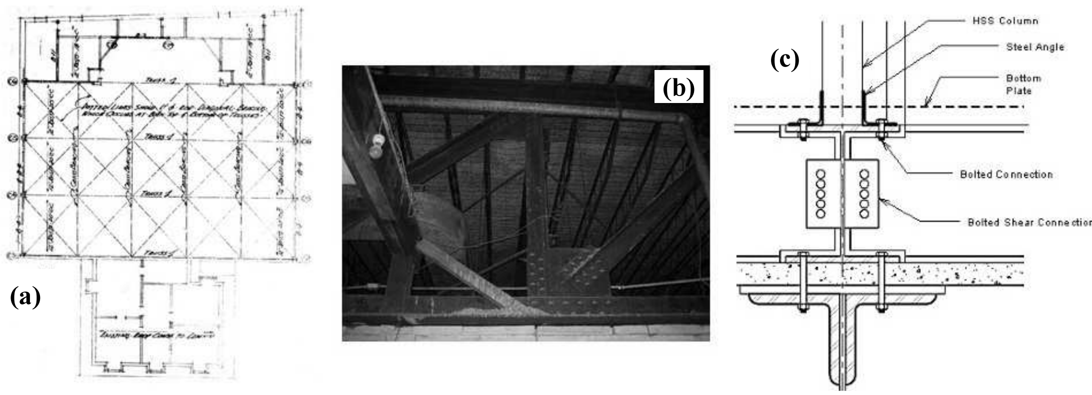

Figure 5. (a) Existing building roof plan; load bearing trusses are orientated left-to-right (b) Photo of load bearing truss (c) Intersection of four corner-post bearing modules.

In this vertical expansion study, both corner-post bearing modular expansions and wall-bearing expansion were modeled to explore advantages of each. It was found that each can have an advantage for different expansion projects. However, for the one- and two-story expansions, modeled in the research, the wall-bearing modules appeared to be more appropriate if combustible material is acceptable for the project. It was also discovered that modular construction may not be the right choice for some vertical expansion projects. Below is short list of some of the feasibility affecting factors discovered during the validation process:

1. Existing building geometry and existing structural connection points are important considerations. In this case study, the existing roof structure had convenient tie-in locations. The 60 ft. long trusses, shown in Figure 5a and b, were arranged at 15 ft.-6 in. spacing’s, which are feasible modular dimensions. The simple structural steel grid, shown in Figure 6c was used to transfer the loads from the conceptual floor plan shown in Figure 6a and b.
2. In this case, it appears that it would be possible to detail the transfer grid, such that is acts compositely with the existing roof trusses. The connection is shown in Figure 5c. The study showed that by engaging composite action and removing of the existing roof-top cinder fill, the effects of the single-story modular expansions on the existing roof trusses were minimal. Internal load-effects and mid-span deflections were comparable to those of the original structure.
3. Considering point 3, a single-story expansion may have minimal effect on the existing structure. If this is so, then the extent of required structural strengthening measures could potentially also be minimized, which could improve project feasibility. A vertical expansion would most likely be categorized as an addition per IBC 2009. Per Section 3403.3, if the gravity-

load on the existing building is not increased by more than 5%, then it is possible that no strengthening measures would be required for the gravity-load carrying members within the existing building. Per the IBC Section 3403.4 exception, if any of the lateral-load carrying elements demand/capacity ratio increases by less than 10% then it is possible to leave those elements unaltered.

4. The redundant structural wall, ceiling/floor assemblies due to the six-sided nature of the modules could be limiting where floor space and story-height is valuable. Preliminary IBC review, for this building, showed that it may be difficult to consider wall-bearing modules, containing any combustible structural components, for a two-story expansion with ceiling heights greater than 7 ft-11 in. Modular construction may not be an option if structural steel corner-post bearing modules are required, due to the high break-even points.
5. The study shows that a two-story corner-post bearing modular expansion increases the demand-capacity ratio to 0.903 in some truss members and increases bearing pressure to greater than 4 KSF under some footings; both results may not be acceptable to the design team. The use of lighter wall-bearing modules, if possible, could increase feasibility.
6. Corner-post bearing modules only require support/connection @ corners, whereas wall bearing modules require support along the entire longitudinal wall. In this case half of the beams in the transfer grid were able to be eliminated when corner-post bearing modules were considered.
7. Story-drift was not a concern with the one- and two-story modular expansions modeled in this study.

Figure 6. (a) Rendering of the wall-bearing single-story expansion used in the study (b) Conceptual maintenance module envisioned to house roof-top mechanical equipment servicing the existing building (c) The finite element model of the steel beam transfer grid.

In this research, finite-element module models were used as tools to help quickly model modular expansions such that the effects of different expansions on the existing building could be studied. Using detailed analytical models, in this case, was not an efficient way of identifying those factors affecting expansion feasibility. By using the coarser finite-element models, design alternatives were able to be evaluated more efficiently. A few examples of some of the beneficial planning information able to be obtained through the use of this approach follows:

1. In this project, the differences in the effects of wall-bearing and corner-post bearing expansions of both one- and two-story were able to be studied effectively.
2. Different variations of the transfer structure were able to be studied as well as strategies for addressing the parapet and the benefits of composite action of the transfer structure.
3. The connection points were able to be identified and basic floorplan geometry was able to be established.
4. In some projects, this method could be used to evaluate whether the expansions effects on the existing building meets the IBC section 3403 exceptions for gravity and lateral loading.
5. One could potentially coarsely define several different wall-assemblies to quickly explore the structural benefits of each in a project. Serviceability criteria such as drift can be generally explored to eliminate, up front, those assemblies that might be too flexible/stiff or light/heavy.

The primitive finite element tool functioned as expected and although detailed module structural design information was not able to be extracted, the model did reasonably represent the effects of each expansion on the existing building and all the important items discussed earlier were able to be identified for use by a design team.

6. Closing Statements

The research discussed in this paper studied one type of prefabricated construction methods which is modular construction. Vertical expansion was identified in the research as an appropriate application for multi-story modular construction. Finite-element models were used to explore feasibility affecting factors. A diligent study of the vertical expansion design process revealed the modular construction specific factors, while case study verification was able to identify those additional considerations.

Modular construction was found to be appropriate for vertical expansions in some cases, but not all. For one- and two-story expansions, wood-framed wall-bearing modules were thought to be the most feasible if combustible construction is allowed on a project. Heavier non-combustible steel corner-post bearing modules were found to have higher break-even production thresholds thus potentially eliminating them from lower square-footage projects. However, considering the 2 ½ - story case study building used in the research, it was difficult to meet the IBC combustible construction requirements, while maintaining reasonable ceiling heights. This situation presented an issue that might eliminate modular construction from consideration on this particular project. In this instance a custom steel module fabricator may have an advantage.

There are improvement that could be made to the finite-element definitions that could improve functionality and broaden the applicability of this approach. The finite-elements were defined as having isotropic mechanical properties, where in reality the performance of the wall and floor assemblies would be anisotropic. It was not necessary for this research to define these finite-elements as anisotropic. The information required from the models did not warrant the increased effort; however, if this technique was applied to other modular design scenarios, it might be advantageous to have the mechanical properties in all directions defined more accurately. Refining the design would allow for more detailed study of out-of-plane behavior of the elements and stresses at connection points.

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Building Enclosure Design for Modular Construction

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ABSTRACT

Many of the purported advantages associated with modular wood-frame construction compared to traditional stick-built framing are generally well accepted in the industry: increased quality control, indoor construction, shorter project schedules, ability to service remote locations, and in some cases favorable labor and material pricing. Despite all of these advantages, special attention needs to be given to the integration and assembly of the building enclosure components, both within and between building modules, to ensure that the performance of these modular buildings meet the expectations of all parties involved.
This paper will focus on the building enclosure functions of heat, air, and moisture control in wood-framed residential buildings, and will apply these concepts to the realities of modular construction. Specifically, this paper will detail lessons learned through design and construction of two recently completed modular construction projects. The first project is a multi-unit dormitory located in an isolated northern climate and incorporates super-insulated assemblies and Passive House certification requiring a high performance building enclosure. The second project is a multi-unit transit-oriented and affordable housing development in the San Francisco Bay Area. This paper will inform designers and builders about building enclosure design considerations and challenges specific to modular construction.

INTRODUCTION AND BACKGROUND

Modular construction is a type of prefabrication method where three-dimensional living spaces are built off-site and transported to site and assembled into the final building structure. At one end of the spectrum, modules could consist of only the primary structural elements (walls, floors, etc.); however, we are increasingly seeing modular units with factory-built windows and cladding systems; mechanical, electrical, and plumbing systems; and complete interior finishes. Modular construction is similar in intent, yet different in scale than unitized, panelized and component construction where smaller components of the building are constructed off site, such as unitized curtain walls, panelized wall cladding systems, or pre-fabricated roof trusses.

There are numerous reported advantages to modular construction: shorter construction schedule, favorable and safer working conditions in a factory setting, better quality control, reduced material waste, and less time lost due to weather. From an owner's perspective, one of the most appealing advantages of modular construction is the potential for greater financial return due to the reduced construction time. Since modules are constructed off site, preliminary site work and modular production can occur in parallel, reducing costs associated with construction general conditions. The Modular Building Institute reports that commercial housing such as apartment buildings and student housing can be built and ready for occupancy in less than 90 days (MBI, 2015). A study conducted on modular housing by Ryan E. Smith, Director and Associate Professor at the University of Utah, concluded an average cost savings of 16% and schedule reduction of 45% over traditional construction methods (Smith, 2015). The MacDougal Apartment Complex in Brooklyn, New York, for instance, is a six story modular housing project consisting of 65 studio apartments constructed with 84 modules. The modules were built at a nearby facility and were placed on site in a record 12 days (MBI, 2012).

As with panelized and unitized component construction, modular construction is particularly suited for repetitive designs where the same two or three layouts can be repeated. Production-line efficiency is achieved by repetition of material cuts, worker tasks and ease of handling modules of similar size. The potential efficiencies associated with modular construction are reduced as more custom non-repetitive designs are implemented. Other instances where modular off-site construction may be advantageous include remote project locations and if labor shortages exist at the project location.

With all of these apparent benefits of modular construction, it may be surprising that permanent modular construction only makes up 2.93 percent of the North American market share value (MBI, 2015). Some commonly cited disadvantages include the architectural limitations associated with repetitive designs, the costs associated with temporary protection for rain and other elements, and the inherent double thickness walls and floors that equates to loss of space and extra material cost.

FUNCTIONS OF THE BUILDING ENCLOSURE

Regardless of the building type or the method of construction, the functional requirements of building enclosures remain the same: the building enclosure needs to provide environmental separation between interior and exterior spaces. In addition to resisting and transferring structural loads, the building enclosure needs to control the following elements:

→ Water penetration

→ Heat flow

→ Air flow and air leakage

→ Vapor diffusion and accumulation of condensation

→ Fire and smoke

→ Light, solar, and other radiation

→ Noise

The building enclosure certainly performs several other functions, including providing security, privacy, views, and the primary architectural aesthetic; however, the above list represents the key performance aspects typically associated with building science and building enclosure engineering.

Various materials are used within exterior walls to perform the control functions listed above. The term critical barrier can be used to refer to materials and components that together perform a specific control function that is necessary for the building enclosure system to perform as intended. A partial list of commonly considered critical barriers and their relationships with different building enclosure control functions is shown below in Figure 1.

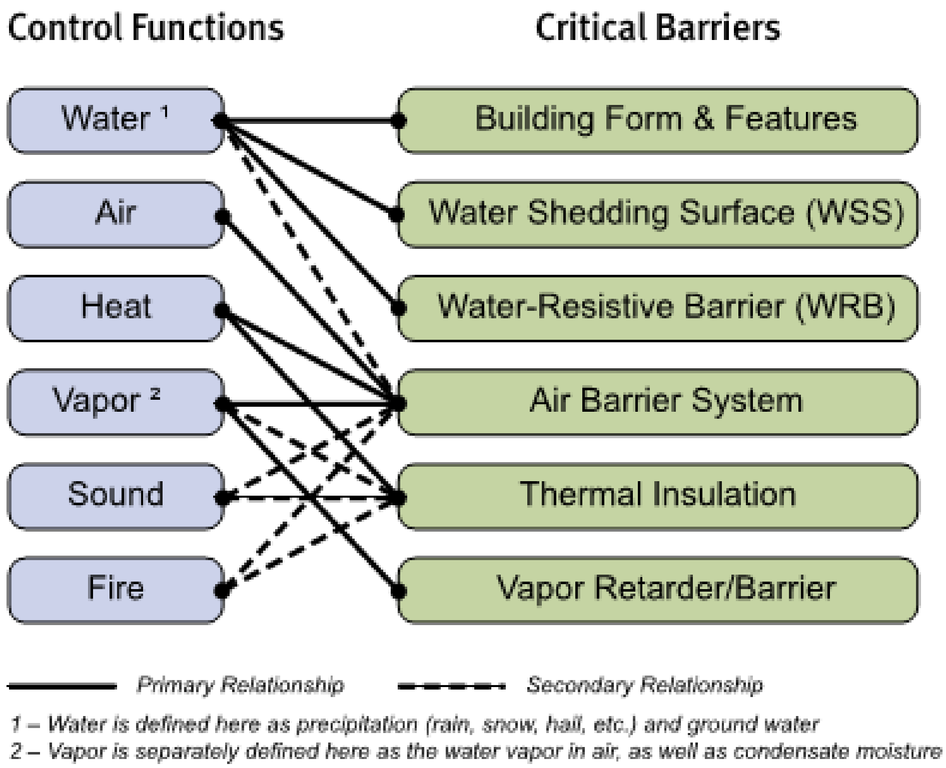

Figure 1. Relationships between building enclosure control functions and common critical barriers

THE CHALLENGES OF MODULAR CONSTRUCTION

Continuity of the various critical barriers – within and between assemblies, across details, and at other transitions – is necessary to ensure that the building enclosure functions as intended. Site-built construction sequencing and staging generally allows for the sequential installation, field inspection, and quality control of each of the critical barriers throughout the course of construction. For instance, a sheathing membrane that acts as both the air and water-resistive barrier can be fully installed prior to the installation of the cladding layers (water shedding surface (WSS)). The water control layers can also readily be installed in shingle-lapped fashion to minimize the risk of water penetration at joints. Furthermore, the installation of the water-resistive barrier (WRB) is generally fully completed prior to the installation of interior finishes and other weather sensitive components. Indeed, "weathering in" your building with a completed roofing membrane and wall WRB is a common milestone in traditional site-built construction.

In contrast, with modular construction, the interior finishes are often installed in the modules and delivered to site before the building is "weathered in" on all sides, thereby significantly increasing the risk of water damage during construction (unless each module is covered on all six sides). For no other type of construction would the owners or building officials consider allowing moisture sensitive interior finishes to proceed until the roofing and WRB were complete. The most overlooked item with modular construction is the joints between adjacent modules. While the continuity of the critical barriers within each module can generally be easily achieved during the factory installation, the joints between the modules require the following additional coordination plans to achieve continuity, listed in general order of importance:

1. How to temporarily protect the horizontal and vertical joints from rain penetration during construction. A contingency plan is also needed to address rain that might penetrate the temporary protection between units.
2. How to seal the joints between modular units:
   - → How to achieve a shingle lapped installation of the WRB or reduce the risk associated with reverse laps.
   - → If the cladding is factory installed, how to provide for a shingled lapped or protected infill cladding at the vertical joints.
   - → Coordinate the structural attachments and plan for how the modules will be lifted and installed with the building enclosure components and joints details.
3. An estimate and plan for accommodating the construction tolerances between site-built foundations and structural components and the factory build modules, including the joint openings between modules.
4. Similar to other factory-built construction such as unitized curtain wall, a comprehensive quality assurance and quality control (QAQC) plan is needed to verify that the installation of the various building enclosure components meets the project's performance requirements.
5. A field QAQC plan that includes field review from an experienced building enclosure specialist or air barrier technician to verify the joints have been sealed as required and to advise on questions quickly as they arise during construction.

Item #1 is critical for all projects but especially challenging for high rise construction or large floor plans where the modules are exposed to the elements for longer periods of time. The Habitat 67 project in Montreal, Canada (Figure 2) featured vertical and horizontal offsets between modular units that were difficult to both temporarily and permanently protect the joints reliably against water intrusion (Guardian, 2015).

Figure 2. Habitat 67, modular project featured at Expo Montreal, Canada

Item #2 requires input and planning during the design phase from both the Design and Construction Team. Our second case study features a project that was originally planned as a modular project and where careful consideration was given early in an integrated design approach on how to detail the joints between modules. In contrast, our first case study features a project that originally was planned as site-built construction and therefore very little planning was provided for the joints between modules.

Item #3 increases in importance depending on the complexity of the project. For example, the Atlantic Yards Building B2 in Brooklyn, NY was envisioned as the tallest modular building in the world at 32 stories (Figure 3). The plan to achieve this record height was to site build a steel frame and then install the modular units into the frame. However, the project completion was delayed by 2 years and is currently in litigation. The primary issue is reported to be that the construction tolerance between the modular units and structural steel frame was not accounted for during design and required extensive field modifications. There was reportedly also extensive water leakage during construction due to both the tolerance in the joints between units and also due to the difficulties of temporarily protecting the ceilings of each floor on a high rise when the site-built structural steel frame extends above and penetrates any temporary protection (Curbed New York, 2015).

Figure 3. Atlantic Yards Building 2, 33 story modular high rise project in Brooklyn, NY

Item #4 is true of all factory-built products or systems. With factory-built systems there is very little ability to modify or correct deficiencies after the system is installed in the field. Having and implementing a factory QAQC plan is therefore critical to the success of modular construction. Factory-built also does not automatically mean better quality. In our first case study we found that windows and window flashings were installed by tradesmen experienced with carpentry and gypsum board installations instead of with window and WRB installations. The errors in installation required extensive field repairs to the window installations, including the removal and reinstallation of many windows.

Item #5 requires the field presence of a building science specialist or technician who preferably also has experiences with how modular units are assembled. The field assembly with modular (and other unitized systems) proceeds so quickly that it is important to have someone on site who can respond quickly to questions or unanticipated field conditions.

CASE STUDY #1: AFFORDABLE HOUSING COMPLEX IN CALIFORNIA

The first case study project was initiated by an affordable housing company in the San Francisco Bay Area. The five-story complex is a mixed-use project comprised of 115 apartment units on the second to fifth floors, two levels of below grade parking, and storefront retail shops at the first floor built by traditional site-built construction (Figures 4 and 5).

Figure 4. Case Study #1: During construction

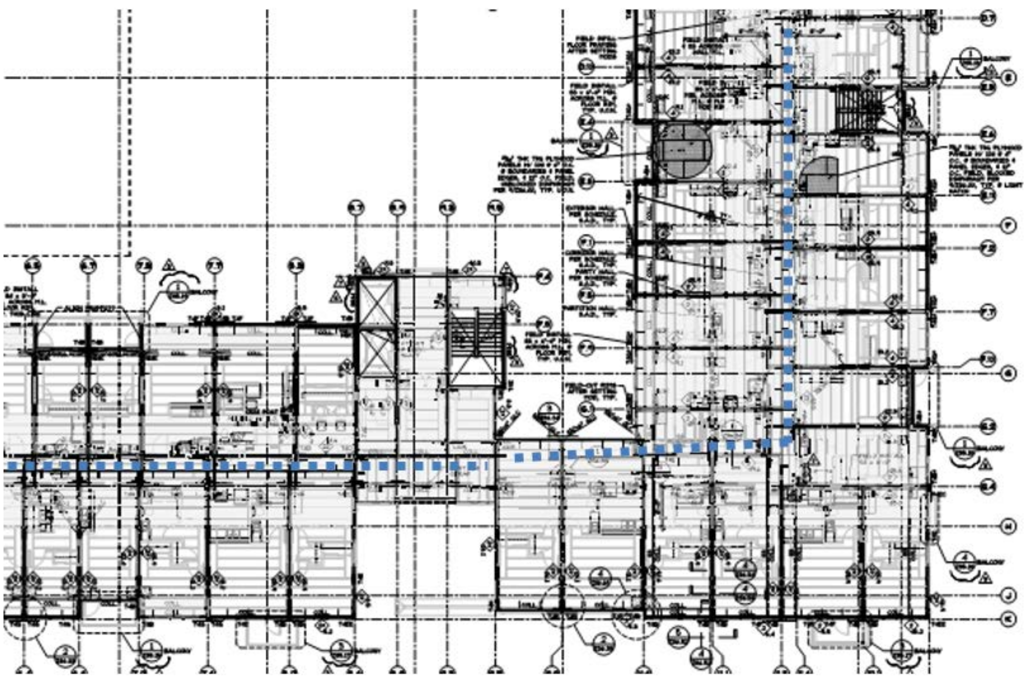

Figure 5. Case Study #1: Partial floor plan (dotted line shows common center hallway)

The project was originally conceived as traditional delivery and site-built construction. However, as the time neared for construction, it became apparent that the San Francisco Bay Area market had recovered from the recession in 2008 and that labor and material costs were rising rapidly due to rising demand. The owner made the decision to convert the project to modular from site-built construction late in the design process as a way to reduce and control against these rising labor costs. Because this is a mixed-use building with the parking and retail to be site-built, there was a redundancy in trades such as drywall installers working at both in the factory and on site. The redundant trades and field labor reduce cost savings, however it was determined that the reduced schedule time and labor savings from going modular on the residential portion of the project would still grant the owner considerable savings.

Factory Construction

The modules were built off site at a factory in Sacramento, 90 miles away, and shipped by truck to site (Figures 6 and 7). The level of interior finishes varies for individual modular projects - anywhere from open stud framing to completed flooring, cabinetry and fixtures. A high level of prefabrication was specified for this project and modules included most interior finishes such as painted drywall, millwork, laminate flooring and appliances.

Figure 6. Case Study #1: Factory construction progress photos

Figure 7. Case Study #1: Lifting and setting units in field

The windows and WRB around the windows were installed in the factory, but the top and side party walls of the modules were not protected with WRB. The exterior cladding was designed as cement plaster and was to be field installed to reduce the risk of plaster cracking during transport and to allow the plaster to continuously cover the joints between modular units. In general, installation quality for the window systems was less than what we would typically see in field construction. Based on our observations, this was more of a factor of limited worker experience and rushed work to keep the assembly line moving. For example, the window flashing sequence was a 13-step rainscreen flashing sequence, consisting of flanged windows installed in a recessed opening with self-adhered membrane flashing and an integrated drained membrane sill pan. There were twenty stations in the factory and each module was at one station for approximately two hours. Every task had to be broken into steps that could be accomplished within two hours. Sometimes workers would move with the modules to follow a task and other times, the tasks would be continued by different workers. Inexperienced window installers found it difficult to install the self-adhered membrane effectively in the short time period and it was apparent that the full concept was not understood by all of the installers or QC workers, despite detailed build sequence details in the design package. Despite these detailed installation sequences, the final installation suffered deficiencies that had to be repaired in the field, including gaps in the flashing, missing flashing pieces, missing or incomplete sealant and interior air and water seals, improperly shimmed windows and cuts in the flashing membrane (Figure 8).

Figure 8. Case Study #1: Defects in the factory installed window flashing included cuts in the membrane, tenting, and gaps that had to be field corrected

Figure 9 shows an example of all of the observed deficiencies on the second level of one elevation of the project. Some of these deficiencies required both the windows and flashing to be removed and reinstalled - a time and field labor intensive process. Material shortages added to delays and shifted resources from the factory to the field to complete the modules. About halfway through the construction of the modules, the modular fabricator determined that the windows could not adequately be installed per the construction documents in the budgeted amount of time at that station and therefore the window installation would have to be corrected in the field. In other words, to meet their contracted delivery schedule, the modular fabricator assumed the extra costs of correcting errors in the window installation in the field, thereby reducing the promised benefits of modular construction.

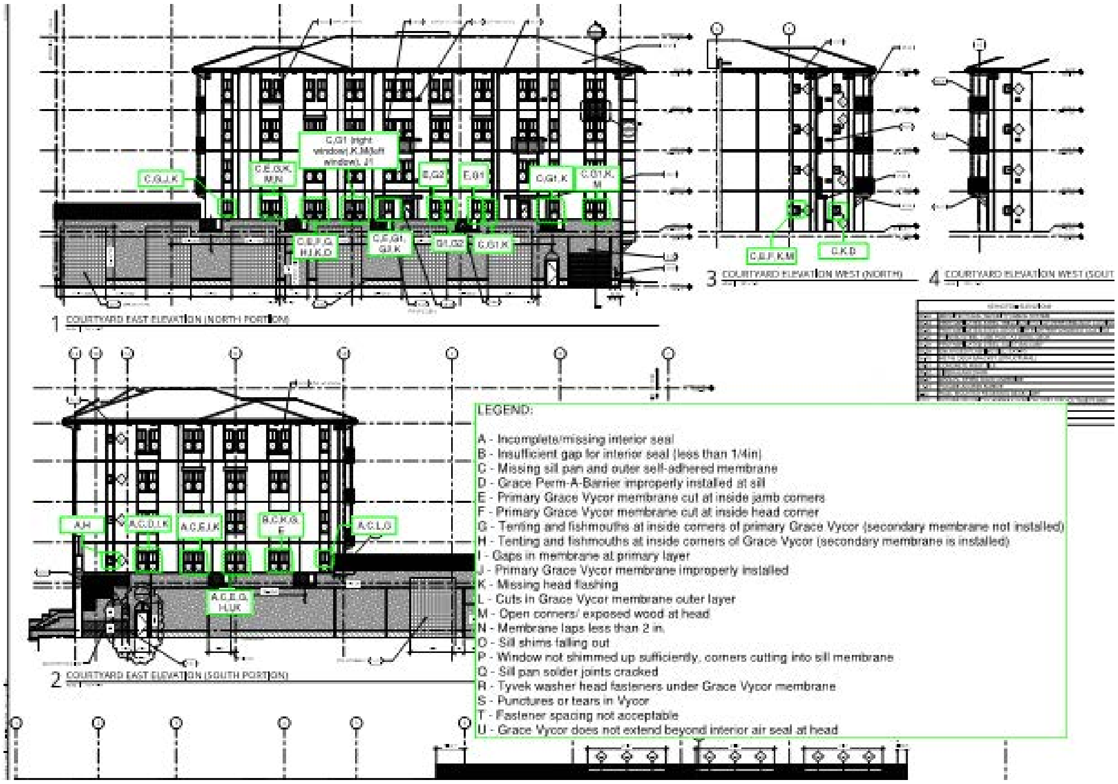

Figure 9. Case Study #1: Example elevation documenting the required extensive field repairs to the factory installed window installations

Delivery and Placement

After installation of factory components, the first finished modules were wrapped in plastic for temporary protection from inclement weather and damage before being transported to the site (Figure 10). The original plan was to complete, transport, and ship the modular units during the summer months which rarely experience rain. The San Francisco Bay Area had also experienced 2 years of sever drought which appeared to further reduce the risk of rain during construction. However, the first shipment was approximately 2 months behind schedule, and the first units arrived during the Fall of 2015 which experienced a higher than normal rainfall due to an El Niño weather pattern that year.

The first level of modules were to be placed on three inch tall concrete curbs on the cast-in-place slab, then subsequent levels stacked on top (Figure 7). Bolted connector plates on the modules with male connectors at the base and female connectors at the top enabled a positive connection but left limited room for adjustment and out-of-tolerance construction. Dimensions of the modules are set in the factory and must line up with field conditions such as pipe blockouts and module curbs, therefore both field and factory crews must adhere to precise dimensional tolerances. Several out-of-tolerance issues surfaced during module placement, including:

→ Pipe blockouts and conduit in the slab not aligning with module pipework (Figure 11).

- → As more modules were set, the weight of the modules caused the slab to deflect resulting in gaps between the curb and modules that had to be filled.
- → Several modules were up to an inch longer or shorter in one dimension. The offset distances are planned to be accommodated by changing the thickness of the stucco cladding or other finish materials at these locations. Even with a cant to taper the stucco, there is a risk the stucco may crack due to the abrupt change in thickness at these locations.

Figure 10. Case Study #1: Despite being wrapped in plastic, heavy rains resulted in water damage to some units during transport

Figure 11. Case Study #1: Misaligned pipe penetrations through slab and curbs Temporary Rain Protection

Our recommendations to fully weatherproof the modules at the factory with waterproof membranes at the walls and roofs was not accepted during the design phase due to cost restrictions and plans of summer installations. Note that a fully waterproof temporary roofing membrane over each unit would require a continuous plywood sheathing or gypsum board substrate over each module which further reduces the cost benefits of modular construction.

The contractor used tarps and plastic to temporarily weatherproof the installed modules, which proved inadequate when the first heavy rains hit. Water infiltrated from leaks through discontinuities in the temporary roofs, through exposed walls and module joints after the modular units were placed, and pooled on the concrete deck under the modules, trapped between the perimeter curbs. Considerable water damage to interior finishes and subsequent mold required that all gypsum wallboard and insulation be removed (Figure 12). Cabinets, electric fixtures, countertops and sinks were removed and stored if they could be salvaged. Materials that were stored in the modules, such as carpet, were saturated and unusable. Water also ran through electrical conduit and mechanical duct work.

Figure 12. Case Study #1: Water intrusion during construction required extensive removal of interior finishes

Particularly challenging to weatherproof was a common hallway between rows of modules. After suffering extensive water damage, the general contractor constructed a pitched roof wrapped in tarps that could be temporarily installed after each floor of modules was installed (Figure 13). This temporary roof structure was subsequently removed and reinstalled after each subsequent floors of modules were installed.

Figure 13. Case Study #1: Improved temporary rain protection during construction

The project at this time has taken as long, or longer than traditional site-built construction. We can take away several important lessons from this project:

- → Modular construction should be considered early in the design and requires collaboration from all parties involved with the design and construction. Provide details for the joints between modules that can accommodate the construction tolerances.
- → Planning for temporary rain protection is fundamental to every modular project. Plan on wrapping all six sides the modules with at least a water resistive barrier. Also plan on providing a moveable temporary roof structure that can be removed and reinstalled after each floor of modules is installed.
- → Consider the use of all non-paper faced gypsum board. Mold was confirmed on this project at all locations with paper faced gypsum board and no mold was documented where fiberglass matt gypsum board and plywood was used.
- → Consider the use of plywood instead of oriented strand board (OSB) due to its increased tolerance of wetting.
- → Provide a roofing membrane over sheathing or other continuous substrate over each module unit. Or consider field installing all interior moisture sensitive finishes.

CASE STUDY #2: MEDICAL STAFF HOUSING FACILITY, BRITISH COLUMBIA, CANADA

This second case study project was initiated by a government health care provider who desired new housing for workers at a hospital in a remote community in northern British Columbia, Canada. The building, required to meet Passive House standards, was factory-constructed in the Lower Mainland of British Columbia, and shipped to the site on barges along the "Inside Passage", a coastal route in the Northern Pacific Ocean. Modular construction was considered early in the design in order to reduce the costs associated with the following factors:

- → Shortage of skilled labor in the remote location.
- → Costs of construction staging and field construction in a remote area.
- → Cost of shipping materials for field installation in a remote area.

Design & Construction Stage

The project incorporated an integrated design approach that included the Owner, factory builder, site installer, architect, and various consultants early in the design process. This step was critical, particularly in light of the high performance requirements of the building to meet Passive House requirements for energy efficiency.

Due in large part to the harsh weather conditions along Coastal British Columbia, and the strict air-tightness requirements of the building enclosures, the entirety of the 6-sided modules were covered in an air barrier and water control layer in the factory – even the sidewalls of modules that would end up forming interior party walls with the adjacent module (Figure 14). This compartmentalization decreased the risk of damage during transit, but also had the added benefit of controlling unintentional interior airflows between units which aids in the design and functioning of the mechanical system.

Figure 14. Case Study #2: All six sides of modular units were wrapped with WRB and temporary roofing membranes

The design included all control layers and cladding to be installed in the factory; however the joint between modules was infilled with a secondary water control layer, exterior insulation, and cladding layers on site. The coordination of this installation with construction tolerances, structural connections between modules, and other variables, and the factory mockups of these conditions were key to the successful installation on site. The integrated design approach was integral to efficiency developing solutions to these atypical details. Figure 15 shows an example vertical joint detail before and after completion. Details were also developed to show how the required temporary structural supports for lifting the modules can be removed and sealed.

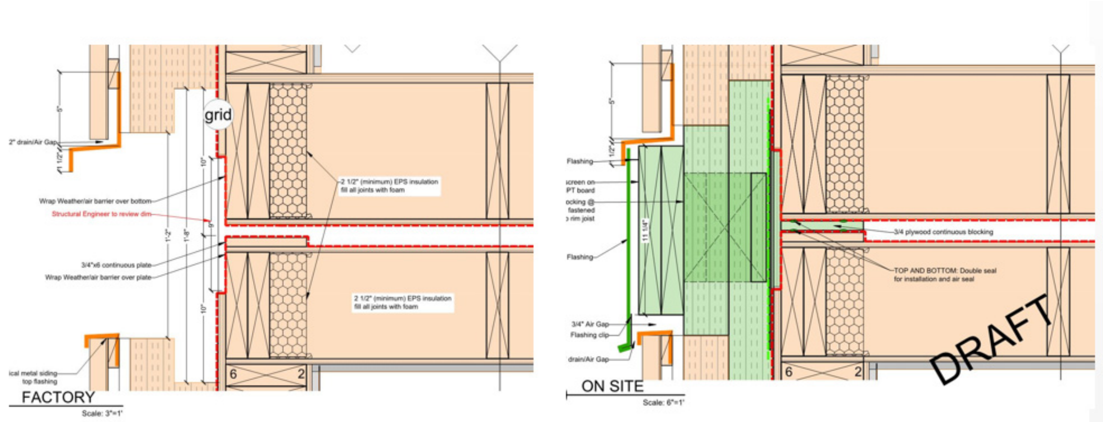

Figure 15. Case Study #2: Example detailing of horizontal stack joint between modules

Training, mockups, and quality assurance testing in the factor setting are critical steps. In many cases, the modular factories do not use specialty sub-trades to complete aspects of the work, and the methods of construction – particularly for Passive House – may not be familiar. For instance, this project included 6 inches of exterior insulation outboard of the sheathing;

the thick insulation layer has large effects on installation of cladding and windows. Despite skilled contractors and fully developed details, mockups in the factory were required for all parties to be comfortable with and to confirm the installation requirements. We also performed air leakage testing on the modules in the factory and on the completed building in the field to confirm the air barrier performance.

Delivery and Placement

Fully weatherproofed modules were shipped up the coast on barges and then erected on site using cranes (Figures 14 and 16).

Figure 16. Case Study #2: Placement of modules and photo of near complete project

Site preparation work, including foundations and crawlspaces for mechanical equipment had already been completed. Despite careful planning, site modifications were required to accommodate unanticipated buildups, interference with crane lifting straps and anchor points, and the accumulated dimensional tolerances of numerous modules placed next to each other. Despite minor construction challenges, the placement of modules and the installation of the site components was completed without significant issues. For this project, modular construction successfully resulted in a higher quality, quicker install, and overall less expensive compared to site building this project.

CONCLUSIONS

Modular construction has many potential benefits that have been successfully realized on many projects, including the potential to provide a higher quality product at a lower cost and quicker construction schedule. However, many larger more complex modular projects have suffered from extensive water leakage during construction and extra costs with field correcting factory installation errors. Based on our research and two case studies presented in this paper, we have the following recommended strategies pertaining to maximizing the performance of the building enclosure design on modular projects:

→ Weatherproof in the factory - don't count on good weather. Plan on wrapping all six sides the modules with at least a water resistive barrier. Also plan on providing a moveable temporary roof structure that can be removed and reinstalled after each floor of modules is installed.

→ Consider using an integrated design process that includes builders, architects, installers, owners, and consultants early in the design process. Modular construction is a team sport and the opportunities to make changes in the field after the modules are placed are minimal. Develop details for the joints between modules that can accommodate the construction tolerances.

→ Consider the use of all non-paper faced gypsum board to reduce the risk of mold should modular units suffer incidental wetting during construction or transport.

→ Measure and review module deficiencies prior to placement - these may be easier to repair on the ground.

→ Include a contingency for a crew on-site to repair factory deficiencies or to deal with the inevitable field modifications that may impact the schedule.

→ Where possible, provide simple, repetitive design details of every component such as window installation. A module stays at one station in the factory for as little as 2 hours, so every task and detail should be designed to fit into this window.

→ Allow for training, numerous mock-ups, and performance testing of modules in the factory prior to proceeding with full factory mobilization. Develop a project specific factory QAQC plan.

→ Develop a field QAQC plan that includes field review from an experience building enclosure specialist or air barrier technician to verify the joints have been sealed as required and to advise on questions quickly as they arise during construction.

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Ferrocast Structural Elements For Mass Housing For Low Income Group In India

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ABSTRACT

The present work aims at providing structural design and methods of manufacturing of structural components designed using light weight ferrocast cement. The Ferrocast technology uses reinforced cement mortar to cast structural components of low cost housing scheme. The method of manufacturing these structural components is suggested. This method of manufacturing when employed for mass manufacturing of components, will control cost of housing at minimum level. The method of construction suggested promotes fast construction, making it advantageous, economical in many situations. The technology proposed for low cost housing using ferrocast cement uses light weight elements, low technology manufacturing and quick responses to constructional need, hence this proposes a solution that is unmatched with normal reinforced concrete construction. This poses a very good alternative for construction industry to face ever increasing demand of low cost, mass housing in India.

KEY WORDS:

Ferrocement, precast structural component, mould, mass manufacturing.

CHALLENGES IN LOW COST HOUSING

Presently new and innovative development program is being vigorously followed by Indian government. Large allocation of funds is made by Governments and Charitable corporate sector. The thrust area being in Sanitation and rural housing. Rural India lacks basic Sanitation facility like toilets. This leads to unhealthy conditions leading to permanent prevalence of communicable diseases like cholera, typhoid etc. This results in high early deaths in young children. The estimated number of household toilet units required for the entire country would be 7 million. An ambitious program is launched to install these numbers of toilets in next ten years. The requirement of housing for the country is seven million units of approximately 250Square foot each, to be completed in next ten years. It is sighted that there should be no difficulty related to ability to construct these units irrespective of geographic spread, temperature conditions, and difficulty in proper access to site and constructional equipment and manpower at its location.

The main problem in India is manufacturing and installing /executing units in such large numbers and its logistics. The facilities are to be constructed all over India, primarily in rural areas. There can be villages located very far from the nearest main road, or in remote jungles to areas in Himalayan region. The cost cannot change much even under changing conditions. There is of course no compromise on the quality, strength and ability to withstand the high Seismic and wind loadings.
Another difficulty faced by contractors in such remote locations is the availability of trained labour. **All these problems can only be solved by constructing the houses with factory made precast elements**. The other requirement for the individual elements is the dead weight. Village roads cannot support heavy trucks. The handling of building parts has to be done manually during removal from the trucks at site and then during erection. This puts a restriction of 125kg (275 lb) for any one part, as the crane access is restricted at site.

MATERIALS AND METHODS: USE OF FERROCAST ELEMENTS

In order to get over these difficulties, design of elements was done in Ferrocement. To be able to use the structural strength of Ferrocement in tension and compression all elements were cast with 30 MPa strength mortar mix. Hand plastering was not used in this construction. ACI committee 549 [1, 2] in its state of Art report in 97 does not give any value for the tensile stresses generated in the section in Bending. Values that can be obtained in tests have been given by Dr. Antone Namman in his book " Ferrocement & Laminated Cementitious Composites ", [4] which are 25 to 35 Mpa. In order to get the stress values, in Tension, slab and beam elements were tested. Ferrocast jacketing rings were tested with 30 MPa inner concrete cores to get tensile capacity of section in hoop tension [5]. All experiments indicated an ultimate value of strength of Ferrocement 23 to 25 MPa for tension in Bending and in hoop. These values were used with a factor of safety of 2 for the design purpose. The design was done on working load as that ensured complete elastic behavior as indicated in experiments.

To confirm the behavior of sections in actual structure, an experiment was carried out by constructing a room of 3.6m x 4m area with 3m height (Figure1).The members were designed as reinforced Ferrocement sections. The simply supported sections carried its own dead load along with members supported on it. After placing steel to ensure continuity for slabs and beams, topping concrete was placed. The structure was designed to support the live loads. The experiment proved the ease of construction and the behavior of the sections as per design assumptions (Figure 2).
One more part of the building is, ` the walling`. Thin section walls were designed with stiffeners to be the external and internal walling. The panels were of about 1m width where handling will be totally manual. Panels of about 1.5m width were used where small cranes could access the site. Where the building construction was to be in zone of extreme temperature, the space formed by stiffeners was filled with foam concrete to give heat insulation.

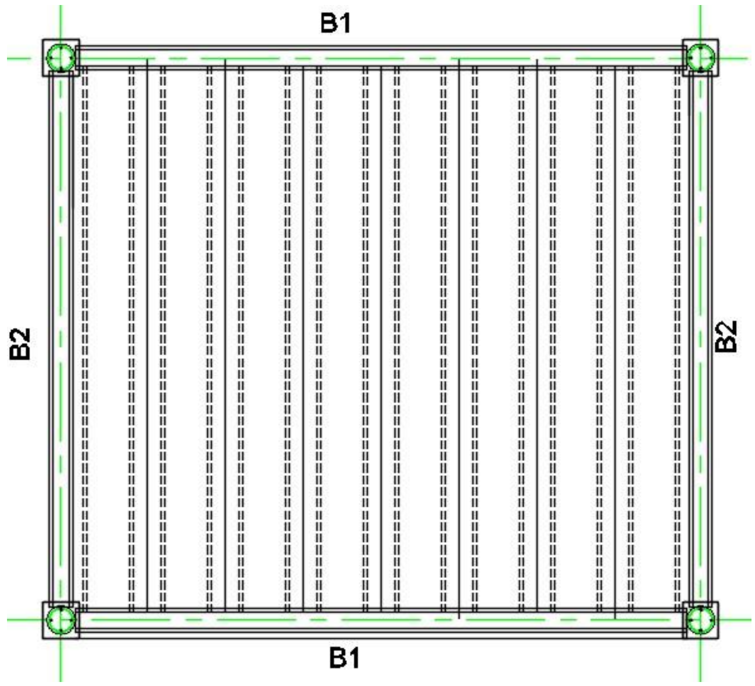

Figure 1. Plan of room constructed using Ferrocement members

Figure 2. Erection of Ferrocement member

MANUFACTURING

Looking to the various problems associated with this housing program, it was necessary to keep the method of manufacturing very simple. It was also necessary to be easily replicable without complex machinery. The level of sophistication had to be such that anyone with basic civil engineering knowledge and experience in precasting like spun pipe manufacturing could enter into this work. The success of this large manufacturing activity depended on large number of units participating in this effort. Following points were incorporated in the manufacturing process.

MOULD DESIGN AND HANDLING.

As weight of each item is critical for ease of handling, the mould design also follows the same principle. All panels are cast horizontally on the bed. The member thickness, for wall or stiffener does not exceed 30mm. This also follows the requirement of the section to be designed as a Ferrocement element. Thus the mould plates are of 3 to 4mm thickness and very light and can be handled manually. Care is taken to impart sufficient rigidity to avoid twisting of the mould plate during use. The minimum number of usage of each mould is taken as 400 for its impact on the cost of casting. Careful handling of mould is therefore necessary. Less repetition of use of mould will impact the cost structure of units which are very cost sensitive.

A good casting is a result of careful placing of mortar mix in the mould and its proper compaction. As the wall and slab mould are cast horizontally, the depth of casting is small. This ensures easy placement and its ingress into all the parts of the mould. The casting has large open surface and it is advantageous to use surface vibrator to get proper consolidation. The surface also gets a plane and smooth surface with application of surface vibration. The beams are cast upside down with bottom flange at top. The two side webs of the channel section could have a depth of up to 450/500 mm. To ensure that it was filled properly, self-compacting mortar of 30Mpa strength was used. The results were excellent. (Figure 3). As the span for slabs does not exceed 4m, the stem of the Double Tee Slab is not more than 100mm. Hence casting of this magnitude of depth does not require self-compacting mortar mix. As all casting is done in horizontal position, a large platform needs to be built on which moulds are placed. The casting is done from a centralized mixing unit and transported to the mould by hand carts. For ease of handling the cast member, "A" frames with a lifting capacity, of **one Tonne** is used. The frame span is same as the platform and has wheels. It can either move on rails or rubber tyre pushed by workers.

The choice is normally made in India on the basis of available power at casting yard and also the cost of labor which varies from INR. 250/day (approximately $4/day) to INR.500/day ($8/day).The location determines the availability of power 24/7 and the cost of the labor. The normal manufacturing quantum expected per day would be about 8 to 10 toilet units and/or 2 to 3 housing units. The casting yards are designed with above stated estimated quantity of production per day. Large capital outlay is avoided as this manufacturing would last from 5 to 10 years only at that location. Thereafter the manufacturing will have to shift to other products.

Figure 3. Ferrocast Beam

SETTING UP CASTING YARD.

The location and logistics of setting and operating a casting yard is different from that in Developed country. Situation in India may be similar to that in Africa or in Latin American States. The main constraint is lack of proper roads and non-availability of electric power supply even during working hours. These shortcomings in operating the plant have to be factored in planning. The emphasis is placed on simple equipment, more manual labor and mostly diesel engine operated equipment like mixers, generator sets for welding and cutting machinery. The logistics of transport of cast parts to location of assembly, is a sever restraint for erection in remote villages in Himalayan region. This will highlight the difficulties encountered during execution of the objective.

MANUAL ERECTION:

With difficulty in taking castings to the location by normal trucks, they have to be delivered by light vehicles. The same is the case of taking erection crane to site. It is therefore necessary to complete the erection with manual labor. The ultimate user of the toilet in the villages is encouraged to do it with a supervisor sent with the material. This sensitizes the end user about the ownership and its continuous upkeep.

PLANS FOR DIFFERENT REQUIREMENTS.

With the construction method explained above, structures needed for mass construction were designed for specific requirements. They were essentially for construction of toilets for different user conditions. The housing units of 1, 2 or 3 rooms were designed. The roofing is either of Galvanized Iron Sheets or concrete slab, depending on the cost restraints.

a) One Room Unit

These are provided for construction workers which are given individual room with a common toilet block having facility for bath. The units are made of wall panels joined together by bolting. It is necessary to dismantle the facility and shift to another work site after completion of work on that site. The wall design and its connection facilitate any number of units in rows. The front wall has one panel with window and another with a door (Figure 4).

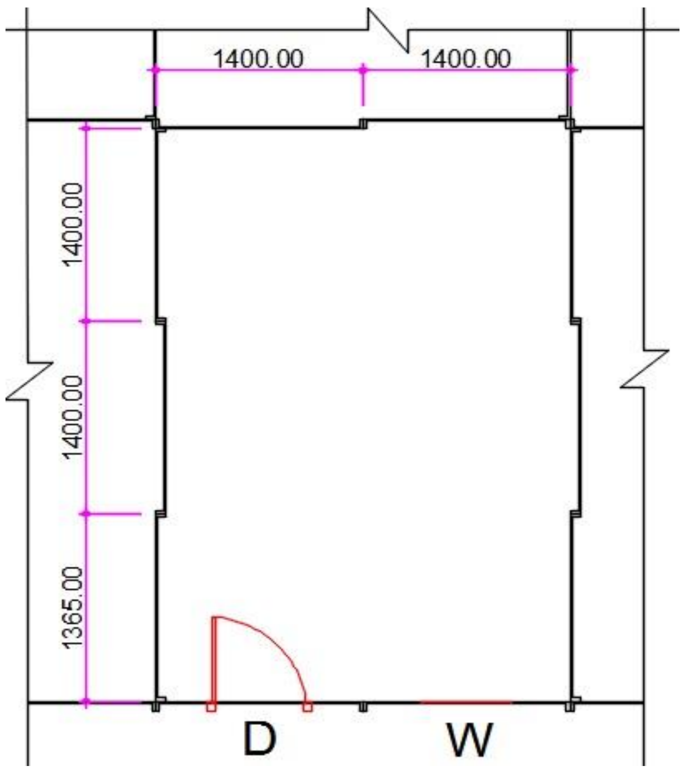

Figure 4. Plan of One room unit

b) Two Room Unit.

The plan shown in (Figure 5) has been proposed by the Central Government for the housing proposed for the poor in rural areas. These are generally in a cluster. It is easier and cheaper to give other services like water supply, drainage and sewage treatment and electric power supply to a group of houses than spread out individual units. The total number of units needed is 10millon to be completed in 10 years. Requirement of more units being in the Northern and Eastern States in India. Two types of roof coverings are offered; with concrete sloping slab or G.I. Sheets on purlins.Precast trusses with channel section used as members are proposed. The cost works out to half that of structural steel. The unit can be constructed in less than 3 weeks and occupied.

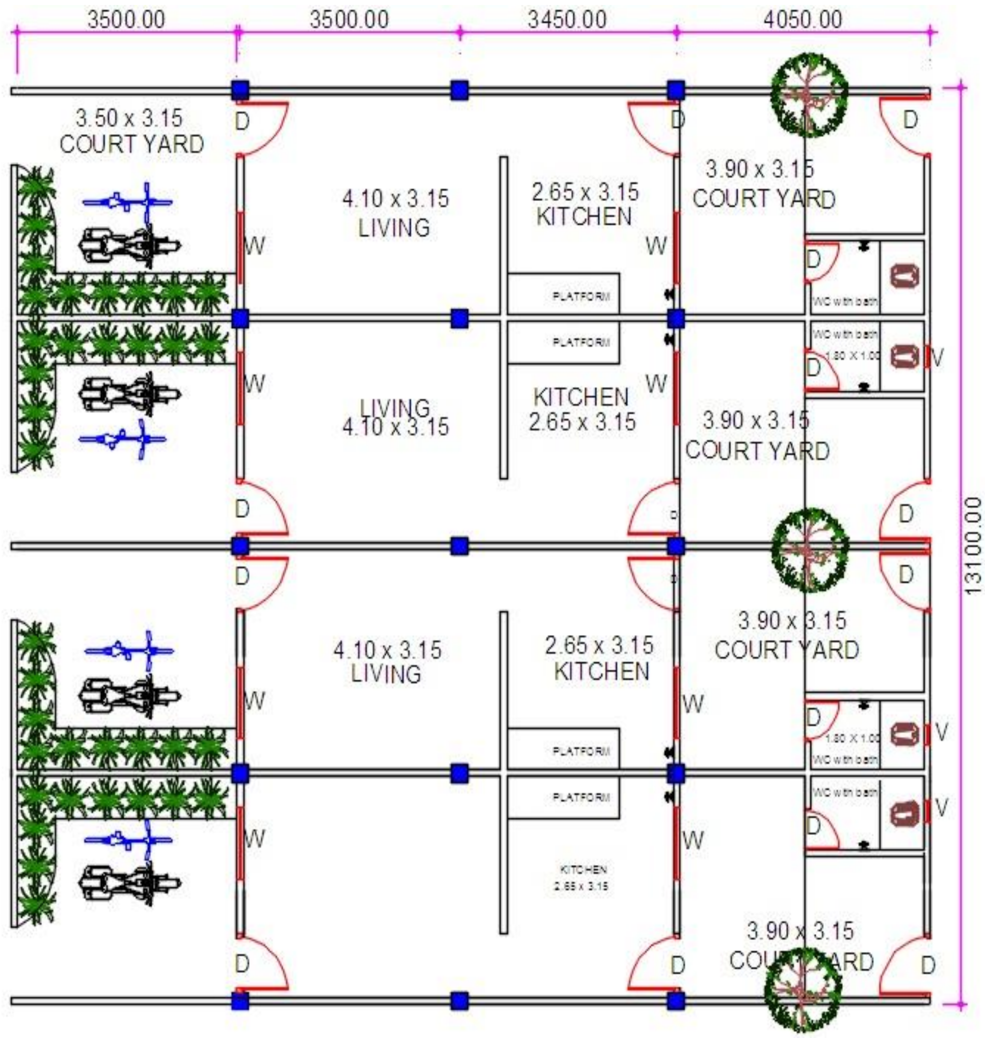

Figure 5. Plan of Two room unit

c) Three room unit.

This is essentially for disaster mitigation where people have lost their permanent houses in Earthquakes, floods, Tsunami, like natural disaster. The unit can be extended one first floor by adding a staircase. The toilet block can be detached or attached. This has its structural frame designed for appropriate seismic and/or wind forces. The construction time would be 3 weeks. Multiple units at one location will give huge time advantage in completion time(Figure 6)

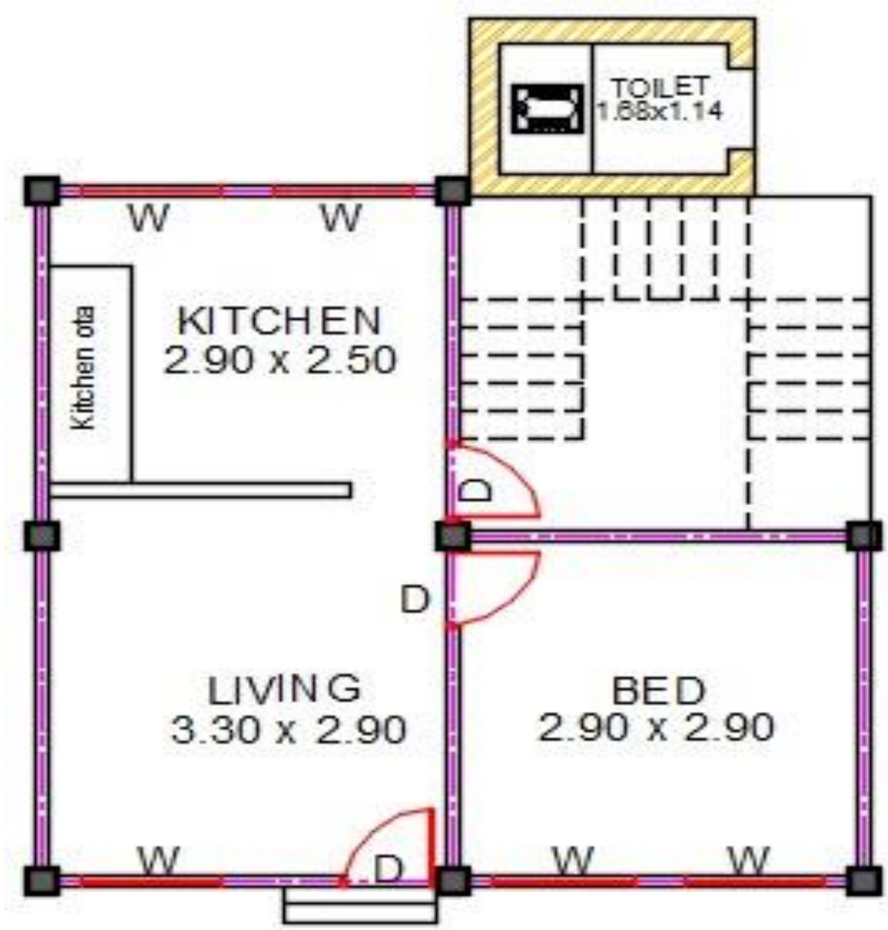

Figure 6. Plan of Three room unit

d) Single and Multiple Toilet Units.

The number of toilet units needed in 10 years is a staggering figure of 100 Million. It is impossible to construct such numbers in that time. As these units are all over the geographical spread, the manufacturing yards will have to be spread all over. Economic distance for transportation is about 75 mile radius from casting yard as the unit cost of one precasting panel set is very price sensitive. The unit cost of one installed toilet without septic tank is Rs. 12000/- ($200) and with septic tank is Rs. 20000/- ($ 335). The multiple unit is for village schools which generally have 100/120 students. The wall panels are so designed that they are common for single and multiple units. The roof can be G.I. Sheets or concrete slabs which are also ferrocast as standard Double Tee Units. Plans of each type and picture of completed unit is shown in (Figure 7, 8, 9, 10)

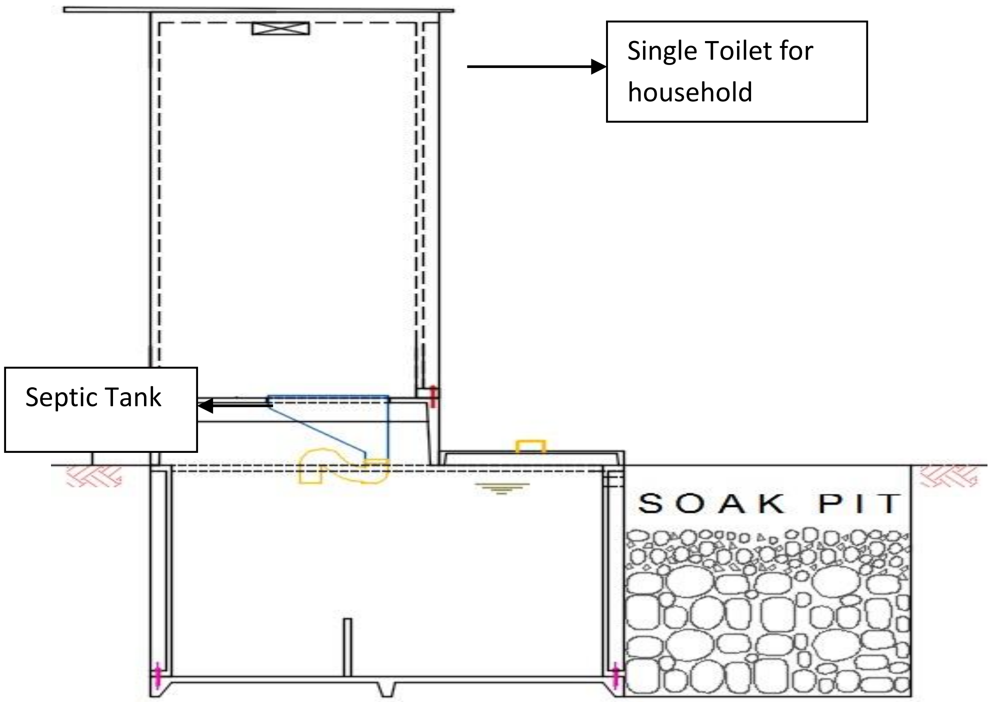

Figure 7. Section of Single toilet unit

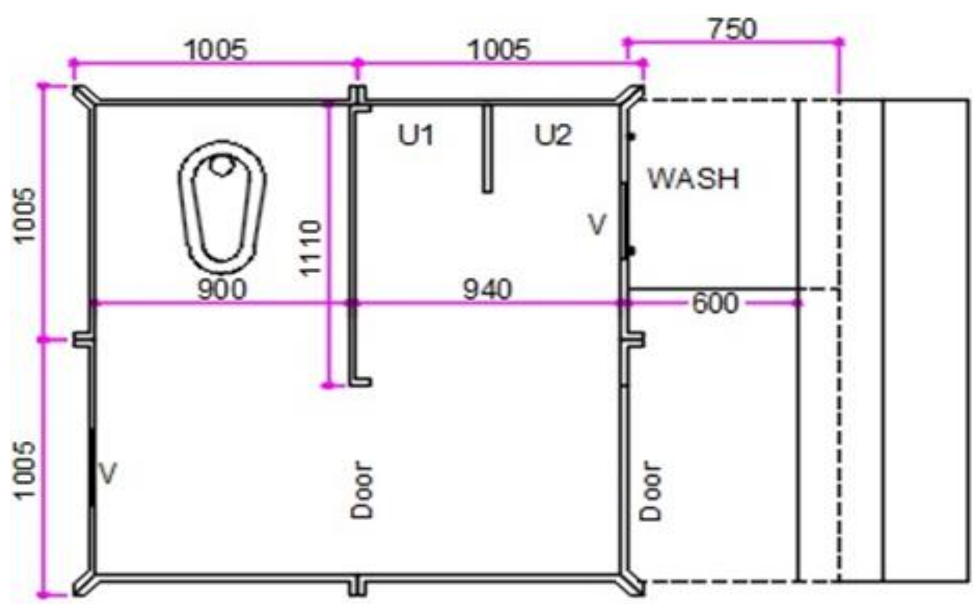

Figure 8. Plan of Double toilet unit

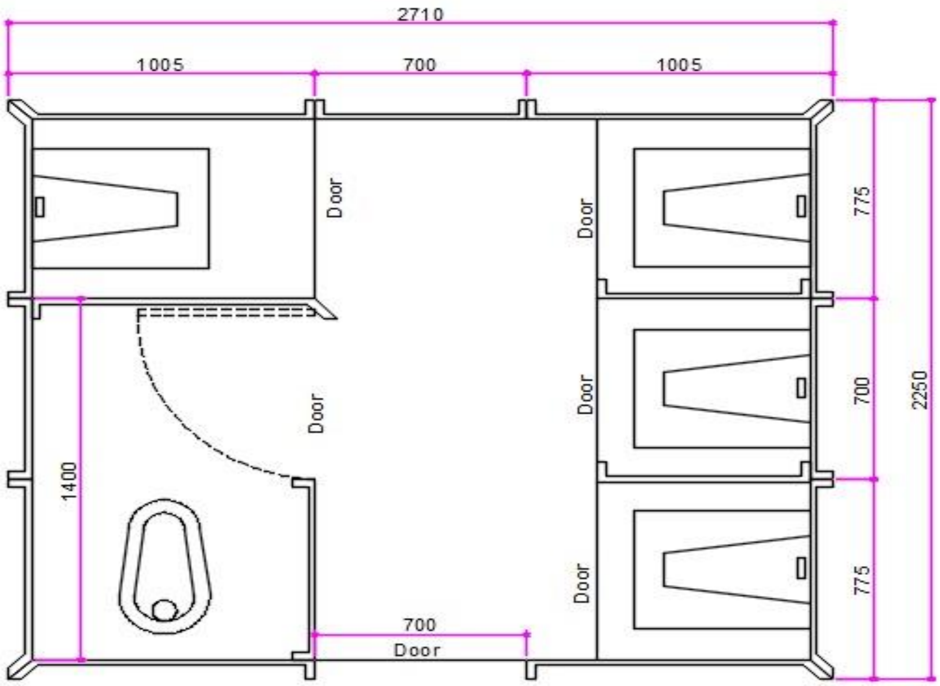

Figure 9. Plan of Multiple toilet unit

a)Toilet installed in farm   b)Toilet installed in slum

Figure 10. Completed toilet unit

SPECIAL CONSTRUCTIONAL ADVANTAGES

When basic amenities like toilets and cheap houses are to be provided in semi developed or undeveloped countries, the major difficulty is in approach roads. The sites are not easily accessible due to which construction materials, labour and equipment cannot reach the location. The quantum of work at each location could also be such that heavy expenditure cannot be made which will impact the price of individual unit. This problem is faced at many locations in India which leads to non-execution of such construction. Ferrocast elements solve most of the problems at such sites. Some such locations encountered in India are enumerated.

a) Remote Villages
b) Tribal area in Hilly terrain
c) Himalayan Region
d) Quick response to natural calamities like
   i) Earth Quake ii) Floods
   iii) Cyclone iv) Tsunami

CONCLUSION

This method of construction should be viewed through its various advantages. It is not only useful for low cost mass housing construction; it could be advantageously used in many situations. The Light weight components of ferrocast material are structural components with same structural behavior as RCC structural components with advantage of light weight and ease of erecting members on site.Much simpler technology is required for manufacturing of these structural components using ferrocast material. Due to ease of construction, this technology supports quick responses to constructional need.The quality of construction, finish and structural stability are unmatched with normal reinforced concrete construction. This technology saves construction time so Indian construction professionals are thinking seriously about this alternative available to conventional RCC construction. This may have revolutionary effect on Indian construction scenario.

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Validation of Integrated Performance Model for Sustainable Envelope Performance Assessment and Design

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ABSTRACT

Many building performance assessment methods have been developed across the world while their designed goal of achieving building sustainability is yet to be achieved. The important shortcomings of these methods include lack of life cycle performance assessment framework for life cycle cost, life cycle energy efficiency, life cycle embodied energy, life cycle carbon emission, thermal energy, inability to connect performance value with weight, inadequate coverage of sustainability issues associating with buildings, lack of multi criteria analysis framework and lack of consideration for social issues. An Integrated Performance Model for sustainable envelope performance assessment and design (IPM-SEPAD) has been developed for the building envelope to address these shortcomings. Therefore, the focus of this paper is to validate the IPM-SEPAD outcomes from the envelope design alternative application with experimental investigation outcomes involving three physical envelope models.

1. Introduction

Today, much effort is being placed on achieving building sustainability (Roderick et.al 2009). Such effort can be seen in the area of passive building design, building energy regulations, building performance assessment method development (Iwaro and Mwasha 2010). Among the leading conventional assessment methods that have been launched to achieve building sustainability across the world include Leadership in Energy and Environment Design (LEED), Building Research Establishment Assessment Method (BREEAM), and Green Star (Roderick et.al 2009; Cole 2005; Seo et.al 2006; Ding 2008). These conventional assessment methods have been widely used for building sustainability assessment and sustainable design. However, some studies have shown that these methods focused on the building sustainability assessment with little focus on building envelope and envelope components' life span during operation (Jamie 2007). This failure on the part of these assessment methods has resulted in a lack of consideration for durability, life cycle cost, life cycle energy performance, social consideration and inability to assess the sustainable performance of building envelope. Also, the possibility of achieving building sustainability through sustainable envelope has been largely ignored due to lack of a comprehensive assessment method developed specific for building envelopes. Consequently, an Integrated Performance Model for sustainable envelope performance assessment and design (IPM-SEPAD) was developed (Iwaro et.al 2014c; 2014d). The focus of this study is to validate this model in order to ensure that it functions as designed for sustainable envelope design using experimental approach.

2. Literature review

Sustainable design is fundamental to sustainable building and construction. This is because decisions made at the initial design stage of a project determine the sustainability and the overall sustainable performance of that project. In essence, sustainable design of the building envelope can be achieved by taking into consideration material efficiency, energy efficiency, recyclability and flexibility of the materials used (Task1206 2014). As such, designing building envelope for long life, minimum environmental and operational impacts are important aspects of sustainable design. According to Moedinger (2014), the degree of sustainable design and sustainability can be measured by the following stated criteria: total energy content- energy required to produce, package, distribute, use and dispose; consumption of the environment- land, forest etc.; emission- greenhouse gas, dust and natural substances; raw material- non-renewable resources; waste generation- production, use and dispose; recyclability; capital- cost and durability- longer periods of usage. Moreover, improving the energy efficiency of the building envelope through efficient glazing system will bring about reduction in the entire building energy consumption and improvement in building energy efficiency (Stanfied 2010). This means that building envelope has a significant impact on the overall energy efficiency performance of the building and its sustainability. Besides, building envelope plays an important role in achieving building sustainability and indoor thermal comfort as it regulates the impact of environmental influences on the building. According to Kibert and Tiong (2011) one of the major functions of building envelope to the occupants is to provide external benefit. External benefits from building envelope involve providing better indoor air quality and an acceptable thermal comfort to the building occupants. Also, HVAC system is a key to building energy efficiency performance as it greatly impacts sustainable performance of the building (Hui 2001). The energy consumed by buildings depends on many factors such as building envelope design, building envelope orientation, outside temperature, window areas, light systems, air conditioning and ventilation, insulation and thermal properties of the building envelope i.e, walls and roofs (Morel et.al 2011).

In light of incorporating sustainability into buildings, the focus of many researchers has been on using existing assessment methods such as Leadership in Energy and Environment Design (LEED), Building Research Establishment Assessment Method (BREAM), and Green Star (Roderick et.al 2009; Cole 2005; Seo et.al 2006; Ding 2008). These assessment methods were designed for incorporating sustainability into building development at every stage of construction. However, there is still a need to incorporate mechanisms that can undertake the life cycle analysis such as Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) of components and materials involved in building design (Jamie 2007). Even though these assessment tools are the leading environmental assessment tools today, some studies have demonstrated the importance of incorporating LCA framework into these assessment tools for life cycle parameters' assessment such as life cycle embodied energy; life cycle cost, life cycle energy performance, etc. (Sinon 2010; Lee 2011). Therefore, an Integrated Performance Model for Sustainable Envelope Assessment and Design (IPM-SEPAD**)** was developed to address these issues.

3. Brief description of the IPM-SEPAD

The IPM-SEPAD is a residential building envelope sustainable performance assessment method and a sustainable design rating system**.** The IPM-SEPAD was developed for residential building envelopes to fill the gap between existing building performance assessment methods and the current demand for building sustainability in Trinidad and Tobago, Caribbean region and developing countries with tropical climate. The Model was developed to integrate sustainable performance values into a single integrated framework. The integrated framework combined three (3) major conventional life cycle evaluating frameworks, namely: Life Cycle Cost (LCC), Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) to develop six (6) new building envelope life cycle performance assessment frameworks. In addition to these six new frameworks, an integrated criteria weighting framework was developed from Modified Analytical Hierarchy Process (MAHP) based on the Analytical Hierarchy Process (AHP) framework and Criteria Relative Important through Objective Rating Technique (CRITORT) based on the entropy framework as shown in Figure 1. The six new life cycle performance frameworks were developed based on six (6) major sustainable performance criteria: Economic Efficiency (EC), Material Efficiency (ME), External Benefit (EB), Regulation Efficiency (RE), Energy Efficiency (EE), and Environmental Impact (EI) and sixty four (64) sub criteria identified for this study (Iwaro and Mwasha 2011; Iwaro et.al 2014b). These new life cycle performance assessment frameworks include the Life Cycle Building Envelope Energy Analysis (LCBeEA), Life Cycle Building Envelope Material Impact Analysis (LCBeMIA), Life Cycle Building Envelope Regulation Impact Analysis (LCBeRIA), Life Cycle Building Envelope Environmental Impact Analysis (LCBeEIA), Life Cycle Building Envelope Cost Analysis (LCBeCA) and Life Cycle Building Envelope External Benefit Analysis (LCBeEBA).

The LCBeEA framework was derived from conventional LCEA framework with the incorporation of the LCEPS, LCOE, LCEE and normalisation via performance efficiency scale. The life cycle subjective energy efficiency performance (LCEPS) component was incorporated into LCBeEA to assess sustainability information that cannot be obtained through an objective method. Other components of the LCBeEA include the life cycle operational energy (LCOE) to undertake envelope life cycle operational energy modelling, life cycle embodied energy (LCEE) to undertake envelope life cycle embodied energy modelling and life cycle carbon emission (LCCEM) framework to model the life cycle carbon emission associated with the building envelope under assessment. In addition, the LCCEM, LCOE and LCEE frameworks were also incorporated into the LCBeRIA and LCBeEIA frameworks while LCEE was included in the LCBeMIA framework.

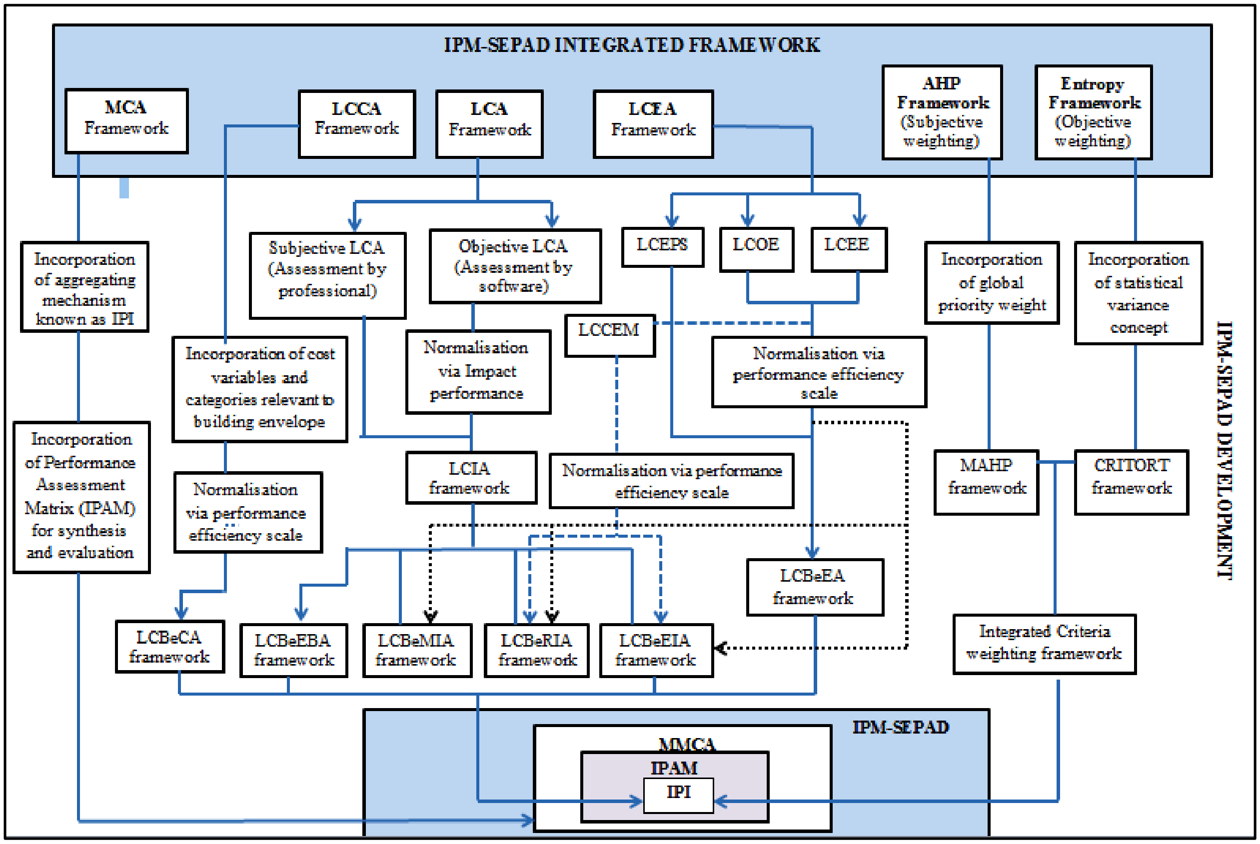

Figure 1. IPM-SEPAD Integrated framework

Moreover, the LCBeEBA, LCBeMIA, LCBeRIA and LCBeEIA frameworks were derived based LCA framework with incorporation of subjective LCA assessed by professionals, and with normalisation via impact performance scale. As shown in the Figure 1, the life cycle impact assessment (LCIA) framework is a function of the LCBeEBA, LCBeMIA, LCBeRIA and LCBeEIA frameworks. Similarly, the LCBeCA was derived from conventional LCCA with incorporation of cost variables and categories relevant to building envelope and normalisation via performance efficiency scale. On the other hand, the integrated criteria weighting framework was developed from two different conventional weighting frameworks. These include the Analytical Hierarchy Process (AHP) framework, which was modified to MAHP framework with the incorporation of global priority weight component to undertake subjective weighting of criteria. This is to standardise the local priority weight component used in AHP and bring IPM-SEPAD into international standard for the purpose of sustainable performance assessment of the building envelope. The objective component of the integrated criteria weighting framework known as Criteria Relative Important through Objective Rating Technique (CRITORT) framework was developed based on the entropy framework with the incorporation of statistical variance concept. This concept was introduced into CRITORT to ensure simplicity of the weighting process and criteria weight accuracy.

Moreover, the MCA framework was used to evaluate, assess and synthesize information from the life cycle performance frameworks and integrated criteria weighting framework. The MCA framework has the capability to combine subjective and objective information into absolute value for decision making. In order to undertake sustainable performance assessment of the building envelope that involves subjective and objective information, the MCA was modified into Modified Multi Criteria Analysis (MMCA) with the incorporation of the Integrated Performance Index (IPI) as data aggregating mechanism and integrated performance assessment matrix (IPAM) for assessment, outcome evaluation, envelope alternative ranting, raking and decision making. In the integrated framework shown in Figure 1, the MMCA serves as the centre assessment mechanism for IPM-SEPAD, and it is being used to evaluate the information from LCBeEA, LCBeEBA, LCBeMIA, LCBeRIA, LCBeCA and LCBeEIA frameworks and integrated criteria weighting frameworks through IPI and IPAM incorporated into MMCA in IPM-SEPAD. The IPI is a function of LCBeEA, LCBeEBA, LCBeMIA, LCBeRIA, LCBeCA and LCBeEIA framework.

Subsequently, an Integrated Performance Index (IPI) was developed by combining all the IPM-SEPAD sub-indexes developed to estimate criteria life cycle performance values and those developed to compute weight for the criteria. The sustainable performance assessment of the envelope was done by applying the weights (W_{Tj}) generated from integrated weighting method to the normalised criteria performance values (P_{ji}) generated from the criteria life cycle performance sub-indexes. Hence, the Sustainable Performance Value (SPV) for building envelope design alternatives was modelled using IPI index through the following equation:

$$\text{IPI}_i = \sum_{j=1}^{n} P_{ji} W_{Tj} \quad (1)$$

Where $P_{ji} = f$ {LCBeCA, LCBeEA, LCBeEIA, LCBeMIA, LCBeEBA, LCBeRIA} (j = 1,2,3 ……….. n)(i = 1,2,3........,m). Also, IPI_i denotes the Integrated Performance Index for envelope design alternatives as denoted by *i*. Also, W_{Tj} stands for the integrated weight for each criterion j, while P_{ij} represents the life cycle performance values computed for envelope design alternatives i based on the criteria performance values j. This means that the higher the value of P_{ji} and W_{Tj} the better is the sustainable performance of that alternative. Also, the higher the overall sustainable performance value from the IPI index, the more sustainable is the alternative. Subsequently, IPM-SEPAD was applied to three envelope design alternatives, where envelope design alternative B with clay block wall and corrugated standing seam sheet roof emerged the most sustainable. More details of IPM-SEPAD application can be found in Iwaro et.al (2014c) and Iwaro et.al (2014d). Consequently, three major experimental tests were conducted to validate the outcomes of the IPM application to case studies of envelope design alternatives. The tests include: energy efficiency test, material efficiency test and external benefit test. Details of the experimental methodologies are presented in the subsequent sections

4. Physical building Envelope Models' description

To validate the outcomes from the IPM application, the sustainable performance of three (3) identical small scale physical building envelope models with different material components were assessed. The main components of these models include roof, ceiling, floor, and wall constructed with different materials such as clay block, concrete block, red clay tiles, galvanized aluzinc sheet, standing seam sheeting, glass fibre and plywood board. Details of the components and materials used are presented in Table 1. The envelope physical models were located at the roof of the three-storey civil engineering department building at the University of the West Indies**.** The main advantage of this location is the openness to direct impact from sun, rain, wind, pollution and other external environmental factors influencing the performance of building envelope. This type of site ensured a close interaction with natural environment needed for this impact study. As such, the site was considered most suitable and appropriate for envelope sustainable performance assessment.

Table 1. Components and material used in the envelope physical models

Components	Model A	Model B	Model C
Roof Sheeting	Red clay tile	26G corrugated standing seam sheeting	26G galvanised aluminium sheeting
Roof Frame	2" X 4" Timber	2" X 4" Timber	2" X 4" Timber
Structural Frame	4" steel RHS	4" steel RHS	4" steel RHS
Ceiling	6mm plywood ceiling board	1.5"fibre glass sheet	1.5"fibre glass sheet
Floor	4" concrete slab	4" concrete slab	4" concrete slab
Wall	100mmx200mm x300mmconcrete block	100mmx200mm x300mmconcrete block	150mmx200mm x400mmconcrete block

Moreover, in Figure 2, the difference between the three structures, models A, B and C is the type of the wall materials, roofing materials and ceiling materials used. The models were tested with the same dimensions, same floor type, structural frame, floor area, gross wall area and size to develop baseline conditions. In the case of Model A with 100mm concrete block wall and red clay tile roof, it was installed with a 6mm thick plywood board and nylon plastic sheet underneath before placing the red clay tiles on top to ensure proper placement. In addition, the exposed parts of the red clay tile roof were covered with mortar prepared using a sand to cement ratio of 3:1(sand: cement). Weak mortar was used to ensure easy replacement of tiles. In order to firmly secure the red clay tiles to the wood frame, two screws were applied to fasten the red clay tile to plywood board and the wood frame. Moreover, Figure 2 further shows the composition of model B made of 100mm clay block wall and corrugated standing seam sheeting roof. Likewise, Figure 2 presents the physical compositions of Model C that involves the use of 6 inches (150mm) vertical hollow core concrete block, 26G galvanised Aluzinc sheeting roof and fibre glass sheet for ceiling insulation.. Subsequently, models' walls were installed with 5 rows of blocks on each sides and running bonds. A waiting period of 3 days was observed for the mortar to cure and attain the required strength. Similar construction procedures were used for the other two models. In order to ensure uniformity, the models were tested at the same time and subjected to the same environmental conditions. Therefore, the physical models shown in Figure 2 were designed with steel frame structure made up of 4 inch hollow steel sections, mild steel box section, 150mm x 100mm and 5mm thick. Steel frame was considered most appropriate for this experimental study due to its strength and durability advantage over other frame materials such as wood and aluminium. Besides, steel frame was selected for its ability to withstand strong wind and earthquake. The same structural steel frame was used for the three models tested.

Figure 2. Physical envelope models

Moreover, in order to ensure easy water run-off and direct solar impact on the roof, a slant roof with 2 x 4 (inches) wood frame at the back and 2 x 6 (inches) wood frame in the front was considered appropriate for the model. This wood frame was used for galvanised aluzinc sheet, corrugated standing seam sheet and red clay tile roof. Bolts were screwed through galvanised aluzinc sheet and corrugated standing seam sheet roofs at 1ft intervals to firmly secure them together. Besides, as the galvanised aluzinc sheet came in 4ft width, the north and south sides of the envelope model with galvanised aluzinc were provided with overhang of 6 inches since they are more subjected to rain impact. In order to ensure that the envelope is airtight, silicon was applied to seal up the roof units from the three models and the steel frame. The walls were built in accordance with the TTS 599:2006 standard, which specified that vertical walls should be placed 2.5m apart and all reinforcement cores are to be filled with concrete. The unreinforced cores used in this study contributed positively to the investigation since it enables the voids (air space) to be analysed in the study. Also, a 250mm x 250mm access hatch was constructed on the southern wall of the models, in order to control the air conditioning system and have access to the internal loggers. The opening was covered with a 300mm wide x 300mm long and 12 mm thick ply board screwed into the frame. The next section present the experimental methods and procedures.

5. Experimental method and procedures

The aim of the experimental study was to validate the sustainable performance of the materials used for building envelope design alternatives assessed for IPM-SEPAD application. This was done by investigating the impacts of the following building envelope materials: corrugated steel standing seam sheet roof, clay roof and Aluzinc galvanized sheet roof, concrete masonry wall and clay masonry wall on the sustainable performance of the building envelope using three physical building envelope models. The physical models served as the testing mechanisms to examine the combined sustainable performance of the materials used in the physical envelope models. This method of validation has been explored in the study conducted by Ozolinsh and Jakorich (2012) on the analysis of heat and moisture transfer affected by temperature difference in the 5 multi-layers structures. Also, a study was conducted by Dimdina et.al (2013) on testing the influence of building envelope materials on energy efficiency and indoor environment using five (5) identical small scale physical building envelope models. As such, in this present study, three (3) identical physical building envelope models were developed and sized with 1.5m ceiling height, 1.5m width and 1.7m length, half of the Dimdina et.al (2013) models' sizes. Besides, in view of the sizes of the model used, the experimental tests were focussed on the roof, ceiling and external wall materials since these are the largest components of the building envelope. Subsequently, the choice of the materials for these three components was based on two main criteria: (a) energy efficiency and (b) locally available resources.

Consequently, three major experimental tests were conducted to validate the outcomes from the IPM-SEPAD application to case studies of the building envelope design alternatives. The validation tests include: energy efficiency test, material efficiency test and external benefit test. As such, the experimental methods, procedures, parameters and the equipment involved in the investigation are discussed as follows. In the case of energy efficiency test, each envelope model was tested for 2 days with air conditioning (A/C) system, while a Multifunctional mini ammeter was used to measure the cumulative energy consumption in kWh at interval of 2hrs. A Panasonic split unit with 12000 BTU cooling capacity was incorporated into the experiment in order to investigate the impact of the building envelope materials on the envelope energy efficiency performance. This was done by quantifying the energy consumption associated with each envelope model tested. Along with the Multifunctional Mini

Ammeter reading, Lascar EasyLog USB Data Loggers were also installed on the outside roof, outside west wall and inside west wall of the models to monitor outdoor and indoor humidity and air temperature. The loggers measured and logged data within the following ranges: temperature, -35^{0C} to 80^{0C}, relative humidity, 0% to 100% and dew point temperature, -35^{0C} to 80^{0C}. The Lascar EasyLog USB-2-LCD data loggers measured and recorded ambient temperature, relative humidity and dew point readings with capability of storing 16,000 readings. The loggers were set to record information at the time interval of 5min for 2 days continuous reading with air conditioning cooling. This was aimed at monitoring the impact of outdoor temperature and relative humidity on the envelope energy consumption, and indoor temperature and relative humidity.

The procedure involved in the external benefit test was designed to help in assessing the impact of the envelope materials on the indoor thermal comfort in terms of indoor temperature, relative humidity and dew point temperature. As such, Lascar EasyLog USB data loggers were installed at three different locations around the models. The locations include outside roof, outside west wall and inside west wall. Consequently, the Lascar Easy Log USB data loggers were set to record information at time intervals of 5min for 2 days continuous reading without air conditioning cooling. This helped to obtain the impact of envelope materials on thermal comfort with respect to wall and roof performance. Parameters assessed for external benefits include outdoor and indoor temperature, outdoor and indoor relative humidity and outdoor and indoor dew point temperature. Moreover, the procedures involved in the material efficiency test were designed to help in assessing the efficiency of the envelope materials by examining the condensation potential performance of the envelope materials using dew point temperature, assessing the thermal mass performance of the materials using density parameter and the durability performance of the materials using absorption parameter. In the case of density and absorption, the measurement was undertaken in accordance to ASTM C20 stipulations. This procedure was done for a total of 15 samples of 6 x 8 x 16 inches concrete blocks, 15 samples of 4 x 8 x 12 inches concrete block and 15 samples of 4 x 8 x 12 clay blocks were tested. The data collected and analysed are presented in section 6.

6. Data presentation and analysis

The data for the physical envelope models were analyzed and compared with the outcomes from the IPM application to determine the best sustainable envelope model. Each model was monitored for a minimum of 4 days, 2 days with Air conditioning system and 2 days without Air conditioning system. The following sections therefore present the data collected during the investigation and the analyses:

6.1 Experimental results

The data collected from this investigation was collected over a period of 48 hours, (2 days) and presented as an average over a 24 hours period. The x-axis of the graphs ranges from 0 to 24 in numerical terms. This range represents the hours during the day and night from beginning (0.00) to the end (24.00). The y-axis of the graphs represents the average data over 24 hours during the testing period of 48 hours. Also, the standard operative indoor temperature was set at 24^{oC} for models assessed with A/C and a standard operative temperature of 25^{oC} was set for models assessed without A/C. This was done to ensure model performance comparison. Likewise, the standard operative indoor humidity was set at 60 percent for models assessed with A/C and a standard operative humidity of 50 percent was set for models assessed without A/C. ASHRAE Standard 55-2010 on thermal comfort recommends that the room's indoor relative humidity (RH) should be between 30 to 60 percent. Furthermore, in the case where the building is not occupied for a long time, the RH should be maintained below 50 percent (Utama and Gheewale 2006). This is because RH higher than 60 percent will encourage mildew and condensation in the building envelope, while RH lower than 30 percent will bring about eye irritation and stuffy nose. Based on the metrological information, the daily mean outside relative humidity for Trinidad is 80 %. On the part of the indoor air temperature, the acceptable range of operative temperature recommended by Standard 55-2010 is between 72^{F} (22.2^{oC}) to 83^{F} (28.3^{oC}) (Stephen and Turner 2011). Therefore, based on these standards, the next section presents the analyses of the experimental investigation conducted.

6.2 Energy efficiency performance

The average energy consumption data for the models were collected at two hours interval over a 48 hours (2 days) period. The result in Figure 3 shows that the energy consumption of the models increases as the outside temperature increases and decreases as the levels of the sun exposure decreases. The result further shows that the energy consumption of the models was at the peak between the hours of 10.00am and 4.00pm. In this specified period, the average energy consumption of Model "B" was the lowest with 0.3420 kWh while Model "C" had the average energy consumption with 0.4683kwh. This indicates higher energy efficiency performance in Model "B".

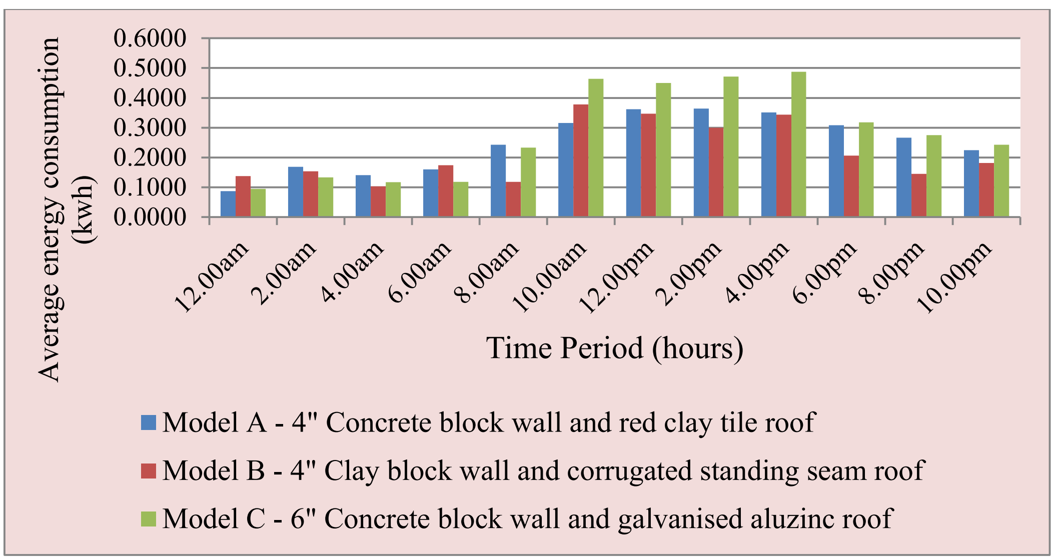

Figure 3. Average energy consumption at two hour interval over 48hours

Besides, it can be seen that more energy was consumed between the periods of 6.00pm-10.00pm than the periods of 12.00am- 8.00am. This is because the building envelope stores heat energy during the period of 6.00pm - 10.00pm and releases the heat energy during the periods of 12.00am – 8.00am for cooling and temperature stabilization. Moreover, the energy consumed between the periods of 12.00am – 8.00am was lower due to the absence of solar radiation from the sun and low heat gain into the envelope indoor environment. Figure 3 shows the average energy consumption for different models tested at two hour interval. In view of the differences in the model energy consumption at two hours interval over 48 hours as revealed in Figure 3, the result depicted in Figure 4 shows that Model "B" has the lowest average energy consumption during the day with high solar radiation from the sun than other two models. The result further revealed that energy consumption was greatest in Model 'C" during the day with highest thermal mass of 150mm (6") concrete block wall , while Model "A" had the highest energy consumption during the night due the presence of thermal mass in the100mm (4") concrete block wall and red clay tile roof. This means that more energy is stored at night in model "A" than the other two models. Moreover, Figure 5 shows the total energy consumption over 48hours for the three models tested. As seen in the figure, Model "B" has the lowest energy consumption of 5.5604kwh, followed by model "A" with 6.2318kwh and model 'C" with the highest energy consumption of 7.2070kwh. This means that Model "B" has a better energy efficiency performance than the other two models.

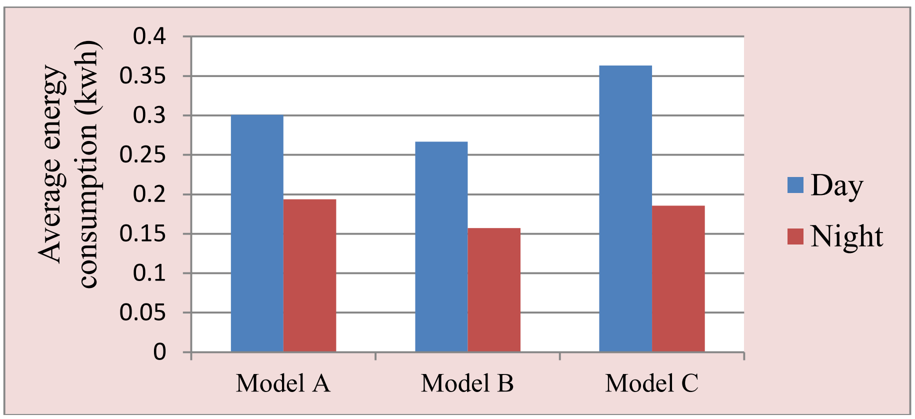

Figure 4. Average energy consumption for 24hours (Day and night)

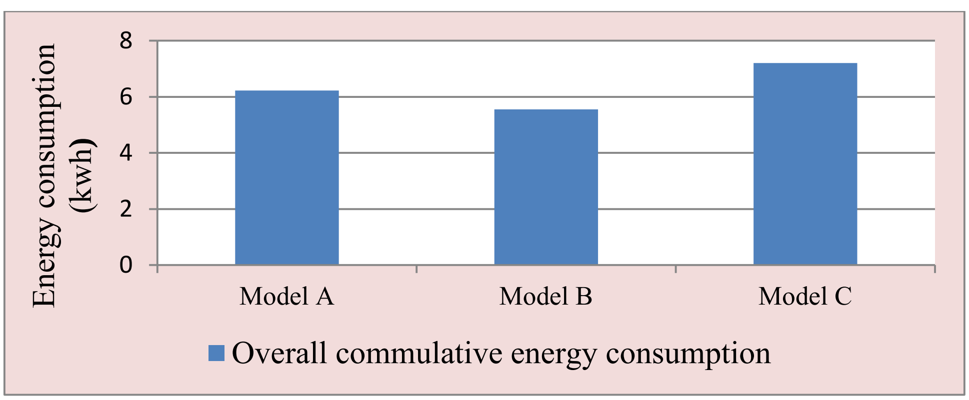

Figure 5. The overall cumulative energy consumption for 2 days (48hours)

6.2.1 Energy consumption and temperature performance of the models

Graph in Figure 6 shows that the outdoor temperature increases as the intensity of solar radiation from the sun increases. The outdoor temperature was at the peak in all models tested between 10.00am to 4.00pm, while the indoor temperature was at the peak between 4.00pm and 6.00pm. This means that during peak periods, the three models continue to store heat energy for cooling until the indoor temperature peaks between 4.00pm to 6.00 and declines with outdoor temperature as the level of the solar radiation decreases. Given the set indoor temperature at 24^{oC}, Model B recorded the lowest indoor temperature when compared with other two models indoor temperature profile performance at the same outdoor temperature.

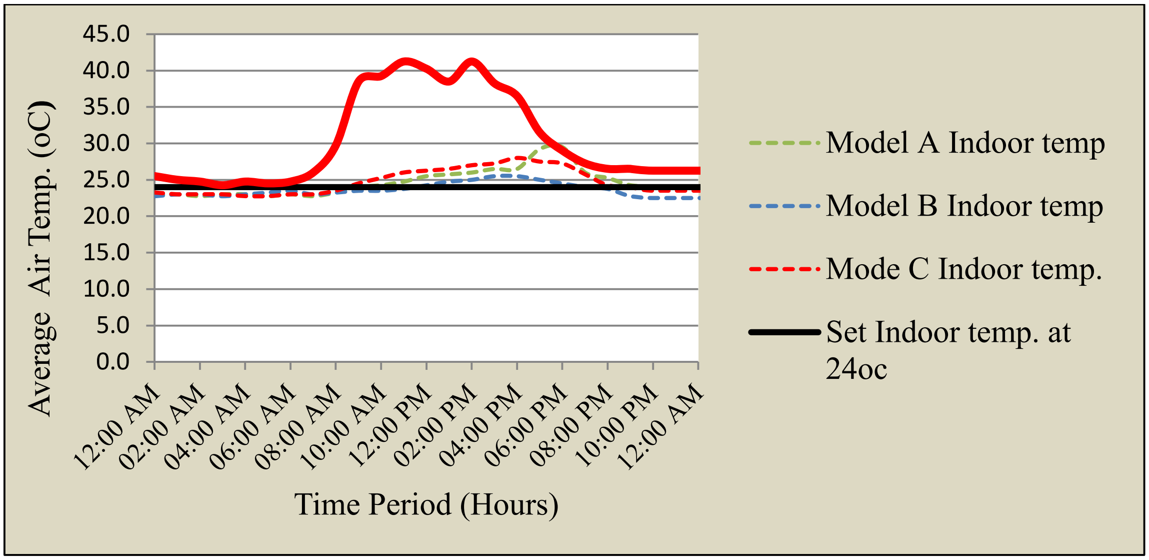

Figure 6. Outdoor and indoor temperature profile (With A/C)

Also, Figure 7 shows that energy consumption increases as the outdoor temperature increases. During the peak period between 10.00am- 4.00pm, Model B used the lowest energy for cooling than the other two models while Model C consumed the highest amount of energy. Subsequently, the rate of energy consumption begins to decrease as the outdoor temperature decreases due to decline in solar radiation from the sun. Moreover, Figure 8 shows that within the peak period between 10.00am – 4.00pm, the indoor temperature of Model B was the least among the three models tested with about 2^{oC} above the 24^{oC} set indoor temperature at its peak temperature. Besides, at peak temperature in Figure 7, Model B consumed the least amount of energy to cool the outdoor temperature at 40^{oC} to the indoor temperature of 26^{oC} when compared to the other two models. Thus suggests better energy efficiency performance of Model B. This is because the model was able to reduce the impact of outdoor temperature at the peak hour of 12.00pm as shown in Figure 7.

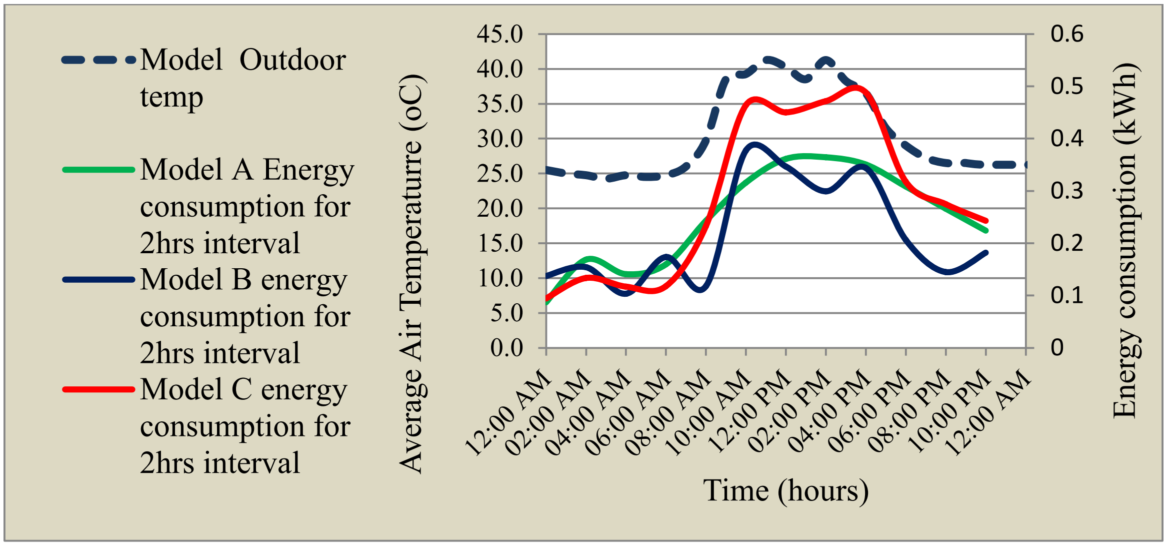

Figure 7. Energy consumption and outdoor air temperature

In addition, Model B continues to maintain the least indoor temperature even after the outdoor temperature and sun radiation started to decline between 8.00pm – 12.000am. This means Model B is more sustainable in terms of energy efficiency as compared to the other two models.

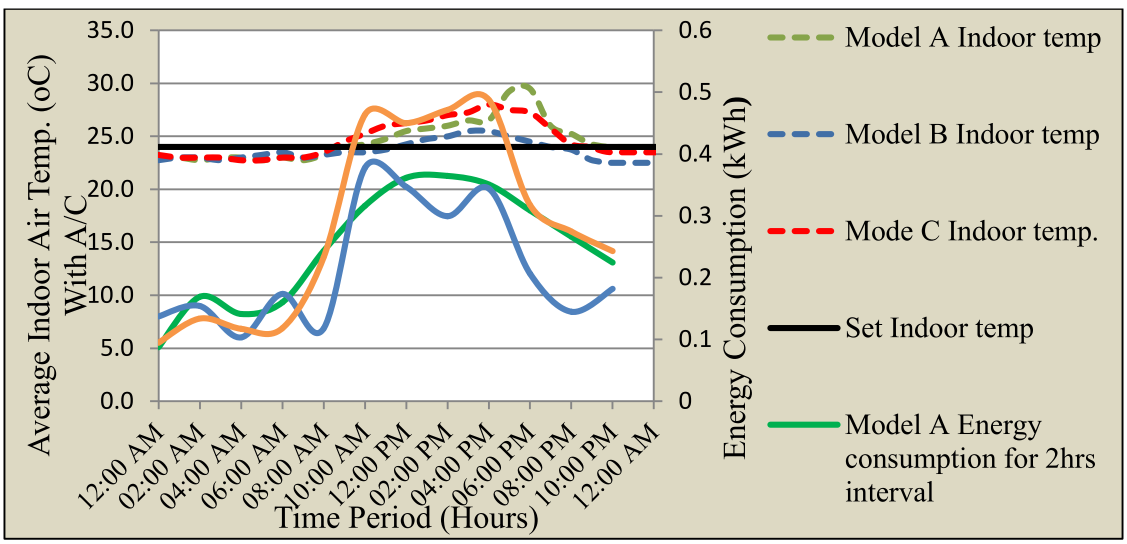

Figure 8. Energy consumption and indoor air temperature

6.2.2 Energy and relative humidity performance of the models

Indoor Relative humidity represents the percentage of the available energy that has been used for cooling. In Model C, the indoor relative humidity was as high as 90% during the peak period of 10.00am to 4.00pm, while Model A was relatively at 62% and Model

B was at 60% as shown in Figure 9. This means that significant percentage of the available energy from electricity has been used for air cooling in Model C as compared to Models A and B where lesser amount of energy was used for cooling. Moreover, given the recommended set indoor relative humidity of 60% with A/C, Model B recorded better performance when compared with Model A. Thus suggests better indoor thermal comfort conditions in Model B in terms of indoor temperature as shown in Figure 8 and indoor relative humidity as shown in Figure 9.

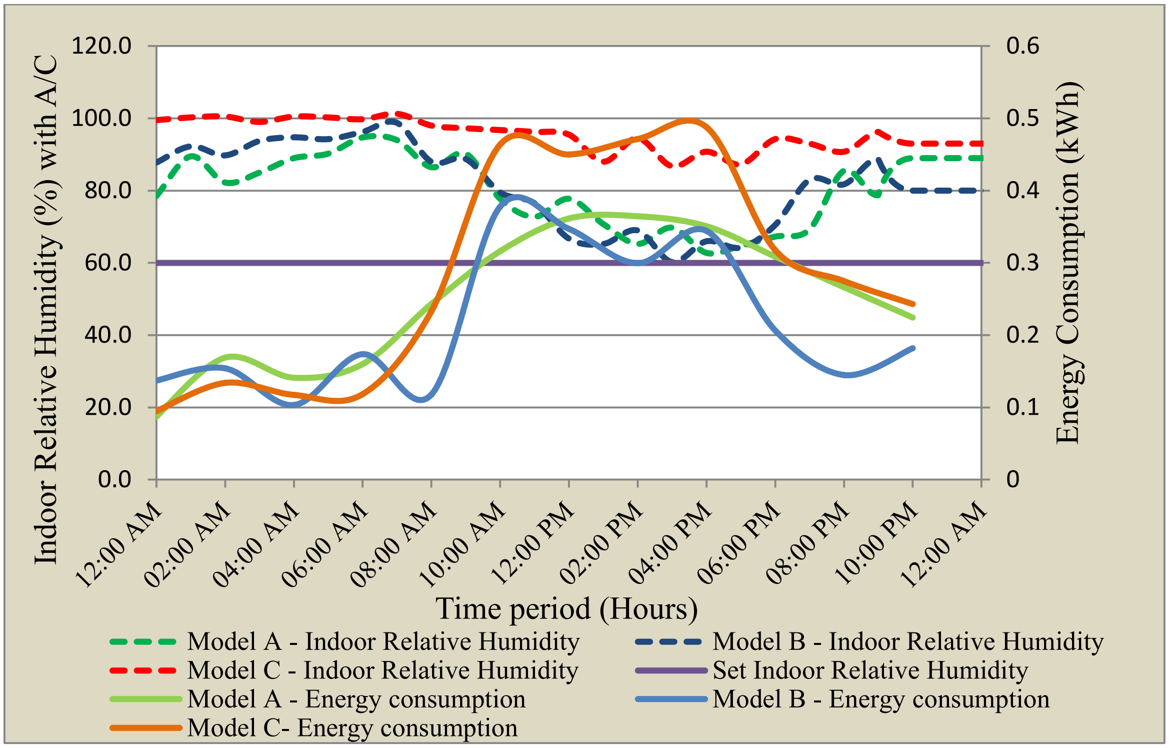

Figure 9. Energy and Indoor relative humidity

On the other hand, Figure 10 shows the relationship between the outdoor relative humidity and the energy consumption. In this case, the outdoor relative humidity represents the percentage of the available energy for cooling. The figure shows that between the periods of 12.00 am to 8.am, the average outdoor relative humidity of the three models was high ranging from 80% - 100% while the energy consumption rate of the three models was low ranging from 0.1 to 0.2 kWh. This means that the percentage of the available energy for cooling is very high between the periods of 12.00am to 8.00am. Moreover, as the solar radiation increases, the outdoor temperature increases and the energy consumption also increase, while the outdoor relative humidity decreases. Thereby reduces the available energy for cooling between the periods of 10.00am to 6.00pm. Within these periods, the three models were impacted with the outdoor relative humidity of 40%. This means that Model B used less energy and has more energy available for cooling than Models A and C. Thus suggests that Model B is more sustainable in terms of energy efficiency and relative humidity performance.

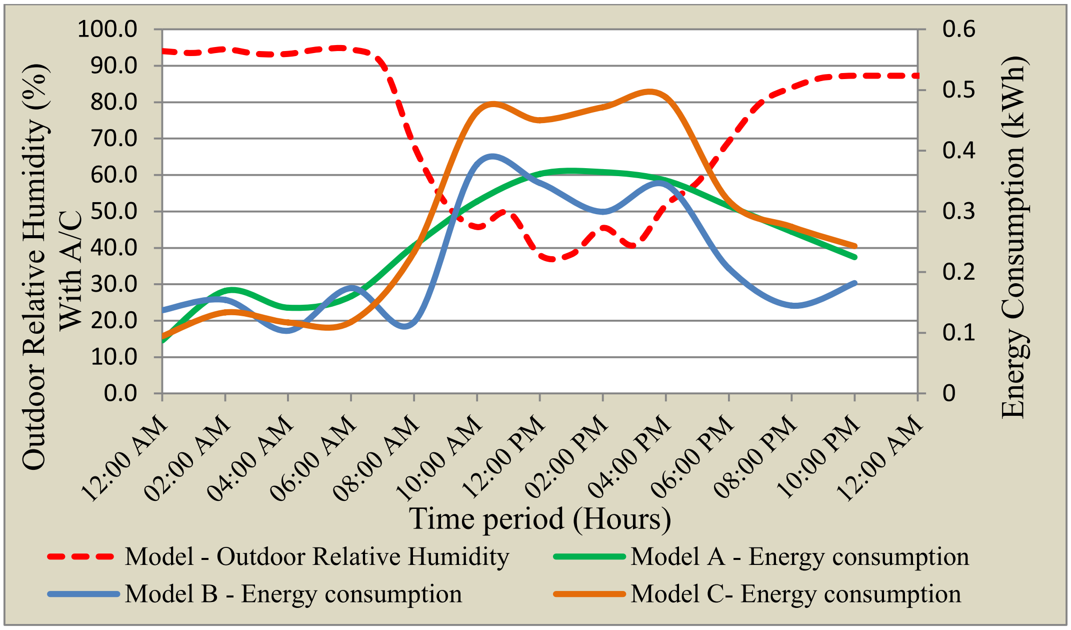

Figure 10. Energy and Outdoor relative humidity

6.3 External benefit performance

Thermal comfort is an important indicator of building sustainability while the indoor temperature, indoor relative humidity and indoor dew point temperature are important components of thermal comfort condition. According to the results shown in Figure 11, the graph shows that the outdoor air temperature was greater than the internal air temperature during the daytime (6.00am – 6.00pm) for the three Models. However, during the night time (6.00pm – 6.00am) the outdoor air temperature dropped faster than the indoor air temperature. Overall, Models B and C maintained the lowest indoor temperature during the day time when compared with Model A. However, when the cooling strength of the model was taken into consideration, Model B emerged the best with the highest cooling strength. This was followed by Model A and then C.

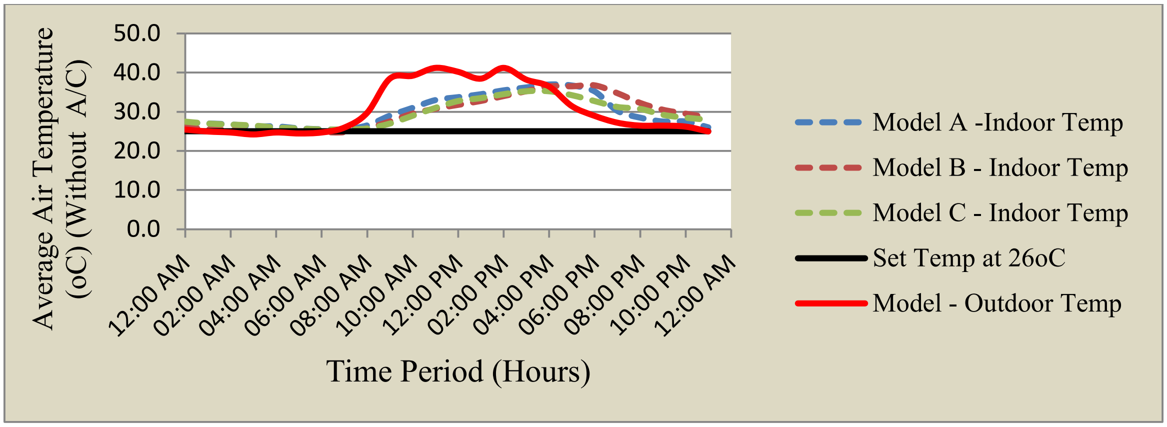

Figure 11. Indoor and Outdoor temperature profile (Without A/C)

In consideration of the model performance during day time (6.00am – 6.00pm), Model B maintained an average indoor temperature of 31.0^{oC} when the average outdoor air temperature was 35.0^{oC}. This means that the model was capable of maintaining a 4.0^{oC} difference between indoor and outdoor temperatures. The difference between the outdoor and indoor temperatures in models A and C was 2.7^{oC} and 1.2^{oC} respectively. Thus means that Model B had the highest capability to maintain the largest temperature difference between outdoor and indoor air temperature and hence considered to perform best, followed by Models A and C. On the other hand, during night time (6.00pm – 6.00am), the outdoor temperature was lower than the indoor temperature for all Models. Model B had the highest indoor air temperature during night time from 6.00pm to 12.00am at 32^{oC} while Models A and C maintained indoor temperature of 29.2^{0C} and 30.1^{oC}, respectively. However, during the period of 12.00am to 6.00am, model B maintained the lowest indoor temperature at 25.2^{oC}, while Models A and C maintained the same indoor temperature at 26.4^{oC}. This means that Model B performed best during day time and recorded the lowest indoor temperature during night time from 12.00am to 6.00am. The high indoor temperature recorded by Models B and C during night could be explained in terms of thermal mass performance. It means that Models B and C stored more heat energy during the day than Model A, which was later dissipated at night. This results in higher indoor temperature in Model B from 6.00pm to 12.00am and Model C from 12.00am to 6.00am. Overall, Model B emerged best with the capability of maintaining the indoor air temperature to acceptable comfort temperature of 26^{oC} without air conditioning system cooling. This is because its indoor air temperature during daytime was significantly less than the outdoor temperature when compared with Models A and C.

In terms of indoor and outdoor relative humidity, the graph in Figure 12 revealed that relative humidity was inversely proportional to temperature. That is, the relative humidity decreases with an increase in temperature. During daytime, the graph shows that the indoor relative humidity of Models A and C with peak value of 75% and 70%, respectively, was greater than the recommended value of 50%.

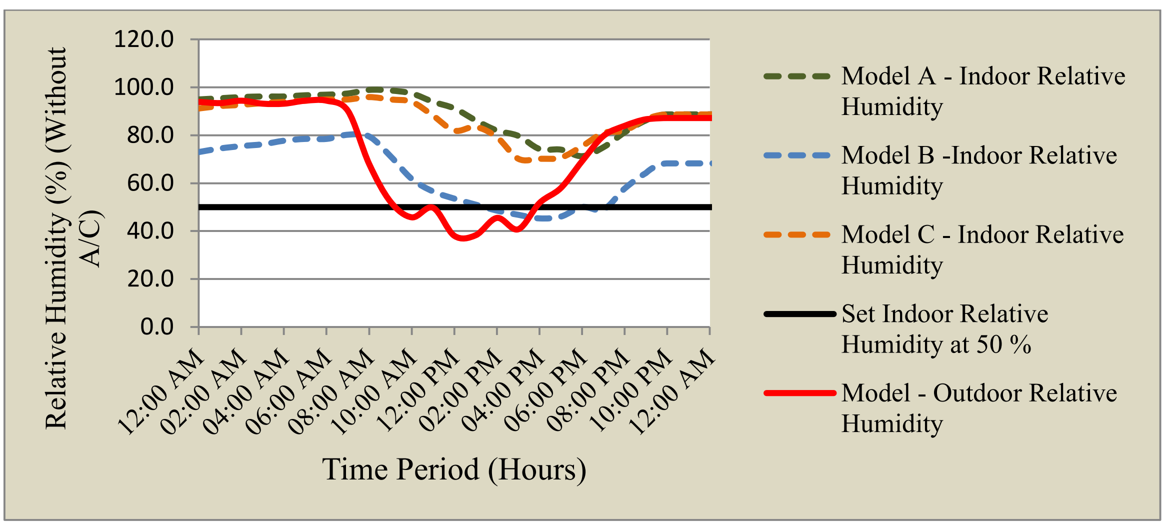

Figure 12. Indoor and Outdoor Relative humidity profile (Without A/C)

On the other hand, at the same period, the indoor relative humidity of Model B was within the acceptable indoor relative humidity with peak value at 45%. This means that the indoor relative humidity of Model B is more acceptable during the day than the indoor relative humidity of Models A and C. Moreover, during the night, the indoor and outdoor relative humidity of the three Models were greater than the acceptance indoor relative humidity. They were as high as 90% during the hours of 12.00am to 6.00am and 85% during the periods of 6.00pm to 12.00am. This means that their indoor relative humidity during the night was far from being conducive. However, notwithstanding the magnitude of these values, Model B performance best followed by Model C and then Model A. The indoor relative humidity of Model B was the lowest and relatively close to the upper level of acceptable indoor relative humidity of 60%. It thereby shows a significant potential of maintaining an acceptable indoor relative humidity of 50% for thermal comfort

Furthermore, dew point temperature is another important parameter for determining thermal comfort. The dew point temperature is closely associated with relative humidity. A high relative humidity indicates that the dew point is closer to the current temperature and that the air is maximally saturated with water. Consequently, the dew point provides an indication of current temperature and relative humidity (air moisture content). This means that the value of the dew point can be used to determine the thermal comfort performance of a building. As such, if the temperature increases, the dew point will increase while the relative humidity decreases accordingly. In Figure 13, the indoor dew point temperatures of the Models increased with indoor temperature and declined with the indoor temperature. During day time, Model B had the lowest average indoor dew point temperatures with 22.8^{oC}, followed by Model C with 27.8^{oC} and then Model A with 28.8^{oC}.

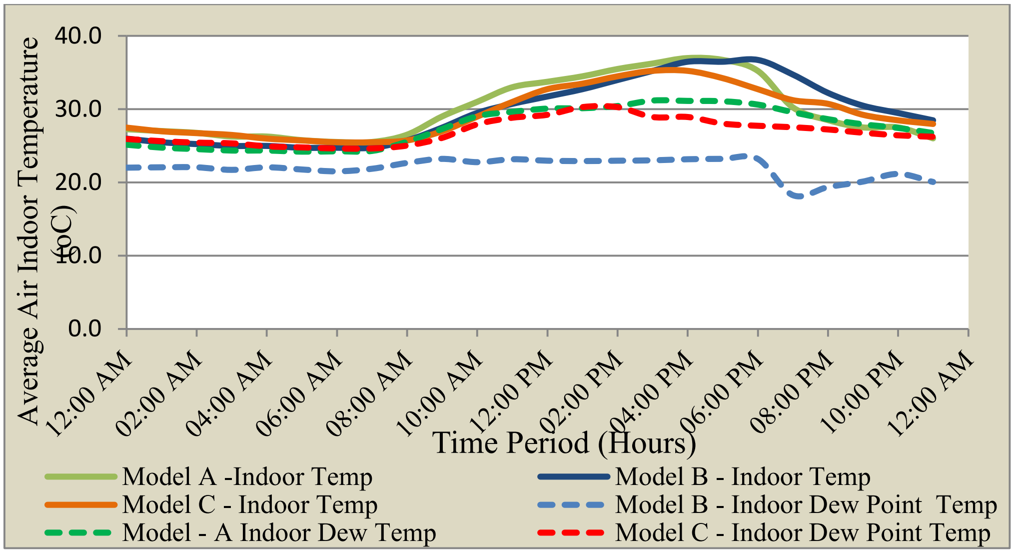

Figure 13. Indoor temperature and indoor dew point temperature (Without A/C)

Moreover, when the indoor dew point temperature was analysed for the span of 24 hours (12.00am – 12.00am), Model B also had the lowest average indoor dew point temperature with 22.0^{oC}. This was followed with Model C with 27^{oC} while Model A had the highest average indoor dew point temperature with 27.6^{oC}. This means that the performance of indoor dew point temperature was dictated by the performance of the indoor temperature and by extension, the outdoor temperature. Notwithstanding the above performances, Model B was able to maintain the indoor dew point temperature close to the recommended upper value of 15.5^{oC} and hence emerged the best. In terms of indoor dew point temperature and indoor relative humidity relationship, Figure 14 shows that indoor relative humidity decreases as the indoor dew point temperature increases for all the models. During day time from 8.00am to 8.00pm, Model B recorded the lowest indoor dew point temperature at the peak indoor relative humidity of 45%. On the other hand, Models A and C indoor dew point temperatures were greater than the recommended comfort value of 15.5^{oC} at the peak indoor relative humidity with 75% and 70% respectively. Overall, Model B emerged best with capability of being able to maintain a comfortable indoor dew point temperature.

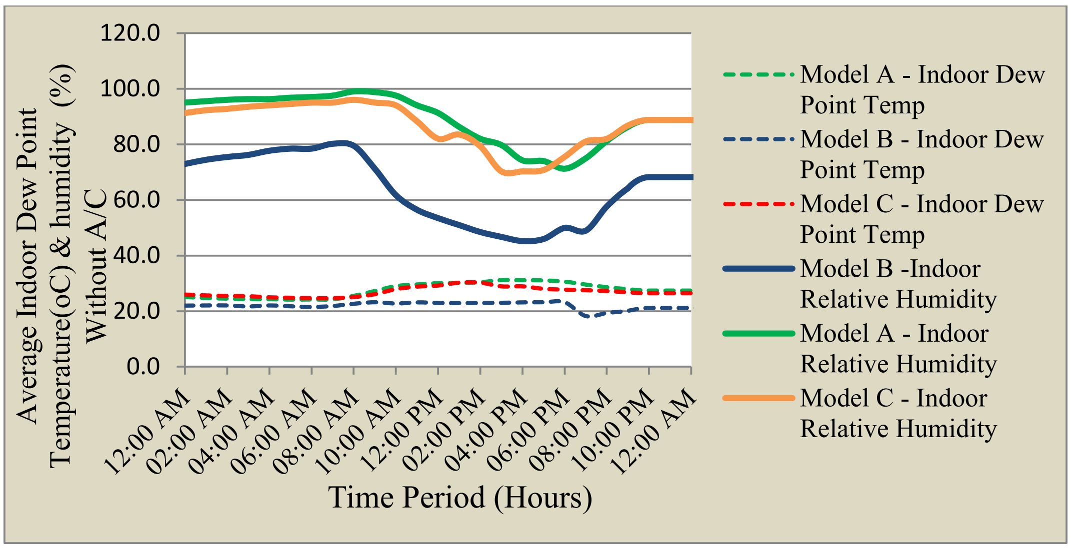

Figure 14. Indoor dew point temperature and indoor relative humidity (Without A/C)

6.5. Summary of the experiment outcomes

The experimental outcomes summarised in Table 2 show that Model B performed best under external benefit test with the highest score in cooling strength of 4.0^{oC}, lowest average indoor temperature (daytime) at 30.8^{oC}, lowest average indoor relative humidity (daytime) at 59.1% and lowest average indoor dew point temperature (daytime) at 22.8^{oC} under the same average outdoor temperature (daytime) of 35^{oC}. This is closely followed by Model C with lower relative humidity and dew point temperature values, and then Model A with better performance in cooling strength at 2.7^{oC}. Moreover, under energy efficiency test, Model B emerged the best with better performance in average energy consumption at 2hrs interval over 48 hrs (Daytime) (kWh), average daily energy consumption (kWh) and overall cumulative energy consumption over 48 hrs (kWh) as shown in Table 2, followed by Model A and then Model C. Also, Model B emerged best under material efficiency test with the lowest condensation potential at 22.0^{oC}, highest thermal mass performance at 2166.10 Kg/m^3 and highest moisture absorption of 156.94 Kg/m^3 but with the highest drying rate, followed by Model C and then model A. Overall, the outcomes from the energy efficiency test, external benefit test and material efficiency test under the experimental investigation as analysed in this paper indicated that physical envelope Model B with clay block wall and corrugated standing steam sheet roof emerged the most sustainable, followed by Model A and then Model C.

Table 2. Experimental investigation outcomes using physical envelope models

SUSTAINABLE PERFORMANCE CRITERIA	ASSESSMENT PARAMETERS		MODEL A	MODEL B	MODEL C
External benefit (Without A/C)	Average outdoor temperature (daytime) oC		35.0	35.0	35.0
	Average indoor temperature (daytime) oC		32.3	31.0	33.8
	Average indoor temperature (night time) (oC)		27.2	28.0	28.1
	Cooling strength in (oC) (Difference between the indoor and outdoor temperature)		2.7	4.0	1.2
	Average indoor relative humidity (daytime) (%)		87.9	59.1	84.2
	Peak indoor relative humidity (daytime) (%)		75	45	70
	Average indoor relative humidity (night time) (%)		90.2	68.9	89.4
	Average indoor dew point temperature (daytime) (oC)		28.8	22.8	27.8
	Average indoor dew point temperature (night time) (oC)		26.4	20.9	26.2
Energy efficiency (With A/C)	Average energy consumption at 2hrs interval over 48hrs (Daytime) (kwh)		0.3007	0.2665	0.3631
	Average energy consumption at 2hrs interval over 48hrs (night time) (kwh)		0.1934	0.1573	0.1855
	Average daily energy consumption (kwh)		0.2494	0.2156	0.2837
	Overall cumulative energy consumption over 48hrs(kwh)		6.318	5.5604	7.2070
	Average energy consumption rate(kwh/oC)		0.00794	0.00689	0.00999
Material efficiency (Without A/C)	Condensation potential	Indoor dew point temperature (oC)	27.6	22.0	27.0
	Thermal mass performance	Density(Kg/m^3)	2144.26	2166.10	2077.94
	Durability performance	Moisture absorption (Kg/m^3)	101.16	156.94	117.31

Consequently, these experimental investigation outcomes were compared with the outcomes from the IPM-SEPAD application to envelope design alternatives shown in Table 3 where envelope alternative B designed with clay block wall and corrugated standing seam sheet roof emerged the most sustainable. The purpose of IPM-SEPAD is to select the most sustainable envelope design alternative with the best overall sustainable performance value in order to aid sustainable envelope design decision making. The IPM-SEPAD framework was designed to integrate sustainable performance values into a single framework. Also, the life cycle performance value (LPV) was modelled using life cycle performance sub index in IPM-SEPAD while the integrated weight was modelled using integrated weighting index in IPM-SEPAD. Hence, the combination of these two values resulted into sustainable performance value (SPV). Then, the summation of the SPV from the criteria resulted into overall sustainable performance value. As such, for the purpose of this validation study, the IPM-SEPAD application was demonstrated based on three major sustainable performance criteria. These include external benefit, energy efficiency and material efficiency. Details of the IPM-SEPAD framework and application used for this validation study can be seen in Iwaro et.al(c) (2014), Iwaro et.al (d) (2014). In the IPM-SEPAD application outcomes depicted in Table 3, the envelope design alternative B emerged the best with the highest overall sustainable performance value of 12.067, followed by alternative C with 10.457 and then alternative A with 9.965.

Table 3. Outcomes from the IPM-SEPAD using integrated performance assessment matrix

	Alternative A		Alternative B		Alternative C		
Criteria	LPV	SPV	LPV	SPV	LPV	SPV	Integrated Weight
External Benefit	15.609	1.701	15.871	1.730	15.438	1.683	0.109
Energy Efficiency	24.596	6.075	30.523	7.539	26.444	6.532	0.247
Material Efficiency	18.869	2.189	24.121	2.798	19.327	2.242	0.116
Overall sustainable performance value		9.965		12.067		10.457	

LPV= Life Cycle Performance Value, SPV= Sustainable Performance Value

Subsequently, in Table 4, the outcomes from the experimental investigation confirmed the outcomes from the IPM-SEPAD application. In the table, model B came out best from the IPM-SEPAD application as the most sustainable with the highest sustainable performance value for external benefit, energy efficiency and material efficiency criteria. Similarly, model B emerged the most sustainable under external benefit, energy efficiency and material efficiency criteria in the experimental investigation. Therefore, the outcomes from the IPM-SEPAD application were validated with the outcomes from the experimental investigation as shown in Table 4. Thereby positions the IPM-SEPAD as an effective and robust assessment method for the sustainable performance assessment of the building envelope and sustainable envelope design with capability of achieving building sustainability.

Table 4. IPM and experimental investigation outcomes comparison

MODEL COMPARISON	IPM OUTCOMES	EXPERIMENTAL OUTCOMES
	Most sustainable Model	Most sustainable Model
External Benefit	Model B	Model B
Energy Efficiency	Model B	Model B
Material Efficiency	Model B	Model B

In terms of the energy efficiency, material efficiency and external benefit performance, model B with clay wall and corrugated standing seam sheeting roof components emerged the most sustainable followed by model A and then model C. These results from the experimental investigation were validated with the outcomes from the IPM-SEPAD application, where an envelope design alternative B with clay wall and corrugated standing seam sheeting roof emerged the most sustainable envelope design alternative.

7. Conclusion

A good assessment tool must possess the right framework and be able to assess the level of sustainability in building. As such, in the experimental investigation outcomes, model B performed best in thermal comfort as shown by its indoor air temperature, indoor relative humidity and indoor dew point temperature performance when tested with and without A/C. Also, the model has the best energy efficiency performance as indicated by its actual energy consumption performance. Besides, the model is the most sustainable in terms of material efficiency with the lowest thermal conductivity, highest density, highest moisture absorption drying rate and lowest condensation potential. Consequently, the analysis results in the following conclusions: first, the model with clay masonry wall has the most significant impact on the envelope energy efficiency performance. There was a significant reduction in the actual energy consumption of model B during the daytime and night time and has the highest heat storing capacity. Also, model B significantly reduced the impact of the outdoor temperature on the indoor environment, thereby recorded the lowest indoor temperature and energy consumption rate when tested with A/C. Besides, model B has the most energy efficient and sustainable envelope materials as reflected in the data analyzed with more energy available for cooling in terms of its relative humidity performance than other models. Secondly, model B materials exhibited the best performance in maintaining and sustaining an acceptable indoor thermal comfort conditions when tested without A/C in terms of indoor temperature, indoor relative humidity and indoor dew point temperature performance. This was reflected in the data as its indoor air temperature during the daytime was significantly less than the outdoor temperature, with the most acceptable indoor relative humidity and indoor dew point temperature. Thirdly, Model B has the best materials efficiency performance as reflected with its condensation potential, thermal mass and durability performance. Model B has the lowest relative humidity far below the 100% required for condensation to occur, the best thermal mass performance, the highest heat retention capability, the highest density and the best durability performance in terms of moisture absorption and drying rate. Overall, model B with clay masonry wall and corrugated standing steam sheeting roof recorded the best sustainable performance and has the highest efficiency performance in reducing the impact of external factors such as sun, rain, pollution and extreme fluctuating climatic conditions on the indoor environment. To this end, the outcome from the IPM-SEPAD application and the experimental investigation agreed that envelope model B, either envelope design alternative B or physical envelope model B with a combined sustainable performance from clay wall and corrugated standing seam sheeting roof is the most sustainable. Based on the outcomes from the validation studies presented in this paper, it was concluded that the IPM-SEPAD is robust and effective in carrying out the sustainable performance assessment and design of the building envelope for building sustainability. Thereby provides an effective assessment method for building professional to aid the integration of sustainable development values into a decision making framework for the assessment and design of sustainable residential building envelope in Trinidad and Tobago, wider Caribbean region and Tropical regions towards achieving building sustainability. The IPM-SEPAD will help to promote sustainable practices in the construction industry, green building, green economy and building energy efficiency. Beyond these benefits, IPM-SEPAD can be further developed into a plug in application software and used along with Building Information Management (BIM) tools such as AUTOCARD, building design software such Smart Draw's building design software, Eco designer software and building maintenance tools where the life cycle performance and the sustainable performance of different envelope designs need to be assessed for selection purpose. However, there is a need to further undertake the tests under wet raining climatic conditions for better performance comparison and validation.

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Different Methods in Building Envelope Energy Retrofit

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Abstract

With about 40% of energy consumption in U.S.A in 2011 consumed by Residential and Commercial sectors, different energy retrofit measures that lead to reduction in energy consumption for these sectors can result in a significant change in total energy consumption nationwide. Therefore, it is important to study the existing energy retrofit methods and investigate how effective these methods can be. These measures can be categorized into three main groups, including energy retrofit and improvement of the building envelope, mechanical, and electrical systems. This paper focuses mainly on different methods of building envelope energy retrofit. Examples of such methods include installation of exterior insulation such as rigid foam to wall or roof, installation of cool/warm roof, reducing air infiltration, changing window properties such as SHGC, application of PCM and Aerogel in different envelope components, and adding overhangs. The required data for this study are obtained from experimental and numerical studies available in the literature. Moreover, a computer model is developed using BEopt to study and compare the effectiveness of single and multiple retrofit methods in a residential building.

Keywords: Energy analysis, opaque envelope retrofit, exterior insulation, air infiltration, Residential and Commercial Buildings

Introduction

About 40% of energy consumption in U.S.A in 2011 has been by residential and commercial sectors. The resources that provide this energy include petroleum, natural gas, coal, and renewable energy that supply 16%, 75%, less than 1%, and 8% of the required energy, respectively (EIA, 2015). Based on the 2009 U.S. data, space conditioning, domestic hot water, and refrigerators have consumed, respectively, about 48%, 17%, and 5% in residential sector. The remaining 30% is consumed by appliances, electronics, and lighting. Energy consumption due to space conditioning varies depending on climate zones and age of home, because besides HVAC system, envelope systems are also responsible for the level of energy consumed for space conditioning. For example, about 25% to 35% of energy for space conditioning is wasted due to inefficient window systems (Oldfield et al. 2015). This is approximately equivalent to 6% of the total energy consumption of the nation. Energy consumption of residential buildings due to space conditioning is approximately 38% and 55% for Marine and Very Cold climate zones, respectively. Residential buildings constructed before 1940 use about 54% of the energy for space conditioning, while consumption is about 43% for houses built from 2000 to 2009. This shows how important and effective energy retrofit of building envelope of existing deficient residential and commercial buildings could be. Different energy retrofit measures can be considered in three main retrofit categories of building envelope, mechanical, and electrical systems. This paper is focused on the first category and mainly discusses different methods of building envelope energy retrofit that could be carried out on opaque and transparent components of existing buildings such as improving wall insulation or enhancing thermal performance of window systems. This paper also compares effectiveness of different energy retrofit methods based on available information in the literature.

Literature Review

In developed countries, the share of energy consumption of residential and commercial buildings is between 20% and 40% of total energy consumption (Pe´rez-Lombard et al., 2007). Energy consumed by residential buildings accounts for 22% of the total energy consumed annually in the U.S. In residential building sector, 42% of energy consumption is due to heating and cooling loads, while 36% is due to heat gain and losses, which is affected by building envelope. Most homes built before 1980 in the U.S. have either no insulation or at most up to R-11. Based on the data provided by the U.S. census, about 60% of existing homes fall in that category (Cooperman et al. 2011).

Energy retrofit can be simply categorized into conventional and deep energy retrofit. In conventional energy retrofit, usually simple and fast methods are used and different systems are considered separately (Zhai et al. 2011). For deep energy retrofit, however, a whole-building retrofit approach is usually considered. In order to decide on energy retrofit measures and options, it is useful to perform an energy audit beforehand. Accordingly, ASHRAE suggests three levels of energy audit for commercial buildings. In order to conduct a deep energy retrofit, it is required to do Level III analysis. Level I, which is also called simple audit, includes review of utility bills and walk-through the building. In Level II, detailed analysis of energy use for base loads, seasonal variation, and effective energy cost for different systems such as "Building Envelope, Lighting, Heating, Ventilation, and Air Conditioning (HVAC), Domestic Hot Water (DHW), Plug Loads, and Compressed Air and Process Uses (for manufacturing, service, or processing facilities)" are studied (microgrid-solar, 2010).

Conventional retrofit measures

Different insulation materials are available for energy retrofit of a building. The thermal conductivity of the conventional insulation materials ranges between 0.023 and 0.068 W/m-K. Depending on the energy retrofit method, a variety of materials can be used in different components of a building. For example, in a study with two different target objectives of cost-optimal and net-zero energy retrofit of a building, adding insulation to the exterior wall, roof and floor, and replacing windows are considered viable energy retrofit scenarios. For the former, Ferreira et al. (2014) used EPS in wall retrofit and XPS for roof and floor retrofits. The PVC frame and double glazed window were also considered as part of the window replacement in these retrofit scenarios (Ferreira et al. 2014). One of the easy methods to increase the R-value of a wall system is to add an exterior foam insulation. For example, R-etro system that includes expanded polystyrene (EPS), plastic clips, galvanized steel starting track, and fasteners provides an additional R-18 insulation to a wall system, which is good enough for avoiding condensation behind the new layer in cold climate zones. The retrofit design would also need providing a ¼" gap behind the foam and the existing wall by placing base plates in the ties, which can be used as a drainage system for any intruded water behind the insulation layer. Finally, it is easy to install different types of siding over the foam layer (Holladay, 2009).

Energy retrofit of building envelope systems is not limited to adding insulation material. For example, in the "overcoat" energy retrofit approach applicable to roofs, the retrofit consists of adding insulation and providing a space above it for ventilation. There are also less conventional materials used in energy retrofit of historical buildings. Pertosa et al. (2014) studied the application of 10 cm insulation layers made of reed over a cement plaster finish. There is also innovative tile system used in this study that has 15% higher reflectance but has the same visual appearance (Pertosa et al., 2014). There are series of reports based on studies conducted by Pacific Northwest National Laboratory for the Department of Energy that investigate different energy retrofit methods. In a study on office buildings (PNNL, 2011), the energy retrofit options for building envelope include adding exterior window film, exterior window shading and light shelves, wall and roof insulation, vestibule, installing cool roof, and replacing windows. Other methods used in other studies conducted by this research institute include installing low solar gain window films, adding continuous air barrier to exterior walls, installing high R-value roll-up receiving door, and adding window overhangs (PNNL, 2013). Depending on the building location, existing envelope systems, climate zone, etc., the energy retrofit might be focused on different components.

New retrofit measures

There are research programs such as EASEE (Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-story, multi-owner residential buildings) devoted to finding innovative and preferably modular solutions for energy retrofit of existing residential buildings. Two prototype prefabricated shapeable retrofitting panel systems were proposed by this group including a single layer XPS with surface finishing and composite EPS panel coated on both sides with textile reinforced mortar (TRM) (Masera et al., 2014). These thermal insulation products can be applied on both external and internal surfaces, but the software models developed by TRNSYS show that using external insulation has 8% better energy performance, while the internal thermal insulation leads to 50% less investment cost and lower payback period (Kolaitis et al., 2013). Retrofit of building envelope can include façade retrofit. For example, one study discusses the use of multi-functional energy efficient façade system (http://www.meefs-retrofitting.eu) for residential buildings in cold climate regions (Paiho et al. 2015). Another type of façade system for energy retrofit is called Active Solar Thermal Façades (ASTFs), which can function as both a building envelope and solar collector component. Zhang et al. (2015) classified different ASTFs based on different methods, which shows that the ASTFs can be used as part of walls, windows, balcony, sunshield, or roof (Zhang et al., 2015).

While most innovative systems have been developed for wall retrofit, there are also a few approaches specific to roofs, one being "cool roof", which basically reflects the sunlight. This requires the surface to have high reflectance and thermal emittance, which is more useful for warm climates as it helps to absorb less heat (Levinson, 2009). Also, there are other alternatives such as Cool-Green roof. A research that uses Helichrysum Italicum plant for the green roof shows that it reflects about 44% of the solar radiation, which is about 4% more than a conventional concrete roof. It also reduces the number of the overheating hours in summer by 98% (Pisello et al., 2015).

Beside R-value, the concept of thermal inertia is also important. The difference between thermal inertia and thermal insulation is that the thermal inertia slows down the changes in temperature by absorbing the thermal energy for later use (release), while the thermal insulation slows down the heat transfer without storing the thermal energy. As a result, the temperature changes within the materials with thermal inertia are more significant. Smart materials such as phase change materials (PCMs) have thermal inertia and can be used for this purpose. The PCM is activated when the temperature reaches a certain level (typically between 23 and 26^{o} C), which means the PCM undergoes a phase transition by absorbing the heat. Phase transition could be from solid-solid, solid-gas, solid-liquid, or liquid-gas. The opposite phase transition occurs when the ambient temperature reaches the set point that is typically the night temperature. These materials can be used in walls, floors, and ceilings with operating temperature range of 20 to 35^{o} C (Casini, 2014). There are different types of PCMs with different latent heat and fusion point that are presented in Table 2.

Application of PCMs can be in two categories of micro- or macro- encapsulation, where the latter can be in the form of tubes, spheres, panels as containers, while in the former, polymer films are used as the container, and the diameter of these particles are less than 1 mm. They can be mixed with building products such as plaster, screed, concrete, gypsum, acrylic paints and wood products such as MDF and OSB (Casini, 2014). Typical building applications of this material include the following: adding Micronal PCM to plaster, gypsum boards, or plasterboards; integration within counter ceiling using prepackaged panels or bags, applying under the floor finish such as under the radiant floors; applying plaster or panel over the exterior side of the walls or roofs; applying on Trombe walls or solar greenhouses as screeds or panels to increase heat gain; and applying inside insulating glass.

An example of more innovative exterior retrofit system is external thermal insulation composite system (ETICS). The final finish over the added insulation layer can be made of other innovative materials such as plasters containing phase change material (PCM). In a research study in Italy (Ascione et al., 2014), a 3 cm wallboard was installed on the inner face of the wall containing PCM with melting point of 27^{o}C, and plaster containing PCM with melting point of 32^{o}C was applied on the exterior of an educational building. The results show that using these materials accompanied by replacing windows with low-e windows and new roof insulation materials can lead to up to 38% reduction in energy consumption of this building. Application of PCM wallboard is investigated in another study using a mathematical model that is available in EnergyPlus. The benefit of applying two layers of PCM plaster with different melting point is that individual layers can be activated in either summer or winter, which has resulted in a maximum impact of about 6% decrease in annual energy consumption (Ascione et al., 2014). However, it is observed that using microencapsulated PCM in construction materials such as concrete can decrease the compressive strength by 25% although it increases the latent heat by 35% (Narain et al., 2015).

Nanotechnology that helps making materials on the size scale of between 1 and 100 nanometer (nm) can be used for insulation applications as well. The thermal conductivity of the materials manipulated based on this technology can be about 0.004 W/mk. As one of these materials, Aerogel is a “solid nanoporous material with ultra-low density obtained by the dehydration of a gel by replacing liquid component with a gaseous one” (Casini, 2014), which can be obtained from different sources such as silicon, aluminum, chromium, tin, or carbon, but the most used is silica-based. Table 1 compares the properties of silica aerogel with glass. There are some products in the form of aerogel insulation mats that can be applied as underfloor and enhance the thermal properties of floors. There are also some panels with thermal conductivity of 0.013 W/mk that can be applied on the wall outer face. There are more options for interior walls such as rolls, semi-rigid panels, and pre-coupled gypsum boards. The latter consists of aerogel base felt coupled with gypsum active-air ® slab. These materials are still about 8-10 times more expensive compared with more conventional insulation materials (Casini, 2014). Energy modeling and analysis using Designbuilder showed that adding aerogel and replacing windows resulted in reducing energy loss through walls, uninsulated attic, windows and doors, and uninsulated ground by 35%, 25%, 25%, and 15%, respectively (Filate, 2014). Also, replacing cement plaster finishing material with 5 cm SLENTITE aerogel insulation board from BASF chemical company with thermal conductivity of 16 mW/(m.k) led to 71% reduction in energy loss through walls (Filate, 2014). Moreover, flooring panels consisting of ThermablokSP aerogel insulation board covered by rigid Magnesium Silicate that is a breathable, impact resistant, and thermally efficient material were used in this project. The total U-factor for the final retrofitted slab turned out to be 0.42 W/(m^2.K) (Filate, 2014).

Double-skin façade is another new energy retrofit method. The second layer is basically an additional façade over the existing façade that is transparent. The space between these two layers acts as an insulation layer that is heated up by solar radiation, and it can be ventilated if over-heated (Kim et al., 2014). Ma et al. (2012) also studied the state-of-the-art in energy retrofit of existing buildings and summarized key findings of multiple studies. The major methods observed in these studies include infiltration reduction, installing green roof, windows upgrading; using insulated reflective barriers, ceiling insulation, foundation insulation, roof insulation, air sealing and replacement of doors, and wall retrofits including replacing the cladding, adding exterior insulation, and installing house wrap over the exterior walls (Ma et al., 2012). Table 3 summarizes different energy retrofit methods that are reviewed in this paper and also the methods used in multiple case studies are summarized in Table 4.

Table 1. Comparison of the properties of silica aerogel with glass (Adopted from Casini, 2014)

Properties	Silica Aerogel	Glass
Bulk Density (kg/m^3)	5-200	2300
Internal surface area (m^2/g)	500-800	0.1
Refractive index at 632.8 nm	1.002-1.046	1.514-1.644
Light transmission at 632.8 nm	90%	99%
Thermal expansion coefficient at 20-80 ^{0}C (1/C)	2×10^{-6}	10×10^{6}
Thermal Conductivity at 25^{o}C (W/mK)	0.016-0.03	1.2
Sound speed in the medium (m/s)	70-1300	5000-6000
Acoustic impedance (Kg/m^2/s)	10^4	10^7
Electrical resistivity (Ωcm)	1×10^{18}	1×10^{15}
Dielectric constant 3-40 GHz	1008-227	40-675

Table 2. Different types of PCMs and their latent heat and fusion points (Adopted from Casini, 2014)

Material	Fusion temperature (^{o}C)	Latent Heat (kJ/kg)
Paraffin	6-76	170-269
Non paraffin	8-127	86-259
Fatty acids	17-102	146-242
Salt hydrates	14-117	68-296
Eutectics	15-82	95-218
Water	0	333

Table 3. Summary of the energy retrofit methods applied on the building envelope

Reference	The objective, building type, or the location of the study	Proposed retrofit measures	Saving determination method	Major results
Ojczyk	-	Exterior Thermal & Moisture Management System (ETMMS)	-	Decrease in ice damn formation and energy consumption
PNNL, 2011	Office Building	Exterior window film, exterior window shading, add wall insulation, roof insulation, and cool roof	-	Decrease in energy consumption
Pertosa et al.	Historical building	Application of insulation layer made of reed and innovative tile system	EnergyPlus model	Decrease in energy consumption
Masera et al.	Development of innovative systems	Single layer XPS with surface finish & composite EPS panel coated on both sides with textile reinforced mortar		
Kolaitis et al.		Thermal insulation composite panels	TRNSYS model	Better energy performance by 5%
Paiho et al.	Cold climate region of Finland and Russia	Application of two different multifunctional energy efficient façade system (Meefs) including Advanced Passive Solar Collector & Ventilation Unit Technological Unit (APSC&VU TU) and Advanced Solar Protection & Energy Absorption Technological Unit (ASP&EA TU) that work based on thermal storage and phase change material.	EnergyPlus model	
Zhang et al.	Classification of different ASTFs	Application of Active Solar Thermal Façade (ASTFs) as a building envelope component.	-	-
Pisello et al.	A residential building in Italy	Application of cool-green roof	-	Reduction in overheating hours by 98%
PNNL, 2013	School	Adding exterior insulating finish system (EIFS), replacing windows, rigid insulation on roof, and slab insulation	-	-
Evola and Margani	Apartment in Italy	Application of external thermal insulation composite system (ETICS) containing stone wool and building integrated PV (BIPV)	DesignBuilder model	Decrease in heat loss through walls by 85%
Ascione et al., 2014		Application of PCM as a plaster over the ETICS, replacing windows, new roof insulation		Reduction in energy consumption by 38%
Ascione et al., 2014		Application of PCM wallboard	EnergyPlus	Reduction in annual energy consumption by 6%
Boarin et al.	Historical building	Application of innovative tile system with higher reflectance rate		
Casini et al.	Materials and systems containing PCM and aerogel	Application of different products containing nano material such as aerogel. These products include aerogel underfloor mats, panels, and pre-coupled gypsum boards with aerogel. Application of Micronal PCM to plaster, Trombe walls, and etc.		
Filate et al.	Office building	Application of Nanogel® Aerogel insulation plaster, ThermablokSP board, and SLENTIT aerogel insulation board.	-	71% reduction in energy loss through walls
Kim et al.	-	Application of double-skin façade		

Table 4. Summary of the energy retrofit methods and their results in different case studies

Case Study	Envelope Retrofit Methods	Notes
Kosny et al.	high R-value exterior foam sheathing, triple-glazed windows passive solar heating from glazed sunspaces	three liters of heating fuel consumption per square meter per year after the energy retrofit
Morelli et al.	Using aerogel-stone wool mixture and vacuum insulated panels on walls Improving windows thermal properties	68% of energy saving after applying multiple retrofit systems including mechanical measures
German et al.	addition of R-13 dense-pack cellulose in wall cavity R-12 polyiso over the slab R-38 polyiso over the roof deck Triple-pane glazing	40% of energy saving after applying multiple retrofit systems including mechanical measures
Harrington and Carmichael	Using windows consisting of using suspended coated film and gas fill addition of reflective barriers behind radiators	32% of energy saving after applying multiple retrofit systems including mechanical measures
Hagerman	Improving air tightness high density cellulose and EPS added to the existing wall cavity	It was aimed for annual heating and cooling energy consumption of less than or equal to 4.75 kBtu/sf/yr
Aste and Del Pero	replacing the glazing system with argon filled double pane glass installing shading system and installing dynamic double skin façade installing ventilated façade consisting of an air gap behind the stone façade installing stone façade to work as thermal mass and glass wool as insulation	40% of energy saving after applying multiple retrofit systems including mechanical measures and solar panels.
Home on the Range	addition of exterior insulation over concrete block walls replacing the windows with low-e glazing system The exterior walls and roof were also painted a light color	Ended up with energy consumption of 46 kBtu/sf/yr after applying multiple retrofit systems including mechanical measures
Beardmore Building	adding extensive insulation to the exterior walls adding R-50 insulation in roof cavities add insulated low-e glazing system in the interior high solar reflectance material converting the roof to a cool roof	Ended up with energy consumption of 32 kBtu/sf/yr after applying multiple retrofit systems including mechanical measures
Aventine	EPA cool roof was installed	Ended up with energy consumption of 23 kBtu/sf/yr after applying multiple retrofit systems including mechanical and electrical measures
Alliance for Sustainable Colorado	a Mylar film was applied on the interior of curtain walls to reflect up to 60% of the heat during sunny days and reduce the internal heat loss in the winter	Ended up with energy consumption of 42 kBtu/sf/yr after applying multiple retrofit systems including mechanical and electrical measures
200 Market building	includes addition of 2 inches Polyisocynurate insulation with a white asphalt cap on the roof translucent cloth shades were used on the single pane window to reduce heat gain and infiltration	After both envelope and mechanical retrofit methods the energy saving is about 30%
Rocky Mountain Institute (UCLA)	using high-performance ultra-clear glazing adding horizontal shading configuration Adding R-15 batt insulation behind the masonry-clad brick	After both envelope and mechanical retrofit methods the energy saving was estimated to be 457,353 kWh per year
Rocky Mountain Institute (Stanford)	adding lightweight external sunshades	After both envelope and mechanical retrofit methods the energy saving was estimated to be 654,500 kWh per year
Rocky Mountain Institute (DMW)	Using double layer façade	After applying both envelope and mechanical retrofit measures annual energy use reduction is estimated to be 3,712 MBtu
Chang et al.	Adding R-10 spray foam over masonry walls, R-35 to roof, and cool roof	Other measures including mechanical and electrical were also used

Numerical investigation of different envelope retrofit methods

In this section, the effect of some energy retrofit measures on building envelope systems that were summarized in the previous section will be studied in order to quantify the influence of each method and compare their performances in different climate regions. In order to study the effect of different retrofit scenarios, a computer model is used and the results are compared with a benchmark house. The B10 Benchmark house in BEopt is used for this purpose (BEopt, 2016). All retrofit scenarios studied in this report are with regards to the building envelope energy performance improvement, including but not limited to application of exterior insulation, window film, roof insulation, advanced façade system, PCM materials, materials with higher reflectance, and materials containing aerogel. Several studies have considered benchmarks or reference houses with different properties. The floor area of houses built in the north-east between 1990 and 2000 ranges between 2105 ft^2 and 2435 ft^2, with typical site-built homes having 2.5 bathroom, 3 bedroom, full or partial basement, wood framing, vinyl siding, and 2 stories (U.S. Department of Commerce, 2014). The building properties related to the building envelope of the benchmark house in BEopt are presented in Table 5. Full basement is not included in the square footage; however, it has the same area as each of the two stories.

Table 5. The building envelope properties of the benchmark house defined in BEopt

Component/System	Properties	R-value (h.ft^2.R/Btu)	Cost ($/ft^2)	Lifetime (Years)
Wall	R13 Fiberglass batt, 2×4, 16 in O.C. Framing Factor = 0.25	11.4	2.54	
Wall Sheathing	OSB		1.29	
Exterior Finish	Vinyl, Light Solar Absorptivity = 0.3	0.6	2.67	30
Unfinished Attic	Ceiling R-30 Cellulose Vented, Insulation thickness = 8.55 in Framing Factor = 0.07	31.3	1.42	
Roof Material	Asphalt Shingles, Medium Color = medium Absorptivity = 0.85 Emissivity = 0.91		1.78	30
Slab	Uninsulated			
Carpet	80% Carpet	2.08		
	0.5 in Drywall		0.65	
Exterior Wall Mass/Partition Wall Mass/Ceiling Mass	Sensible Capacity (Btu/F.ft^2) = 0.42			
	15%			
Window to Wall Ratio (B, F, L, R)	Perimeter/Area Ratio = 1.41			
Windows	Medium-Gain and Low-E Non-metal Frame Double-Pane and Argon-Fill	2.86	22.4	30
				30
Door Area/material	20 ft^2 Fiberglass - Swinging		14	

From the summary of various building envelope energy retrofit methods reviewed in this report, eight different retrofit scenarios listed in Table 6 are considered in this simulation study.

Table 6. Different energy retrofit methods used for computer modeling

No.	Energy Retrofit Method	Required change in computer model	No.	Energy Retrofit Method	Required change in computer model
1	Exterior insulation	Change in wall R-value by adding exterior insulation	4	Roof insulation	Change in roof R-value
1-1	Thermal insulation composite panel		5	Slab insulation	Change in slab R-value
2	Exterior window film	Change in window properties	6	PCM as plaster or wallboard	Change in thermal mass properties
3	Cool roof	Change in roof reflectance properties	7	Components containing or coated by aerogel	Change in wall and slab R-value
3-1	Tiles with higher reflectance		8	Decreasing air leakage	Change in air leakage properties

The analysis results of all the retrofit methods presented in Table 6 are explained in this section. Figure 1 through Figure 8 are obtained directly from BEopt and contain useful data that need to be interpreted to evaluate the impact of single and multiple energy retrofit methods. There are both electricity and gas as main energy resources for this building, therefore the energy consumption outputs are categorized into two types based on the energy source. For example, Figure 1 shows the required energy for Hot Water and Heating as provided by Gas (G) while other energy consumption components based on Electricity (E). The locations considered in this study are assumed to be in cold climate region, therefore, the heating load is the dominant energy consumption source. Some of the source energy consumption components do not change between different retrofit methods such as Lights, Large (Lg) Appliances, and Misc. The vertical axis shows the source energy consumption (vs. site energy consumption) in Million BTU per year, and the horizontal axis shows different retrofit cases. However, show the annualized energy related cost (AERC) versus the source energy saving. It should be noted that in BEopt the energy related cost includes both energy bill and loan cost (based on 30 years) that means the construction costs are also considered. All retrofit cases in this section are compared with the benchmark house in Table 7. The difference in initial construction cost and energy saving percentage compared with benchmark house is presented.

Adding exterior insulation

The first energy retrofit scenario studied is the effect of adding exterior insulation. Adding exterior insulation should increase the R-value of the wall system and decrease both heating and cooling loads by slowing down the heat flow through conduction to and from the interior space. Different scenarios are considered for exterior insulation, including R-5 XPS, R-10 XPS, R-15 XPS, R-6 Polyiso, and R-12 Polyiso, where all options include a layer of OSB. In the discussion that follows, the scenarios are referred to as Point and the benchmark house is shown as User-defined option in all figures. Figure 1 shows the results, where Points 1 through 5 refer to R-5 XPS, R-10 XPS, R-15 XPS, R-6 Polyiso, and R-12 Polyiso, respectively. It can be observed that R-15 XPS (Point 3) led to the lowest energy consumption, followed by R-12 Polyiso, R-10 XPS, R-6 Polyiso, and R-5 XPS. Table 7 summarizes the output in terms of construction cost and energy consumption. It can be observed that construction cost can increase up to $3,200 and energy saving would be up to 10.8%.

Increasing SHGC of windows

The next energy retrofit method is adding a layer of window film that changes the solar heat gain coefficient (SHGC). In general, in cold climate regions where the heating load is more dominant, it is more desirable to have larger SHGC in order to reduce energy consumption. The low, medium, and high solar heat gain coefficient (SHGC) values considered are 0.3, 0.44, and 0.53, respectively. Figure 2 shows the energy analysis results. It can be observed that there is no significant change in the annual energy consumption. The energy consumption for the 0.3, 0.44, and 0.53 values of SHGC corresponds to Point 2, User-defined point, and Point 1, respectively. The magnitude of these effects also depends on the window area and these percentages could be higher or lower in other cases with different window areas. Table 7 summarizes the energy consumption and construction cost. It can be observed that energy saving of about 0.1% compared with benchmark house is insignificant.

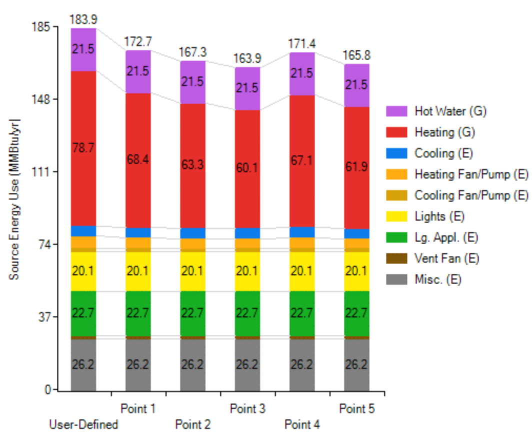

Figure 1. Comparison between different exterior insulation scenarios in terms of energy consumption

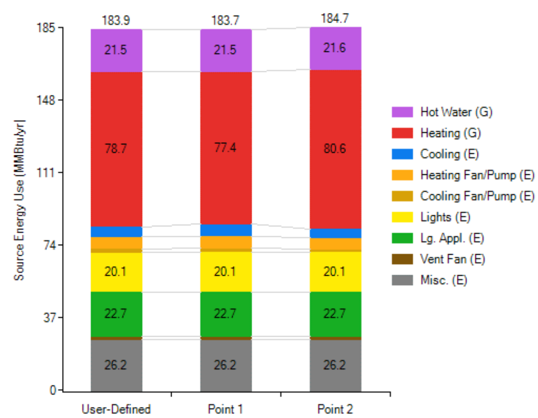

Figure 2. Comparison between the energy consumption for different glazing systems with different SHGC

Adding roof insulation

The next energy retrofit method is increasing the roof R-value, which in this case R-49 and R-60 are the assumed retrofit targets. Different materials considered for improvement of wall R-value include blown-in cellulose, closed cell, and open cell spray foam. In the first scenario, R-11 and R-22 cellulose will be added to the existing insulation, while other scenarios will replace the whole existing insulation with spray foam insulation. Figure 3 shows the results of the analysis, where Points 1 through 6 correspond to R-49 & R-60 cellulose, R-49 & R-60 closed cell spray foam, and R-49 & R-60 open cell spray foam. It can be observed that the change in energy consumption would be up to 1.3% between the benchmark house and other retrofit scenarios. Based on the initial cost estimation outputs, the difference between the benchmark house and the lowest cost (for cellulose) and the highest cost (for open cell spray foam) is $500 and $6,000, respectively. Table 7 presents the summary of the outputs and shows that compared with previous single retrofit methods, it has relatively higher impact in energy consumption.

Different roofing materials

The studied house is located in a cold climate region and the heating demand is higher than cooling; therefore, it was decided to use the same concept and model the material with higher solar radiation absorptivity to decrease the heating load; this is what we may consider a warm roof. The absorptivity of roofing material in benchmark house is 0.85 that is relatively high. Also white metal, dark asphalt shingles, and dark metal with absorptivity of 0.3, 0.92, and 0.9 are modeled, respectively. In Figure 4, Points 1, 2, and 3 correspond to dark asphalt, dark metal, and white metal, respectively. The initial cost difference between the minimum cost (dark asphalt) and maximum cost (white/dark metal) is about $1,200. Table 7 shows the summary of the energy modeling results for different roofing materials. Again, it can be noticed that the energy saving percentage is low.

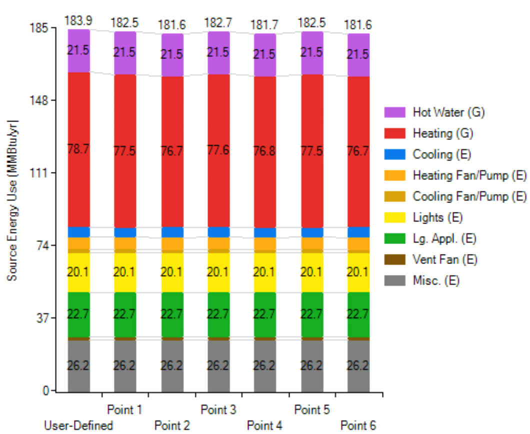

Figure 3. Comparison between energy consumption of different roof insulation

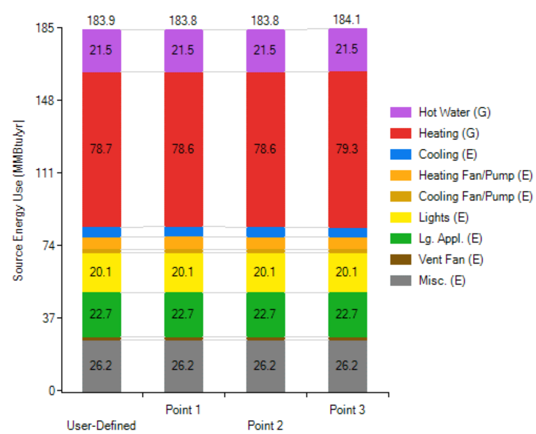

Figure 4. Comparison between energy consumption of different roof material with different solar radiation absorptivity

Adding slab insulation

There is no option in BEopt to add insulation for floor slabs. In this study, a carpet was assumed (as additional insulation) to cover 100% of the floor area as opposed to the benchmark house that is assumed to have a carpet covering 80% of the floor area. Based on the available information in BEopt different scenarios to investigate the effect of this retrofit method include using R-10 and R-20 fiberglass batt with a cost of \$0.24, and \$0.48 per ft^2, respectively. Figure 5 shows the energy performance of two different retrofit scenarios, including adding R-10 (Point 1) and R-20 (Point 2) fiberglass batt to the slabs. The results show that there is no significant improvement in terms of energy consumption, and the source energy saving is less than 1%; however, it still leads to 2.3 MMBtu saving in annual energy needs for heating. Table 7 summarizes the outputs.

Application of PCM

The PCM application method investigated here is limited to using PCM plaster as a coating material over an existing wall sheathing such as drywall or PCM wallboards that has embedded PCM capsules. To model these options, BEopt has two options to model drywall impregnated with PCM or PCM application on drywalls and these options are available for exterior wall, partition wall, and ceiling that can be covered with either of these components. The floor area considered for the interior walls is assumed to be 2232 ft^2, which is based on the floor area for two stories. Figure 6 shows the energy consumption of the benchmark house and two other retrofit scenarios, a house with external wall, partition wall, and ceiling covered with PCM drywall (Point1) and one with PCM coated drywall (Point 8). The results show that both scenarios can lead to lower energy consumption up to 4 MMBtu/year. However, the cost estimate outputs shows that the difference in initial construction costs between the benchmark house and two retrofit scenarios for points 1 and 8 are about \$55,200 and \$13,300, respectively, which are much higher construction cost compared with the benchmark house that is about \$59,000. Table 7 also presents a summary of the results.

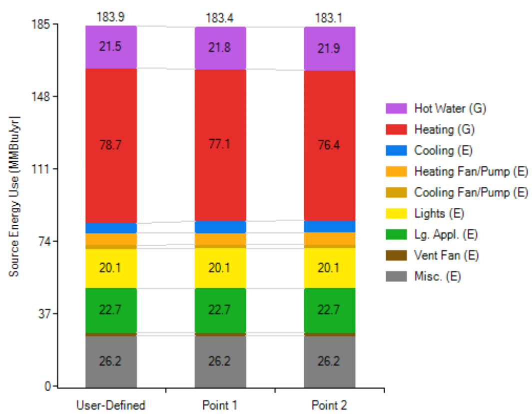

Figure 5. Comparison between energy consumption of different slab retrofit scenarios

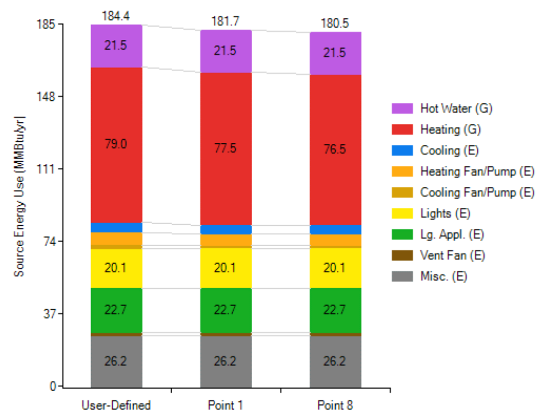

Figure 6. Comparison between energy consumption for two different scenarios of using PCM drywall and PCM coated drywall

Application of aerogel

The next method is application of layers of aerogel over walls, floors, and ceilings or adding panels containing aerogel. Based on two recent studies (Filate , 2014 & Casini, 2014), it was decided to define aerogel with thermal conductivity of 0.016

W/(m.K), which means an inch (2.54 cm) of aerogel would be equivalent to an R-value of about R-10. Also, it was assumed that the retrofit would include adding extra R-10 (1 inch of aerogel) to the walls and floors. The approximate cost of 10-mm thick aerogel blanket is $5.5/ft^2, which means that for an inch of aerogel, it will be about $14/ft^2 (http://www.buyaerogel.com/ & Shukla et al., 2011). The benchmark already has 80% coverage of R-2.1 carpet; therefore, a new layer of R-11.7 was defined for floors (80%×2.1 + 100%×10 = 11.7). While the labor cost for installing carpet is considered to be zero in BEopt, in this study, a labor cost of $0.5/ft^2 was considered in obtaining the total costs. Another scenario consisting of adding R-5 XPS as exterior insulation was also considered. As it can be observed in Figure 7, points 3 and 6 that correspond to walls with aerogel and floors without and with aerogel, respectively, show the minimum annual energy consumption compared to all other cases. The initial cost difference for these two new scenarios compared with the benchmark house is about $31,200 and $63,600, respectively. Although both scenarios lead to high energy saving (10.8% and 11.3%, respectively), the first scenario is relatively more economical with 52% increase in initial cost compared with the second scenario that leads to 108% increase in construction cost. As noted earlier, retrofitting of floors does not improve the energy performance significantly. Table 7 summarizes the results.

Decreasing air leakage

In this method, the difference in initial cost also includes the difference in HVAC sizing. Table 7 shows the properties of different scenarios considered for this retrofit method and it can be observed that despite the negligible difference in initial cost, the saving in source energy consumption can be up to 8.0% if the air leakage is decreased to 2 ACH50 from 7 ACH50. Table 7 also shows that point 2 (2 ACH50) leads to about 65 MMBtu/Year heating load.

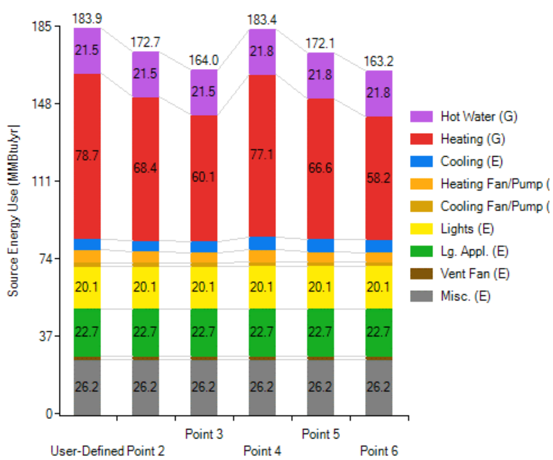

Figure 7. Comparison between energy consumption for different scenarios of using aerogel in floors/walls

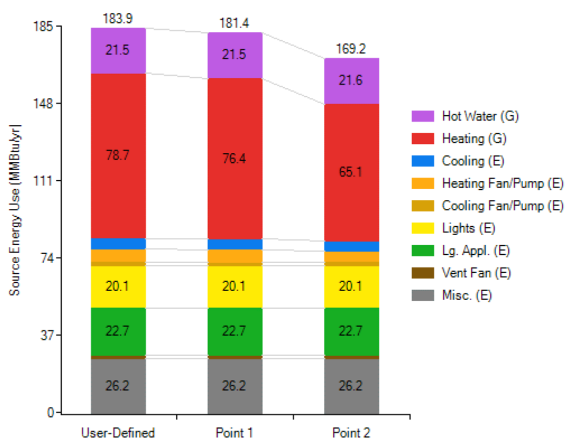

Figure 8. Comparison between energy consumption for different scenarios of air leakage

Summary of BEopt modeling and analysis results

Table 7 summarizes the source energy saving and construction cost of different single energy retrofit methods. It can be observed that single energy retrofit methods listed below can lead up to 11.3% or 10.8% source energy saving. However, the difference in initial cost is about $31,200 or $63,600, which is about 52% or 107% higher than the benchmark house, respectively. These two scenarios correspond to the application of aerogel in walls or floors, while there are other options such as adding exterior insulation that can save source energy by about 10.8% and keep the initial cost difference to about $3,200, which is only about 5.4% higher than the benchmark house. It is also observed that for cold climate regions such as Pennsylvania that heating seasons are dominant in terms of energy consumption, retrofit measures such as low SHGC windows, overhang, and white roof have negative impact on the annual energy consumption. Results about effectiveness of aerogel also show that walls that are retrofitted with aerogel have much higher impact on energy saving compared with floors.

Table 7. Summary of modeling different retrofit methods

Retrofit measure			Initial cost difference*	Source Energy Saving (normalized)**
Exterior insulation				
R-5 XPS			$1,200	6.1%
R-10 XPS			$2,200	9.0%
R-15 XPS			$3,200	10.8%
R-6 Polyiso			$1,000	6.8%
R-12 Polyiso			$1,800	9.8%
Window SHGC				
0.53 (High)			$-180	0.1%
0.30 (Low)			$-120	-0.5%
Roof Insulation				
R-49, Cellulose			$500	0.8%
R-60, Cellulose			$1000	1.3%
R-49, Closed cell spray			$3,700	0.7%
R-60, Closed cell spray			$4,800	1.2%
R-49, Open cell spray			$4,900	0.8%
R-60, Open cell spray			$6,000	1.3%
Roofing materials	Color	Absorptivity		
Asphalt Shingles	Dark	0.92	$0	0.0%
Metal	Dark	0.9	$1,200	0.02%
Metal	White	0.3	$1,200	-0.14%
Slab retrofit				
R-10 Fiberglass batt			$1,500	0.3%
R-20 Fiberglass batt			$2,100	0.4%
PCM application				
PCM Drywall			$55,200	1.5%
PCM coated Drywall			$13,300	2.1%
Air leakage				
5 ACH50			$130	1.3%
2 ACH50			$270	8.0%
Aerogel in wall	Aerogel in floor	XPS in wall		
-	-	✓	$1,200	6.1%

✓	-	✓	$31,200	10.8%
-	✓	-	$32,300	0.3%
-	✓	✓	$33,600	6.4%
✓	✓	✓	$63,600	11.3%

* Difference is calculated from the initial cost of the benchmark house that is $59,000.
** Negative sign shows increase in energy consumption compared with benchmark house.

Effect of climates

In order to investigate the effect of different single retrofit methods in various climates it was decided to do the analysis in two more locations including Boston, Massachusetts and Arlington, Virginia. Table 8 shows the annual energy consumed in each location. Figure 9 shows a few selected single retrofit methods that have higher impact on energy saving and the vertical axis shows the maximum annual energy saving on heating loads for different method in Million Btu compared with the benchmark house. It shows that using aerogel on exterior walls, exterior insulation, and reduction in air leakage lead to high reduction in heating loads and this value is larger in colder regions. Using PCM shows higher impact in relatively warmer regions however, it is not significant. Roof insulation, slab retrofit, and adding window film show a better performance in relatively colder regions.

Table 8. Annual energy consumption of benchmark house in different locations

Location	Annual Energy Consumption (MMBtu)
Boston, MA	79.7
Pittsburgh, PA	78.7
Arlington, VA	51

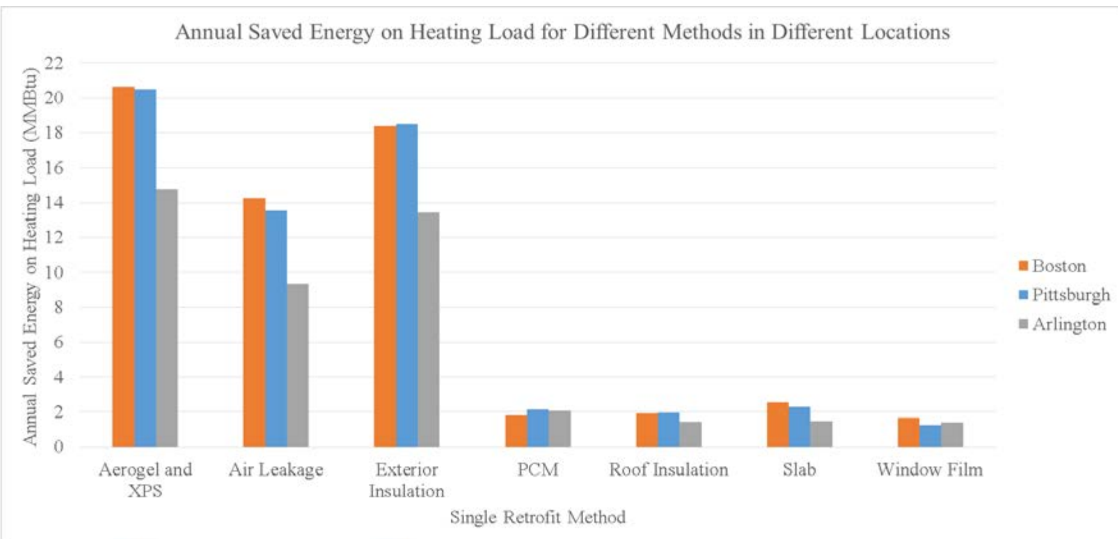

Figure 9. Annual saved energy on heating load for different single energy retrofit methods compared with benchmark house

Summary and Conclusions

Among different sectors that contribute to total annual energy consumption in the U.S., residential construction has 22% share. About 42% of this energy use is considered resulting from heating and cooling, while about 36% is due to heat loss and gain during heating and cooling season, respectively.

In order to study the effectiveness of several single energy retrofit options, computer models were developed using BEopt software package, which helped compare the total cost (including construction and energy related cost) and source energy saving percentage against a benchmark house. To define the properties of the benchmark house, the predefined benchmark house in BEopt was edited based on the census data for residential buildings in the U.S. between 1990 and 2000. Results show that single retrofit measures studied in this report can reduce the total source energy saving up to 11.3% such as using aerogel in walls and floors, however it can increase the construction cost up to 63%. On the other hand, application of R-15 XPS can lead to 10.8% source energy saving and limit the increase in construction cost to only 2.3% compared with benchmark house. There are also other methods that can improve the energy consumption up to 8.1% including decreasing the air leakage to 2 ACH50 from 7 ACH50. It also limits the increase in total cost to about $270 that is only about 0.33% increase in initial cost. Moreover, the results show that using certain retrofit measures can lead to increase in energy use such as windows with lower SHGC, and white roofing material. This can be understood by considering the climate region that the house is modeled for. In cold climate regions such as Pennsylvania, it is more important to have higher solar heat gain rather than preventing the solar radiation absorption because the heating season is the dominant one in terms of energy consumption. Other retrofit measures such as using PCM in different components as coating or encapsulation within sheathing materials can lead to 2.1% and 1.5% energy saving, respectively. Initial cost with respect to the benchmark house, however, can increase up to 20% and 90%, respectively. The highest impacts are related to adding exterior insulation, roof insulation, reducing air leakage, using aerogel and PCM; the first one is the most economical option specially compared with using aerogel and PCM. The results of the simulation study would depend on the properties of the house under study. In order to find the impact of these retrofit methods for other existing houses, appropriate computer modeling would be required. It should also be noted that other retrofit measures such as improving mechanical and electrical components can have significant impact in energy saving of residential buildings. Such retrofit options, however, were not within the scope of the present study.

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Out of Site: A Pedagogical Perspective of Emerging Transitions in Architectural Practice

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Keywords: Sustainable Development, Sustainable Design, Integrated Project Delivery, Integrative Design Process

ABSTRACT

Energy Efficiency is one of the five strategic themes of the Penn State Institutes of Energy and the Environment (PSIEE), which has supported a Sustainable Housing Initiative (SHI) that intends to leverage faculty and student expertise on residential building planning, design, and construction. The goal of this initiative is ambitious - to initiate a process that will radically transform the residential building sector, with partners that will scale-up innovation to a regional and eventually national or international scale. There is significant interest and expertise related to these ideals at the Pennsylvania State University notably within the Stuckeman School.

As a short-term agenda for the collaborative team of the Sustainable Housing Initiative, two classes worked in coordination with Penn State's Office of Physical Plant (OPP) and Housing, Food Services and Residence Life to improve the environmental performance of buildings on campus, particularly the new residence halls. The intended outcome of this challenge can be achieved as outlined below by approaching it through two different methods - curriculum and research; two strengths of Penn State.

As a curricular idea, a 'real' project was used to make suggestions from the sustainability standpoint to enhance a Request For Proposal (RFP) document for Trippe Hall, a proposed design-build residence hall project on the Behrend campus of Penn state. This project was chosen as a case study for projects assigned to Architecture and Architectural Engineering (AE) students in the fall semester of 2014. While the Architectural Engineering students in the ARCH 441 studio produced design proposals for Trippe Hall with a focus on environmental design using their expertise in building systems; the Architecture students in the ARCH 412 seminar class worked in a series of integrative design charrettes to develop presentations of sustainable strategies relevant to Trippe Hall. The two student groups worked in a collaborative manner – the ARCH 412 class acted as consultants on sustainable practices to help enrich the design projects of the ARCH 441 students. Both groups engaged with 'client' representatives from Penn State's Office of Physical Plant and Housing and Food Services on a regular basis.

The information gathered and analysis developed during this curricular effort are informing a larger agenda of the Sustainable Housing Initiative – the process of leveraging the University's strong research base to distill the lessons learnt from this collaborative project and understand the potential implications for the architecture, engineering and construction (AEC) industry.

CHALLENGES FOR SUSTAINABILITY IN THE HOUSING SECTOR

By 2030, the housing market in the U.S. will have added an estimated 58.9 million housing units that did not exist at the turn of the century (Nelson, 2006). This will create an enormous burden on existing finite natural resources, and some steps have been taken to implement policy change by raising the bar at both the government level (through more stringent ASHRAE and local building codes) and through organizations such as LEED, Green Globes, etc. While these systems are creating awareness about better construction practices and safer building materials, there is still some debate about whether they have caused a fundamental shift in the way buildings are designed and consequently the way they approach energy consumption reduction and sustainability. For example, the Residential Energy Consumption survey by the U.S. Energy Information Administration notes that newer homes (built post 2000) in the U.S. consume the same amount of energy as homes built prior to 2000; primarily because these newer homes are approximately 30% larger than the older ones. Therefore, in combination with the facts presented earlier; we can assume that energy consumption by the residential sector has only increased over the years notwithstanding the efforts of the government and other stakeholders.

SUSTAINABLE HOUSING INITIATIVE AND THE DEMONSTRATION PROJECT

The Sustainable Housing Initiative (SHI) was formed in 2012 at the Pennsylvania State University as a response to energy and environment-related challenges in the residential sector and to discuss the potential for a game changing initiative in the areas of housing and sustainability. The SHI builds off of past Penn State successes, including the 2007 and 2009 Penn State Solar Decathlon Homes, the Union County Energy Efficient Housing Program projects, the American Indian Housing Initiative, and the GridStar Smart Grid Experience Center modular home at the Philadelphia Navy Yard. Each project demonstrates the importance of a holistic approach and the necessity for establishing local connections and reinforcing community development in realizing a replicable and “scale-able” model for sustainable housing. The SHI working group consists of members with a diverse range of research expertise – from building science and design, to community behavior and materials research. Over the last three years, this working group has collaborated to identify a vision for the Initiative at Penn State, and this vision developed out of a significant overlap in interests - these include sustainability, specifically social sustainability related to community and occupant / resident impacts, energy efficiency and a fordability.

The SHI’s faculty members’ interests and prior experience link all three measures of scholarship – research, teaching and outreach – and the working group members saw an opportunity for the SHI to serve to connect the three through a focused and immersive collaborative experience. In turn, a compelling aggregate of university research resources would be brought to the table to examine human behavior, material sciences, energy systems science, architecture, architectural engineering, landscape architecture, agriculture, community development, and Penn State institutes and centers. From the discussions within the working group emerged the search for a demonstration project that is characterized by extreme energy and sustainability best practices, one that is large enough to inform and impact multifamily housing production and provide a research industry / academic platform with a process that is scalable and repeatable.

This sub-typology of the ‘demonstration project’ in the housing sector was then debated in the context of the resources available, potential for industry partnership, the strengths of the SHI members and the possibility of involving all the three aspects of scholarship mentioned earlier (research, teaching and outreach). Housing typologies that were considered included multi-family housing projects appropriate for brownfield sites, Infill housing in existing urban fabric, and University housing (residence hall) projects.

It became apparent that the SHI could best leverage its strengths in a University housing project as it could:
- Best integrate available research, teaching and outreach opportunities
- Create a more ‘controlled’ and conducive environment for experimentation
- Offer the best possibility for influencing change in a ‘real project, and
- Answer a conundrum that is unique to residence halls: “Who is the client?”

In University housing projects, the definition of the ‘client’ falls in a gray area – is it the University and its facilities management organization (in the case of Penn State, the Office of Physical Plant) which sets out the spatial requirements of the project and directly hires and pays the designers for their services; is it the office of Housing, Food services and Residential Life, which is responsible for identifying the needs and supplying funds for the project; or is it the students, who are not only the users of the residence halls but also pay for the design and construction of the residence halls indirectly through their University fees? Unlike most other building typologies, in which the client is considered to be the person / organization that directly pays for the designers’ services and inhabits the building; in University housing projects, the students - who despite being the users of the building and paying indirectly for the designers’ services – are rarely considered as vital stakeholders. The selection of a residence hall project as a test-case for the SHI would therefore provide distilled recommendations for not only the general residential sector, but also specific strategies for residence hall design and construction arising out of a unique collaborative process with the designers, the university and the students. The Penn State residence halls also have a strong tradition of sustainable lifestyle education programs and have become a site for beta-testing new programs at Penn State, including many recycling program improvements, energy-saving initiatives and an active student group called Eco–Reps - a group that includes freshman volunteers who engage in peer–to–peer education. Therefore, it is only fitting that a more formalized sustainable vision for the residence halls be developed to inform decisions now and well into the future.

THE PROCESS

In the summer of 2014, the working group engaged with representatives from the Penn State Housing and Food Services (HFS) and the Office of Physical Plant (OPP), to use the proposed Trippe Residence Hall (Fig. 1) as a real demonstration project for the execution of student research and professional interchange. It is to be noted that Trippe Hall was represented a certain 'standard' in residence halls - it was a 250-bed, $25 million freshman hall similar in spatial requirements to residence halls on most university campuses. This project would help the University and the design team of the Trippe Residence Hall to better understand the expectations of the end users of the building, the students. Two members of the SHI working group led a class each in the fall 2014 semester – while the students of the ARCH 441 class (Juniors in the Architectural Engineering department) produced design proposals for the Trippe Hall project with the objective of designing a 'net-zero' building; the students in the ARCH 412 seminar (predominantly graduate and undergraduate Arts and Architecture students) worked in a series of integrative design charrettes to develop presentations of sustainable strategies relevant to Trippe Hall and other Penn State housing solutions. In addition, the students of ARCH 412 acted as consultants on LEED® (USGBC Leadership in Energy and Environmental Design) and sustainable practices to the design projects of the ARCH 441 students. The aim of this curricular exercise was to promote interdisciplinary opportunities and to further research in sustainable approaches to multiple-dwelling unit design that, in turn, will inform Housing Services at Penn State.

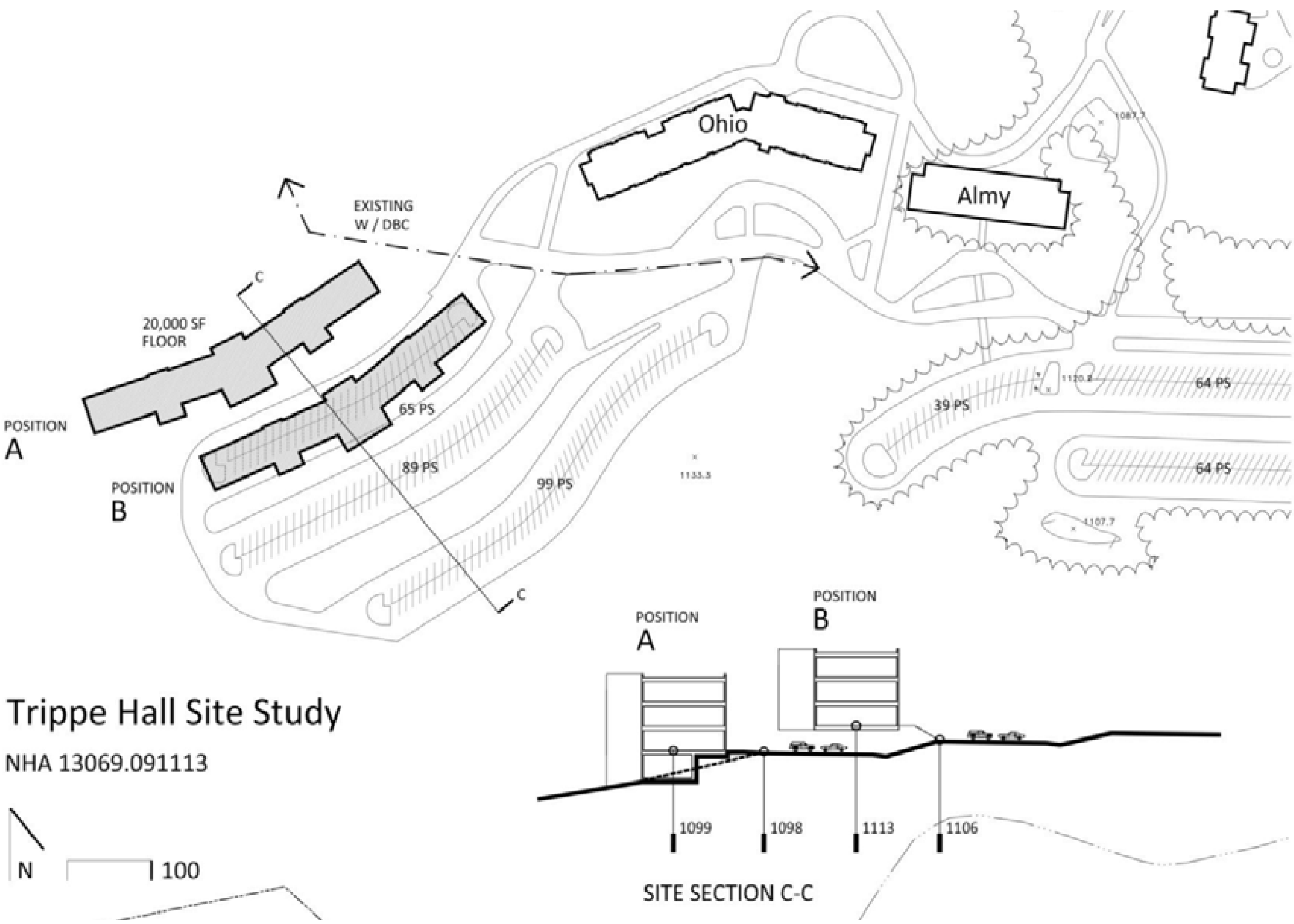

Figure 1. Trippe Hall site study showing the proposed location of the residence hall at the Penn State Behrend campus in Erie

Collaborating with Penn State's Office of Physical Plant / Housing and Food Services, the Penn State Sustainability Institute, and the students enrolled in ARCH 441, the graduate and undergraduate students in ARCH 412 worked in teams (Fig. 2) to research sustainability strategies and develop a 'Living Green' presentation and report intended to inform Trippe Hall and future University residence hall projects.

Students enrolled in ARCH 412 worked in teams to produce a final report that would provide guidance for the new construction, retrofit, operations, and occupation of residential life facilities and set the groundwork for future student projects and initiatives. This project was seen as an opportunity to integrate sustainability design goals and educational objectives into a vision in a way that allows the residence halls to be a working example of Penn State's sustainability initiatives. The goals specific to this class were to

- Provide an opportunity to integrate environmentally conscious design goals / green design principles into a real project by working with campus professionals
- Develop education goals and materials on sustainable design appropriate for Penn State design and construction projects and
- Develop the leadership and facilitation skills to become productive contributors on sustainable design project teams by gaining experience in inter-disciplinary sustainable design collaboration and participating in the Integrated Design Process (IDP) during collaborative project charrettes

Arch 412 student teams were comprised of four students each, and the teams and the project were conceived to simulate an emerging paradigm shift in architectural design and project delivery, the Integrated Project Delivery (IPD) process. An important tenet of IPD is cross-disciplinary collaboration, and this process, at its best, provides for a more integrated, resolved and cost effective final project. However it is often marred by conflicts during collaboration – often, miscommunication is the cause of conflicts between team members, with reports of different disciplines "not speaking the same language". The fact is that different disciplines tend to use similar terminology in very different ways. Therefore the "common language" sought for this project is not that of a specific discipline, but rather a collaborative dialog to set common project goals as a solid foundation for individual and disciplinary exploration. For this project the teams of four students provided an atmosphere for collaboration and an opportunity to set project-specific goals based on different personal perspectives: students reflected on experience that they brought to the class, as students / Penn State residents and from their disciplinary training in architecture, integrative arts and engineering. They also brought newfound knowledge to the discussion based on explorations of what defines "sustainability" for the built environment and research into one of four categories of sustainable development: Sustainable Sites, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality (IEQ). Thus the students were asked to represent themselves as "experts" on a particular subject while balancing the many, sometimes conflicting, personal and cross-personal viewpoints

The students utilized various resources in order to prepare for the collaborative charrettes, including "A Handbook for Planning and Conducting Charrettes for High-Performance Projects" (Lindsey et al., 2012) and "Integrative Process (IP): Design and Construction of Sustainable Buildings and Communities" by the American National Standard Institute (ANSI, 2012). These manuals provided guidance on collective decision-making and served as appropriate references for ideas and the development of the student projects.

Figure 2. Representatives from the Housing & Food Services and the Office of Physical Plant conversing with students in the ARCH 412 seminar class during the strategy development charrette

A brief description of the collaborative charrettes is provided below:

Project Charrette 1: Kickoff

- Charrette concept and facilitator role introduced, project and participant description provided;
- Teams of 4 people formed; and one "expert" in each of the four categories – Sustainable sites, Energy and Atmosphere, Materials and Resources and Indoor Environmental Quality - identified
- Initial team goals established and documented in collaboration with representatives from OPP and HFS.

Project Charrette 2: Goal-Setting Charrette

- Project goals and objectives confirmed
- Specific issues related to sustainable design strategies relevant to the future of Green Dorms in general and Trippe Hall in particular identified
- Strategies and project intentions coordinated between team members.

Project Charrette 3: Strategy Development / Decision-making Charrette

- Most appropriate sustainable 'good, better, best' design strategies evaluated and identified
- 'Big picture' items relating to process, education and community outreach identified
- Guidelines and conceptual design sketches illustrating examples of implementation of strategies developed;
- Coordinated visions for how sustainable strategies will work together established;
- Overview report on strategies to be implemented and rationale for inclusion outlined.

Public Project Presentation

- Project and team goals introduced;
- Participants educated about the sustainable design strategies included and the rationale for selection;
- Full-project report submitted, integrating all charrette reports and project documentation.

During each charrette, one of the four team-members acted as a 'charrette facilitator', whose responsibilities included:

- Establishing the desired outcomes for the charrette;
- Maintaining motivation and encouraging participation from the team members;
- Keeping track of time to assure that all goals are met;
- Recording discussions and decisions during the charrette; and
- Coordinating a charrette report summarizing discussions and documenting outcomes and decisions.

ANALYSIS OF THE OUTCOMES

Over the course of this collaborative design process, we realized that the sustainable design strategies suggested by the ARCH 412 students that contributed to the majority of energy consumption reduction in the projects of the ARCH 441 students were those that needed to be implemented in the early stages of the building design and construction. A schematic breakup of the major sustainable design strategies that we considered are plotted over the anticipated time frame of the building design process in Fig. 3:

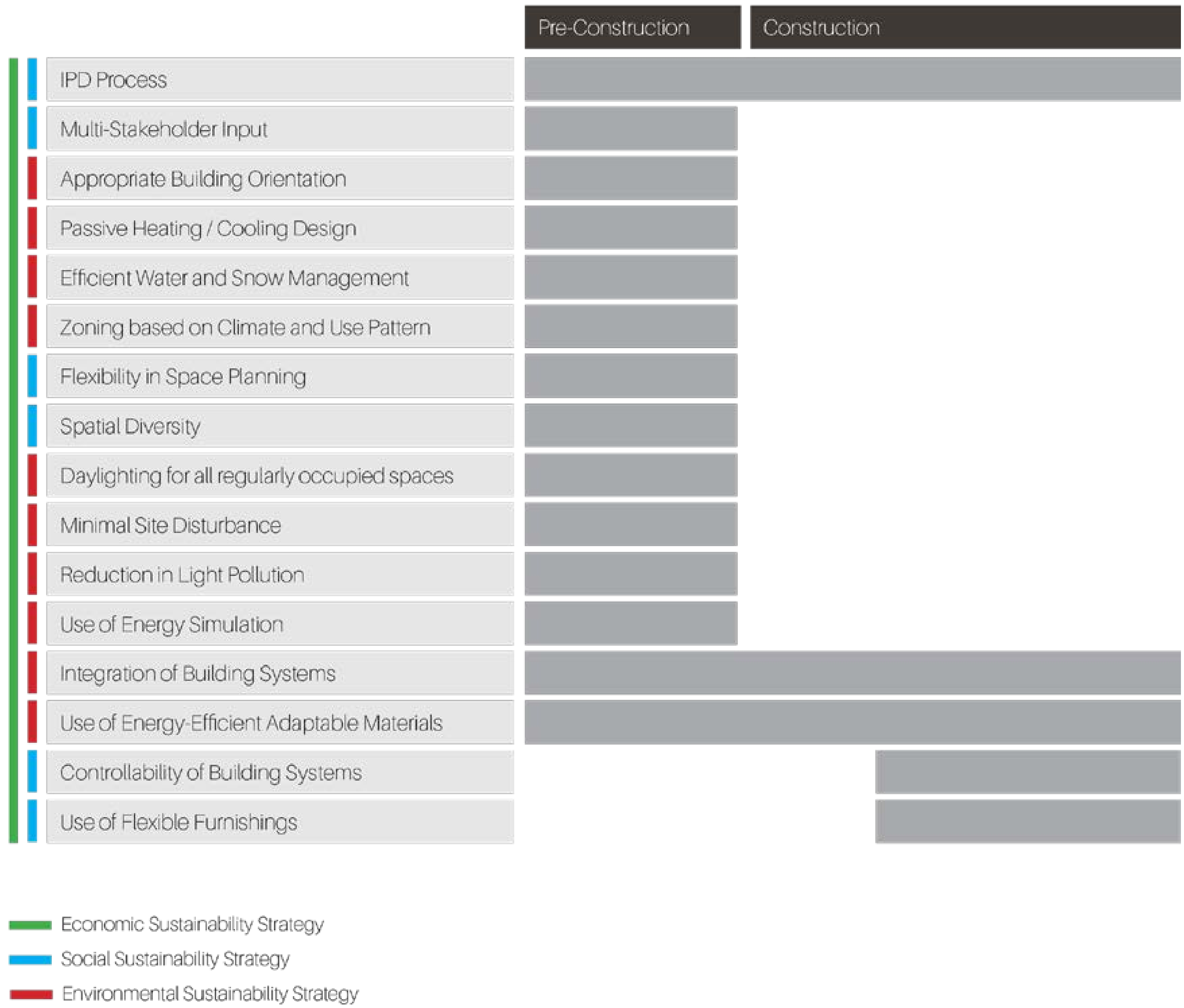

Figure 3. Sustainability strategies considered by student teams plotted over the building process timeline

Throughout the Trippe Hall design charrettes, it became clear that the most time-intensive part of our design would be the schematic design stage, as it involved multi-stakeholder consultation at an early stage in the project. If we construct a time-effort curve based on the previous diagram, with the 'effort' (sustainability strategies) on the vertical axis and the building design & construction timeline on the horizontal axis; we identify the pattern shown in Fig. 4:

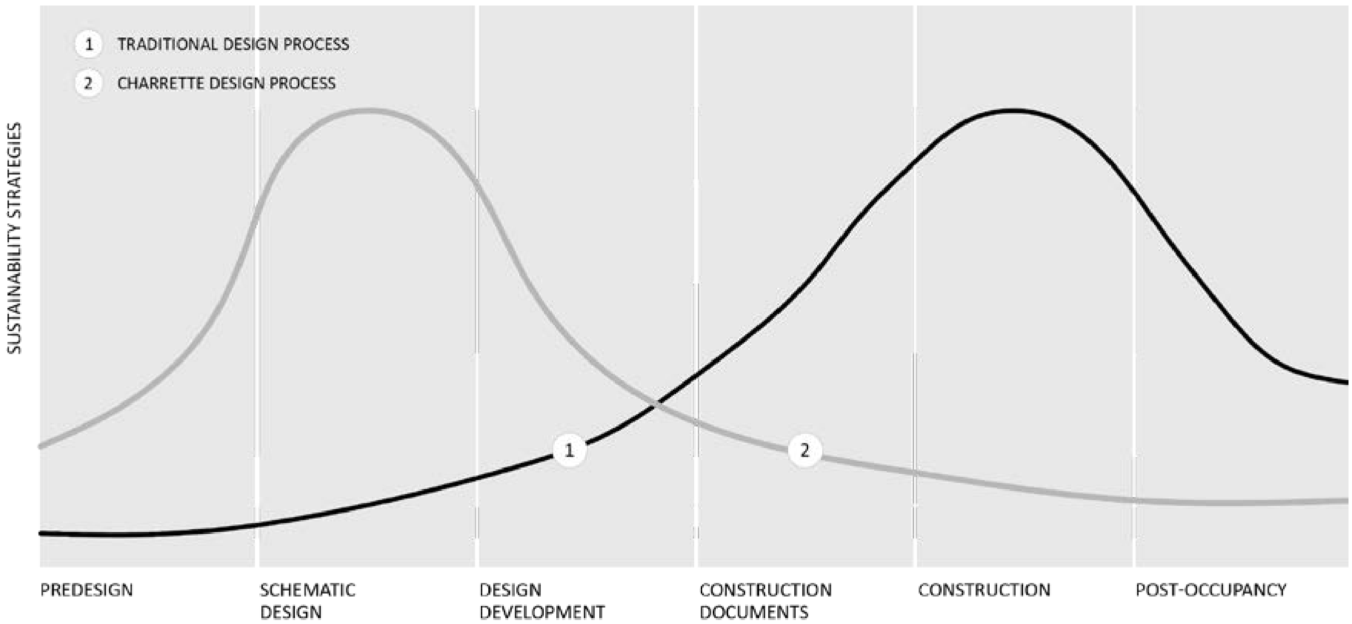

Figure 4. Time-effort curve comparison between a typical sustainable building design process and the Trippe Hall charrette design process

The darker line in Fig. 4 represents the time-effort curve for a typical building, in which the majority of the time and effort is spent in the construction stage of the project. The AIA published the following graphic (Fig. 5) in their publication 'Integrated Project Delivery: A Guide' (2007):

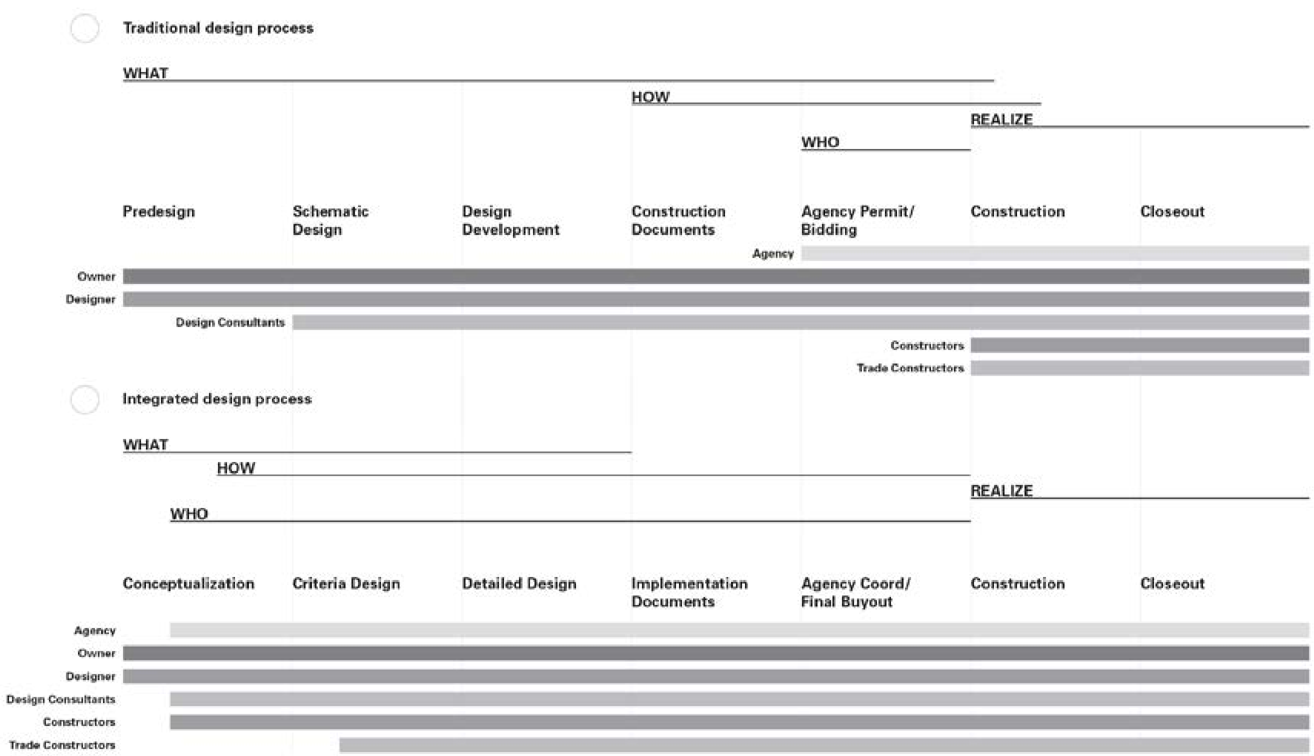

Figure 5. Comparison of traditional delivery to integrated delivery methods showing the shift in effort to earlier phases of the project (AIA California Council, 2007)

Translating the data from Fig. 5 into what has now become known as the MacLeamy curve - in which the cost and the ability to change is plotted on the vertical axis, while the building design-construction timeline is mapped on the horizontal axis - the following diagram (Fig. 6) is generated:

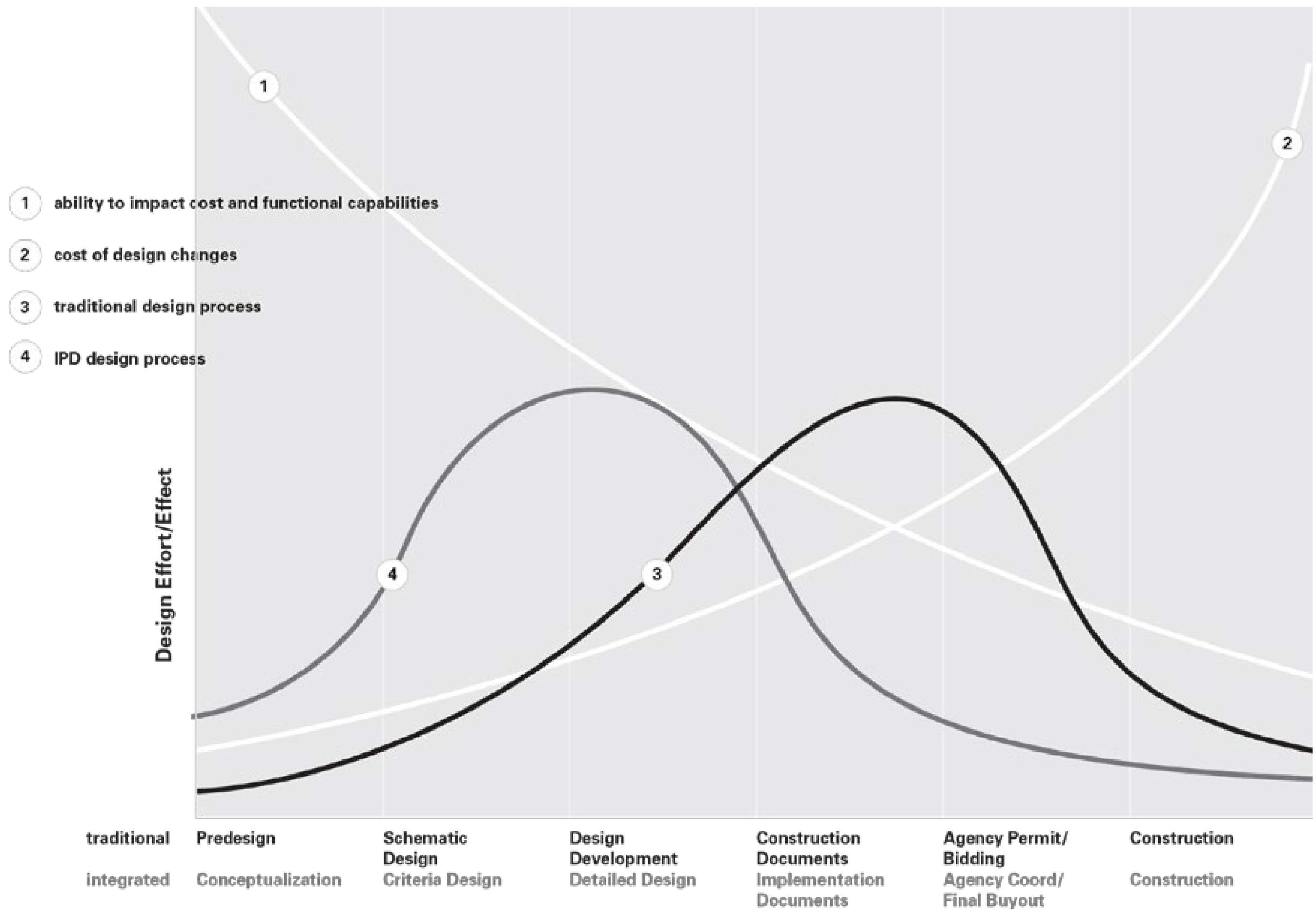

Figure 6. The MacLeamy curve: Time-effort comparison of a traditional and IPD design process illustrating the benefits of early decision-making – opportunity to influence positive outcomes maximized and cost of design changes minimized (Source: Integrated Project Delivery: A Guide, AIA California Council, 2007)

From this, we notice that the time-effort curve for a sustainable design process (as exemplified by the Trippe hall design process) and the IPD process are strikingly similar - there is a shift in the curve from the typical emphasis on the implementation phase of the project to the conceptualization phase, which has been proven to have a major improvement in building quality metrics (El Hasmar, 2012).

Therefore, it makes sense to consider sustainable design in a holistic manner from the very beginning of the building design process, as it has a greater ability to impact cost and a minimized cost for design changes. However, a quick look at green building rating systems (in the case below, LEED-NC) suggests that the graph with the same parameters may, in fact, look like the graph shown in Fig. 7:

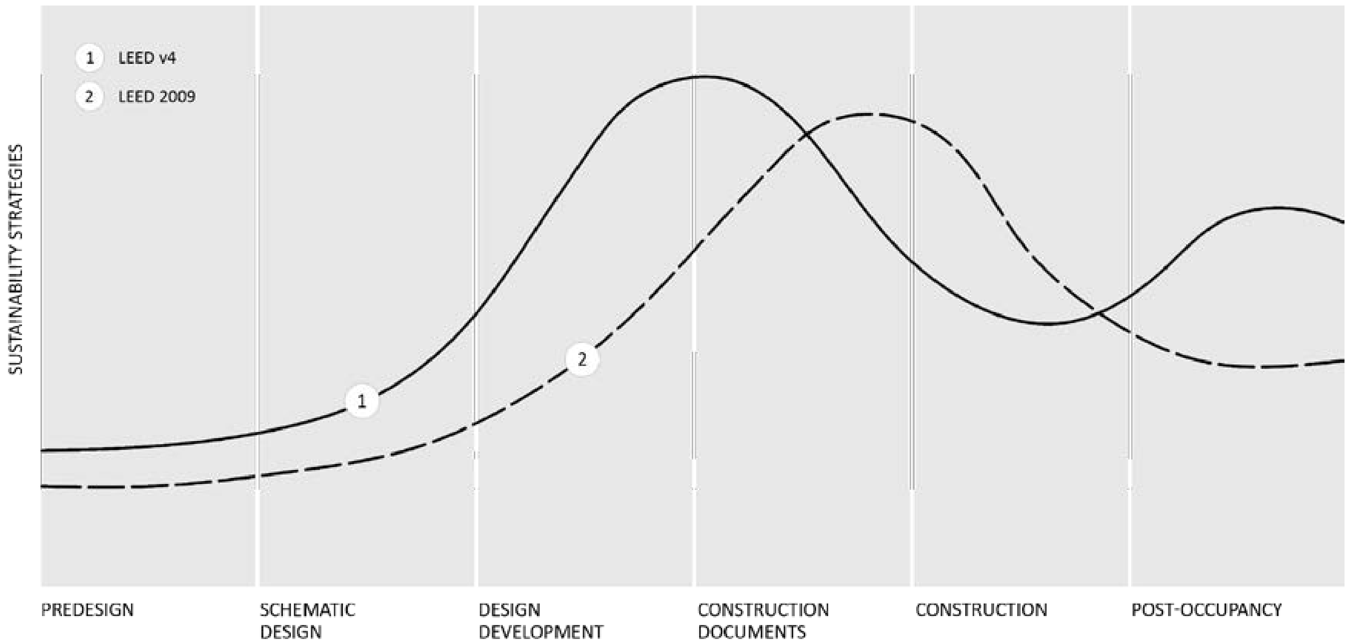

Figure 7. Schematic comparison of time-effort curves of LEED v4 and LEED 2009

The second, smaller 'bump' in LEED v4 is a more recent, welcome addition of the post-occupancy phase of energy-efficiency in a project – because energy-efficiency or sustainability needs to be considered over the entire life-cycle of the building, and not just through the end of the construction process. An emphasis on energy-efficient post-occupancy strategies is also particularly important for University projects like Trippe Hall, as in this case, the same 'client' is involved in multiple projects and the 'lessons learnt' can be applied by OPP and HFS in future projects. However, the crucial thing of note in the graph above is that there is little emphasis on the design phase, and most of the credits focus on the construction-related aspects of sustainability. In retrospect, this is not surprising; as these rating systems essentially focus on the 'tangible' aspects of sustainability – quantifiable aspects such as Energy Metering, IAQ assessment, etc. This analysis perhaps provides the answer to the observation made earlier in the Introduction about the absence of the intended 'fundamental shift' in the reduction of energy consumption in buildings – there is a lack of focus in current evaluation systems on the most critical aspect of a 'green' building project; the pre-design and design phase.

Some of the sustainable post-occupancy strategies considered in the Trippe Hall design charrettes by the ARCH 412 and ARCH 441 students are shown in Fig. 8:

Figure 8. Post-occupancy sustainability strategies considered by student teams during the charrette process

Therefore, by incorporating these strategies into our initial time-effort representation of the Trippe hall charrette design process; we posit the time-effort graph of the 'ideal sustainable building' to be as shown in Fig. 9:

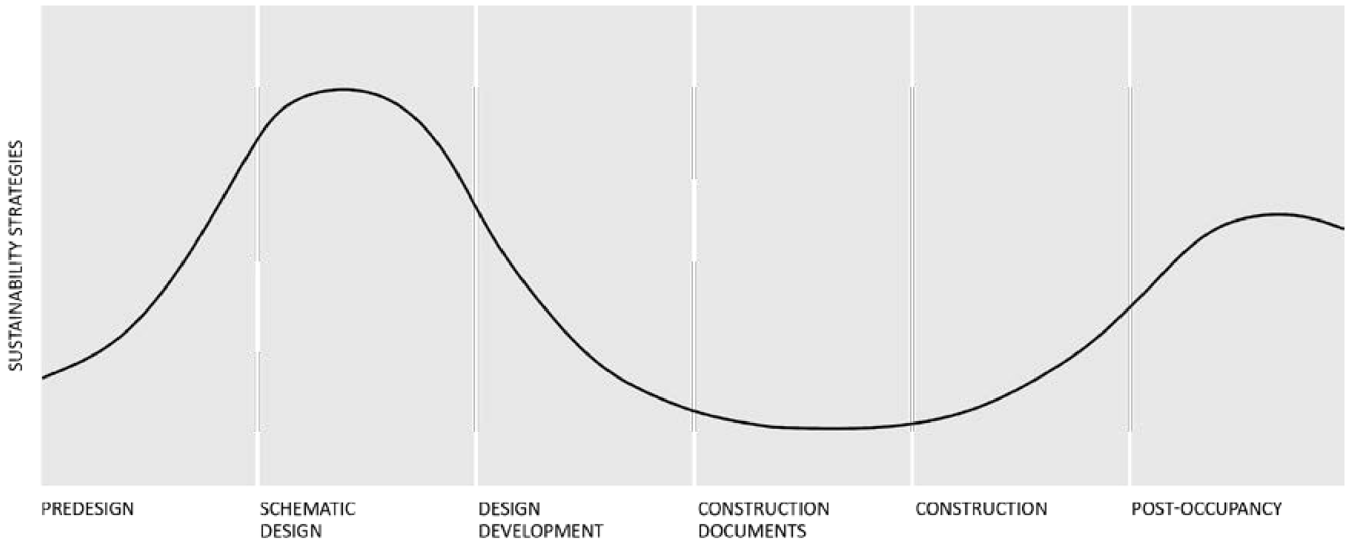

Figure 9. Projected time-effort graph of an 'ideal sustainable building'

This would be the case for a sustainable building designed in a holistic manner; which shows a clear, primary emphasis on strategies employed in the design stage and a secondary emphasis on the post-occupancy phase. For this IPD / Collaborative design + Sustainable design process to become popular in the industry, it needs to be proven that the area covered by the graph in Fig. 9 (time x effort, a loose interpretation of which is money) is lesser than that of a typical comparable building. It can be postulated that this is a very realistic scenario, as data is available to support this claim individually for both the IPD process and the sustainable design process - while there are numerous sources to make the case for sustainable buildings from an economic perspective, Asmar and Hanna (2012) prove quantitatively that IPD systems result in higher quality projects at no significant cost premiums

The following factors make the case for a collaborative process in the design and construction of new buildings:
Procedural symmetries: As shown in the preceding pages, in terms of their procedure, a collaborative design process and the sustainable design process are a natural fit – the factors of time and effort are emphasized in the same initial stages of the project. Both these processes require close collaboration, but the benefits of this are immense - for example, in the traditional linear design process, the input of the mechanical or lighting engineers are not taken into account by the designer when deciding the orientation of the building, even though they have the expertise to weigh in on the topic.
Cost savings: A marriage of these two design processes would pass on greater savings to the owner - while the collaborative process would save project costs by reducing the number of design changes in the later stages of the project and encourage lean construction (cost reduction during building construction); the sustainable design process would help reduce energy consumption and maintenance costs (cost reduction over the life cycle of the building post-occupancy).
Quality: In a survey of quality performance metrics of IPD projects that included structural and mechanical systems, the number of deficiency issues and the cost of warranty and latent defects, it has been shown that there are significant benefits over traditional delivery systems (Asmar and Hanna, 2012). Aspects of sustainability such as safety of materials and finishes, creation of demand-response systems, occupant satisfaction measures etc. will only

serve to enhance the quality of the building over not just the construction process (as a result of the collaborative process), but also the life cycle of the building (because of the sustainable design process).

CONCLUSIONS AND THE WAY FORWARD

The latent potential for designers that employ the combination of these two processes is immense in the construction sector, which consumes approximately 40% of energy, but has a time-effort-material wastage of 57% compared to just 26% wastage in the manufacturing sector (NASFA, 2010). In an era where specialization is considered to be key, it may just be that integration of these diverse processes in a sustainable manner is the way to go in the construction industry.

While the specific strategies of sustainability do not change as they are tangible aspects and are well documented; the way we implement them, in other words, the process, is the key. The impact of this demonstration project has already begun to take shape; as the Request For Proposal (RFP) document of the Trippe Hall project specifically mentions the work of the students and the Sustainable Housing Initiative:

"…this project has been selected to support an important initiative that combines student's classroom experience with the University's commitment to energy efficiency and environmental sustainability. Two classes, one in Architecture and one in Architectural Engineering, have used this project to research sustainability strategies and develop a "Living Green" presentation and report that will inform future residence halls. We expect this project to "raise the bar" and go beyond LEED to comprehensively address the social, economic and environmental aspects of sustainability and set the standard for future projects of this type. It is our intent to integrate these classes in the design/build process and hope that as you respond to this request you consider how this can be done. We also understand that this ambitious goal must be accomplished within the constraints of our typical process and cannot impact schedule and budget. Going forward, the SHI intends to collaborate with the University and its facilities management organizations in initiating a dialog with the designers of Trippe Hall."

Process, and the success of the project outcome is ultimately only as strong as the collaborative 'actors' impacting the decisions. The process of interaction in this project, which was initiated as an independent study by faculty members (research), developed by students in a classroom environment (academia), and involved the development of a 'real' building (industry) shows the potential of universities to act as initiators of positive change in collaborative environments. The civic issues embedded in this campus 'living laboratory' project are multifaceted and potentially informative for the future of the architecture, engineering and construction (AEC) industry in general, and particularly design professionals.

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An Assessment of Utilizing Phase Change Materials (PCM) Towards Energy Performance in Building Enclosures

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ABSTRACT

This paper assesses the opportunities of utilizing Phase Change Materials (PCMs) in building enclosure systems to improve energy performance and thermal comfort in buildings. The building sector continues to grow along with population growth, which will further increase energy consumption that is needed for space heating and cooling to provide thermal comfort for occupants. With many practical applications, PCMs are capable of storing and releasing significant amounts of energy by melting and solidifying at a given temperature and can play an important role as a thermal energy storage device by utilizing its high storage density and latent heat capacity. PCMs not only have the potential to reduce air conditioning energy consumption in residential and commercial buildings, but also have the potential to improve occupancy comfort by better maintaining desired surface temperatures. PCMs can be utilized to decrease the overall required energy of buildings by shifting part of the heating and cooling loads to off-peak hours when there is less energy demand within our utility grids. One of the potential applications for PCMs in buildings is to incorporate them within the building enclosure for energy storage. Our research investigates PCMs in an experimental study, from which we will extrapolate results to apply for residential application in different U.S. climate zones. The research extrapolation will be supported by simulation tools, which are capable of simulating PCMs in the building context. The study will also explore different factors contributing to other thermal performance criteria, such as the thermal conductivity and applicable temperature ranges of different PCMs. The results will be presented for better understanding of PCMs' thermal behavior as well as demonstrating the applicability of using PCMs towards improving building performance and overall energy consumption in different climate contexts.

INTRODUCTION AND BACKGROUND

Buildings are designed to create an isolated space from the surrounding environment and provide desired interior environmental conditions for occupants. The essential role of any building is to provide users' needs and to protect humankind from climatic extremities. Individual needs vary from person to person and from area to area. This

means the requirements in building components in one geographic area do not have to be the same as in another area. Therefore, the properties of buildings are different based on location, and they are designed with considerations for climatic conditions that keep the inside spaces cool in summer and warm in winter.
Construction practices continue to change as new equipment is developed, new materials are innovated, and housing requirements are changed. The difference between interior and exterior temperatures in summer and winter require high-energy consumption. In 2009, the United States Department of Energy (DOE) performed an energy consumption survey on residential buildings and found that residential heating and air-conditioning consumes 49% of all residential energy usage in the United States (US Department of Energy 2009). Proper building materials, such as high performing insulation, are considered essential for most building construction in order to provide thermal comfort inside buildings (Arafah et al. 1995).
At the same time, Phase Change Materials (PCMs) play a major role as Thermal Energy Storage (TES) in different successful applications such as transport and storage containers, clothes for human body, packaging for medical and food supplies, and electronic equipment. TES allows heat and cold to be stored and used later. It can be stored under two methods: physical methods and chemical methods. PCMs have the ability to absorb thermal energy, which means removing or reducing the need for heating and cooling by using sensible and latent heat storage as shown in Figure (1) (Building for Change 2010).

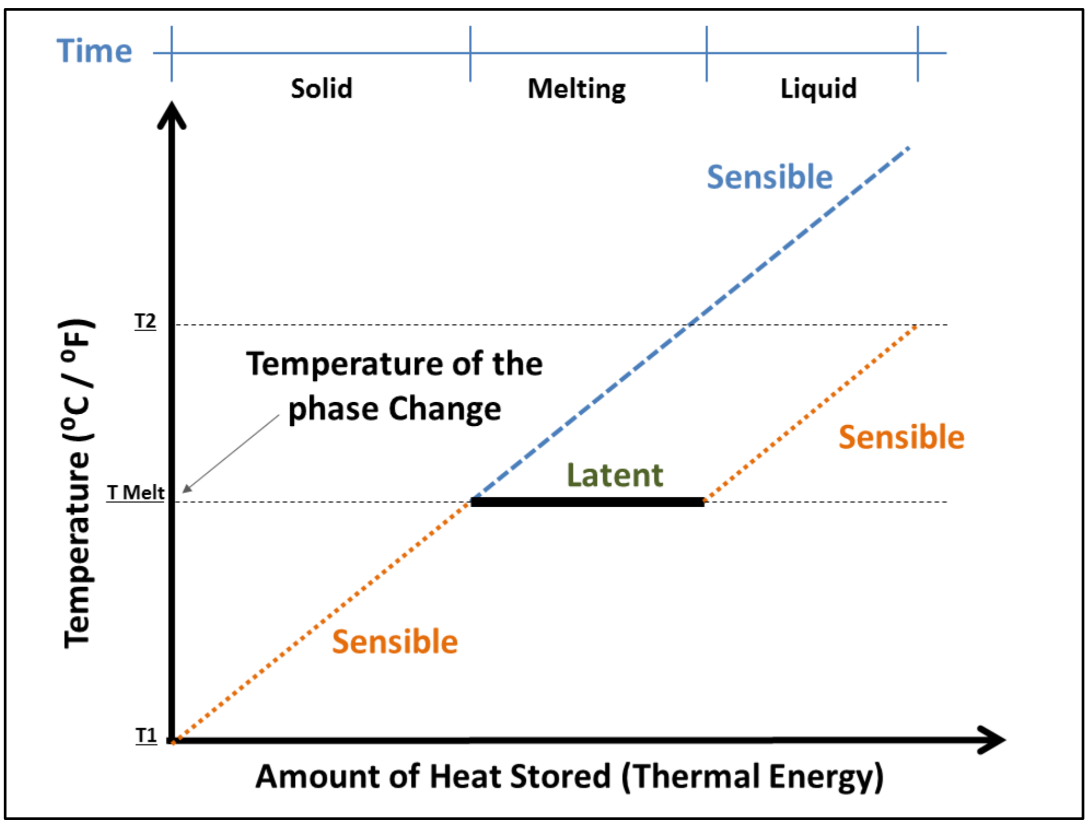

Figure (1):Temperature profile for changing phases by sensible and latent heat (Bayern 2015).

PROBLEM STATEMENT AND RESEARCH GOALS

Air conditioning energy consumption in different seasons represents a challenge in many areas with hot or cold climates. Providing thermal comfort for building occupants is a very important task for architects, engineers, and contractors. PCMs work efficiently in many fields as a temperature controller, but their application in building construction is very rare. PCMs are ideal products for thermal management solutions. This is because they store and release thermal energy during the process of melting and freezing—which refers to the change from one phase to another. Yet, high performance PCMs are still not used frequently as thermal storage in building construction, and some challenges exist regarding applying PCMs as building materials to be used in the building enclosure. For example, the affordability of organic PCMs, the availability of inorganic PCMs with high enough thermal resistance values, or the role of some architects and their knowledge in regard to selecting PCMs in building construction remain challenges that currently limit the use of PCMs in construction practice.

There are several significant potential applications of integrating PCMs in buildings that allow for reducing energy demand, but further investigations are needed to assess their actual utilization and benefits. This paper focuses on an assessment of utilization options of PCMs towards energy performance in building enclosures.

PROJECT GOAL, OBJECTIVES, AND SCOPE

The overall goal of our research direction is to bridge the gap between known and functional applications of PCMs in various fields outside of construction and their potential utilization specific for building enclosure systems of residential buildings.

To achieve this goal we define the following three core objectives in this research path. First, we need to study existing PCMs that have the potential to be used in construction practice. Second, we will have to define and conduct field experiments to assess the practical utilization of PCMs in building enclosure systems, mostly from a thermal performance perspective. Third, we will have to identify and measure the respective thermal performance values of the most common types of PCMs that can be used in buildings and compare them with relevant insulation building materials to clarify and justify any possibility of using PCMs in building construction practice.

The scope of this study will be limited to an assessment of the most popular PCMs that have the potential to be used in building construction in order to utilize them as thermal control materials in residential construction. This study will focus on the applicability of using PCMs as insulation materials in the building envelope for residential construction.

ASSESSMENT OF PCM APPLICATIONS

PCM Definition

Phase change materials (PCMs) as defined by Tyagi and Buddhi (2007) are latent heat storage materials, which can be used as a temperature controller. PCMs are a substance with a high heat of fusion that are able to store and release a large amount of energy when they melt or solidify while more or less staying at this certain temperature until the phase has completely changed (Haghighat 2013) and (Sharma et al. 2009). As they store and release heat by using chemical bonds and thermal energy transfers occur when the material changes from solid to liquid or vice versa, these processes are called a change in state or phase (Vuceljic 2009) and (Tyagi and Buddhi 2007). PCMs can be viewed as a thin layered version of larger mass walls that can be used to create the thermal comfort in the interior environment of buildings, and they are able to cycle continuously through changes of state without losing their attributes and preventing loss in mass through evaporation (Rohles 2007). Figure (2) demonstrates the concept of PCMs capability of absorbing and releasing heat with repeated melting and freezing cycles (Pazrev 2015).

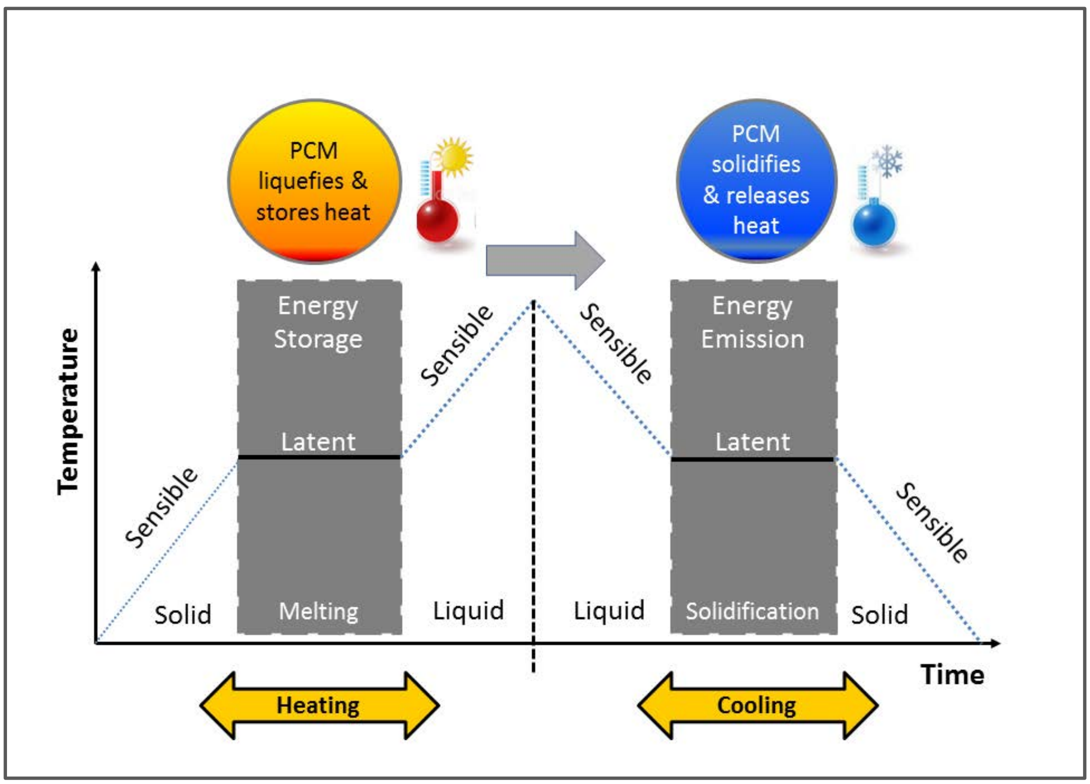

Figure (2) The concept of PCMs capability of absorbing and releasing heat with repeated melting and freezing cycles (Pazrev 2015)

Cooling and heating have their effects on PCMs. They change the state of the materials from solid to liquid or liquid to solid, and during this process the heat is absorbed or released. Figure (3) shows the cooling and heating effects on PCMs (Shim et al. 2001).

PCM Properties

Sharma et al. (2009) mention that PCMs have different thermo-physical properties, chemical properties, and kinetic properties. High thermal conductivity, solid and liquid phases and acceleration time of charging and discharging of energy, are examples of PCMs' thermo-physical properties. They also list some examples of chemical properties, such as chemical stability and absence of degradation after a large number of freezing and melting cycles. Nucleation rate, which is beneficial for avoiding super cooling of the liquid phase, is an example of kinetic properties (ibid).

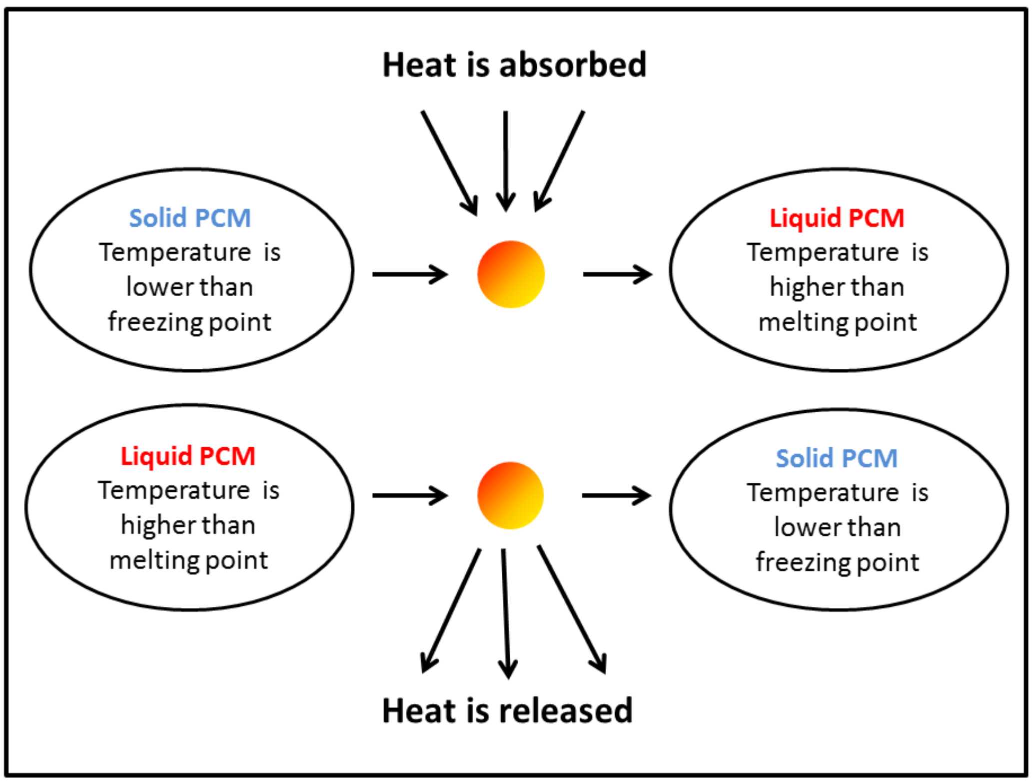

Figure (3) Cooling and heating effects on PCMs (Shim et al. 2001)

The core property of PCMs is based on their latent heat storage capability around their melting points, because large amounts of energy can be stored in a comparatively small volume of PCMs (Madhumathi and Sundarraja 2012).

PCM Types

There is a large number of PCMs , which can be classified based on different criteria, such as their melting temperature and latent heat of fusion, the changing of phases, or their source material (Haghighat 2013). Khudhair and Farid (2004) and Vuceljic (2009) clarify the types of PCMs based on their most common criteria—which is their sources and components. The main sources can be classified into organic compounds, inorganic compounds, and the mixture of two or more components, creating a kind of hybrid type, called eutectic, as shown in Figure (4).

Advantages and Disadvantages of PCM types

Although organic and inorganic compounds both have high latent heat, which is the most significant feature of PCMs, each type also presents distinct advantages and disadvantages. On the one hand, organic compounds have some advantages such as a low volume change at phase change as well as chemical and thermal stability. On the other hand, organic compounds have some disadvantages such as their rarity, a rather low thermal conductivity, and greater cost in comparison with inorganic PCMs' compounds (Harland et al. 2010). Moreover, organic PCMs are typically highly flammable, though this can be alleviated in some applications by a proper container (Dubey and Mishra 2014).

Conversely, inorganic compounds have a lower performance of thermal insulation than organic compounds, and have rather high thermal conductivity, while at the same time being more affordable (Harland et al. 2010). Some of their main disadvantages are a lack of thermal stability and change of volume after repeated melting and freezing cycles (Mondal 2008).

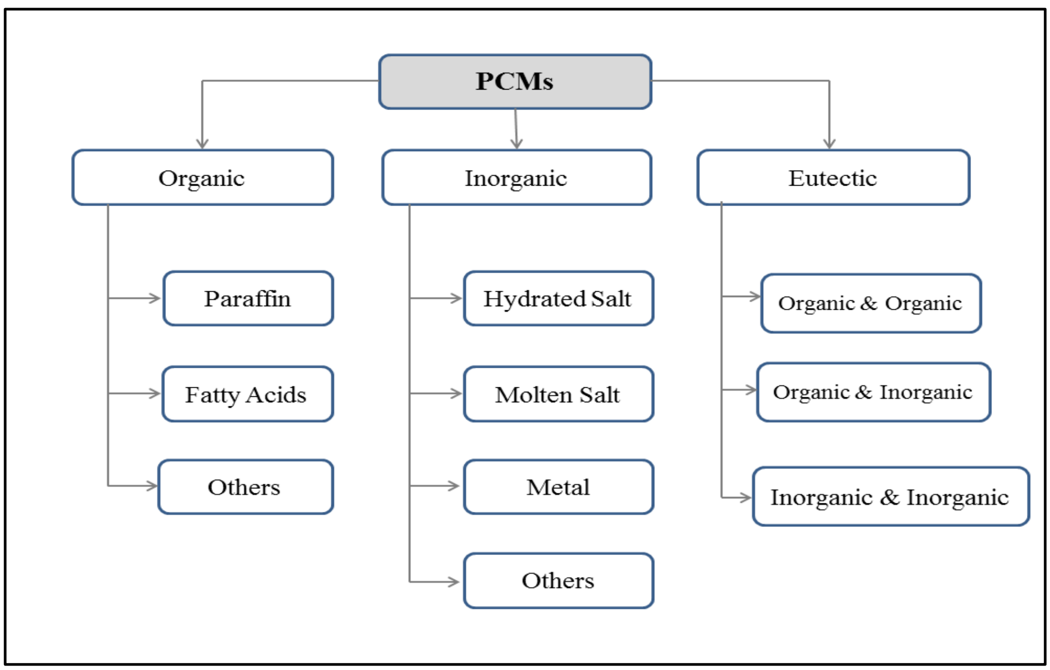

Figure (4): Types of PCMs according to their sources (Khudhair & Farid 2004 and Vuceljic 2009)

Eutectic compounds, the third type of PCMs, are a combination of the inorganic and organic types try to bridge advantages from different base materials. The development of less expensive but highly capable PCMs at a desired temperature, such as fatty acids, is currently being explored (Harland et al. 2010). Also, the authors examined some eutectic products that express the beneficial functions of PCMs specifically to create thermal comfort and reduce the energy consumption for cooling or heating (ibid).

In summary, organic, inorganic, and eutectic PCMs each have their own advantages and disadvantages. Table (1) shows a brief overview of the advantages and disadvantages of PCMs according to their classification.

Table (1): Advantages and disadvantages of PCMs (Mondal 2008), (Sharma et al. 2009), and (Nath 2012).

	Organic	Inorganic	Eutectic
Advantages	• High latent heat • Non-corrosive • Chemically & thermally stable • Little sub-cooling • Durable and recyclable • Efficient for thermal comfort • High heat of fusion • Low vapor pressure	• High latent heat • High melting enthalpy • High density and latency • High thermal conductivity • High heat of fusion • Sensible heat storage • Non-flammable • Low volume change • Affordable	• Sharp melting Temperature • High volumetric thermal storage density
Disadvantages	• Not affordable • Low melting enthalpy • Low density • Low thermal conductivity • Rare availability • Flammability (depending on containment) • Volume change	• Sub-cooling • Corrosive of container materials • Phase separation • Phase segregation • Lack of thermal stability • Instability of volume after repeated change cycles	• Lack of test and limited data of thermo-physical properties

Broader Application of PCMs

Depending on their positioning PCMs have the properties for both, to harvest energy from solar gains where desired, or to protect against solar gains, due to their high thermal storage characteristics. Typically this protection is used during transportation or storage of goods to provide thermal comfort against heat and cold (Prim 2013). Therefore, PCMs have different applications that are currently used to reduce or avoid heat exchange between different temperatures in areas/spaces that need to maintain these properties for different purposes.

There are many applications that benefit from PCMs' useful ability to stabilize temperatures—such as protection of solid food, cooked food, beverages, pharmaceutical products, blood derivatives, hot and cold medical therapy, electronic circuits, clothing, and many other applications yet to be discovered (Prim 2013). More importantly, possible PCM applications include the utilization in refrigerators and freezers that can use less energy, high-performance textiles that provide relief from hot and cold climate conditions, and shipping containers that maintain goods at the desired temperature for longer periods.

Currently, the global PCM market is experiencing high growth due to an increasing demand for eco-friendly and energy-saving materials in industries such as thermal energy storage, refrigeration, textiles, and electronics. Table (2) shows an overview of some examples of existing applications of PCMs in different fields (Mantz 2014) .

Table (2): Examples of PCMs' applications (Mantz 2014)

Field	Examples of Applications
Consumer Products	**1)** Textile **2)** Apparel & Shoes **3)** Furniture **4)** Car Seats **5)** NASA Dive Suit **6)** Lunch & Beverage Containers **7)** Outdoor Gear (sleeping bags, etc.)
Packaging	**1)** Medical **2)** Pharmaceutical **3)** Chilled Food **4)** Vaccines **5)** Drug & Laboratory Testing **6)** Chemicals & Biological samples
Bedding	**1)** Mattresses **2)** Mattress toppers **3)** Protectors **4)** Pillows **5)** Linens **6)** Quilting **7)** Ticking
Electronics	**1)** Computer parts **2)** Outdoor electronics **3)** Laboratory equipment **4)** Handheld devices & phones **5)** Remote telecom stations

PCM Applications in Building Construction

PCMs as latent heat storage materials can be an efficient way of storing thermal energy, and they are applicable to materials and products that can be used as temperature-controllers in construction and architecture (Vuceljic 2009).

The concept of storing heat within a building's walls has been around since 1881 (Pacson 2011). The first documented use of a house using a PCM for passive solar heating was done by Dr. Maria Telkes in 1948 (Harland et al. 2010). Tyagi and Buddhi (2007) mention several forms of bulk encapsulated PCMs that can be used in building construction in their research. These materials provided for active and passive solar applications during the 1980s (ibid). In addition, they found that most encapsulated commercial PCM products at that time were inadequate for delivering heat to the building passively after the PCM was melted by direct solar radiation. This can clearly be seen in the buildings' envelopes, which offer large areas for passive heat transfer. The need for proper building materials with high performance insulation is considered one of the most important building construction applications to create thermal comfort in buildings (Arafah et al. 1995).

▪ Current Applications of PCMs in Buildings

The uses of PCMs in buildings as thermal storage systems has been of great importance since the second half of the twentieth century (Kośny 2015). Most frequently, latent heat storage materials are used to stabilize interior building temperatures. The application of PCMs in air conditioning systems reduced room temperature fluctuation by lowering the high temperatures from the external daily temperature and reducing home heating and cooling loads by reducing the electrical power consumption (Zalba et al. 2004). Also, the use of PCMs to store coolness has been developed for air conditioning applications and reduced the energy consumption, where cold temperature is collected and stored from ambient air during the night, and is released indoors during the hottest hours of the day (Zalba et al. 2004).

The main applications of PCMs in buildings are when spaces are directed to the sun and require larger thermal storage units to be used as an insulation layer within building envelop components. PCMs were traditionally used to provide a comfortable interior building temperature (Vuceljic 2009). PCMs are currently utilized by using a packaging method in micro- or macro-encapsulated cells for some applications such as interior wall construction that are adjacent to insulation and wallboard, between attic joists, above ceiling panels in a drop ceiling, and floor tiles (James and Delaney 2012). Jaworski and Abeid (2011) reference three existing ways of incorporating PCMs in building structures:

1. Blending PCMs with building materials during the manufacturing process of construction elements such as bricks or plasterboards in wall components.
2. Incorporation of macro-capsules with PCMs in free spaces inside the building such as placing PCMs above suspended ceilings or under floors.
3. Incorporation of PCM in parts of furniture or window blinds.

Tyagi and Buddhi (2007) list a number of major applications of PCMs in buildings, which they classified into two different methods for temperature control. The first application deals with passive storage systems, such as PCM trombe walls, PCM wallboards, paints, PCM shutters, PCM building blocks, and air-based heating systems. The second application relates to active storage systems, such as floor heating and ceiling boards. PCMs are used to enhance building performance in many building elements. The following are some examples of current applications:

1. PCM enhanced solar thermal storage walls
2. Impregnated concrete blocks and ceramic masonry
3. PCMs enhanced gypsum board and interior plaster products
4. Use of PCMs to enhance wall cavity insulation
5. PCMs to enhance thermal performance of floor and ceiling systems
6. PCMs utilized in roofs and attics to enhance insulation
7. PCM enhanced windows and window attachment products
8. Use of PCMs for pipe insulation and HVAC systems
9. Implementing PCMs for fireplace protection
10. PCMs to enhance wallboards and insulation foams

As expected, each of these PCM types has different applications in building construction. Table (3) shows some example of existing PCM products that are currently used, and list their location of implementation.

Several studies analyze PCMs as energy saving materials due to their flexibility and applicability. PCMs are gaining popularity due to their properties of reduced heat transfer in lightweight materials. The search for capable, efficient, economical, and achievable sources of energy is a continuous attempt carried out by researchers, practitioners, and scientists.

Table (3): Examples of PCMs' applications in Building Construction (Jaworski and Abeid 2011)

PCM Product	Application
Micro-encapsulated Paraffin Wax	Wallboard
	Ceiling Tiles
	Floor Panel
	Interior Wall Construction
Bio – Based (organic) Materials	Interior Wall Construction
	Attics / Drop Ceiling Plenum Floor
Eutectic Salt Mixtures	Interior Wall Construction
	Attics / Drop Ceiling Plenum Floor

- **Motivation for utilizing PCMs in building construction**

In the last decade, the demand for air conditioning has increased greatly and large demands for electric power have led to an increase in efficient energy applications (Vuceljic 2009). In building construction, there is a lot of energy saving potential and possible ways for improvement. Vuceljic (2009) found that electrical energy consumption varies significantly between day and night, and how PCMs can be helpful in building materials because of their high storage density and small temperature swings. The author supposes that encapsulating or embedding suitable PCMs within envelope surfaces will enhance thermal energy storage in the building enclosure. The author further states that PCMs can either capture solar energy directly or capture thermal energy through natural convection. The thermal storage capacity of PCMs can provide a valuable solution for the supply and demand of electrical energy, and shift the peak of energy consumption for HVAC systems to cheaper off-peak hours. PCMs can increase human comfort by decreasing the frequency of internal air temperature fluctuation and provide the desired temperature in the indoor building environment for a longer period (Vuceljic 2009). PCMs can reduce the electrical power consumption by lowering the high temperatures in comparison to the external daily temperature and reducing home heating and cooling loads (Zalba et al. 2004).

The motivation for the use of PCMs in building construction can be found in two main factors: 1) Effects of PCMs on electrical energy consumption and 2) Effects of PCMs on thermal performance and comfort of buildings.

1) Effects of PCMs on electrical energy consumption

In many countries, cooling and heating of any type of building contributes significantly to the electrical consumption and this demand of electricity is critical when it occurs during peak times (Al-Hadithi 2011). For example, according to the US Department of Energy (2009), in Arizona, 25% of electrical energy consumed in homes is for air conditioning, which is more than four times the national average. Figure (5) shows the comparison between Arizona and the U.S. overall regarding electrical consumption.

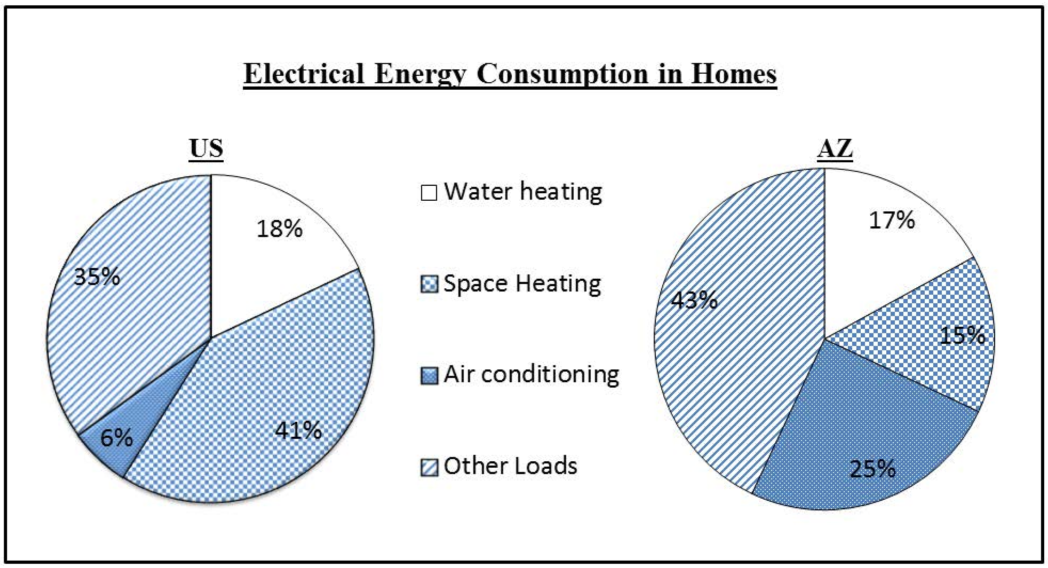

Figure (5): Electrical energy consumption in homes (US Department of Energy 2009)

Currently, providing electrical energy is often achieved with extra equipment and cost, and the use of PCMs in construction practice could reduce or avoid the need for this energy (Sharma et al. 2009). Creating a comfortable environment inside most buildings requires a large amount of energy expense and costs a large share of the building's operating cost. From an economical perspective, PCMs can remedy the trend of increased energy consumptions in building. This, combined with a renewed interest in many aspects of conservation, has led to creating thermal comfort in buildings with minimum expenditure of conventional energy. It should be noted, however, that electrical energy's actual performance for residential buildings, which is integrated with the building component and the consumption of energy, also depends on building design and the operated environmental context (Harland et al. 2010).

2) Effects of PCMs on thermal performance of buildings

PCMs can be used in building construction for thermal storage in conjunction with both passive and active solar storage for heating and cooling (Tyagi and Buddhi 2007). A PCM's temperature remains constant during the phase change, which is useful for keeping the subject or object (e.g. the surface of an exterior wall) at a uniform temperature and can thus provide a comfortable environment inside the building when they are used in the building enclosure (Sharma et al. 2009).

The applications of PCMs in construction practice could reduce or at times entirely avoid the need for cooling or heating energy (Sharma et al. 2009). Moreover, PCMs provide similar functionality for improving the comfort of the interior space in buildings and reducing electrical energy consumption as compared to high density materials typically used for thermal storage. However PCMs now achieve this without the issue of adding significant mass, which can be inappropriate at some levels of construction (Harland et al. 2010). Figure (6) compares PCM with different conventional building materials and shows the necessary thickness to store as much heat as a 1 cm thick layer of PCM based on certain temperature interval (Mehling and Cabeza 2008).

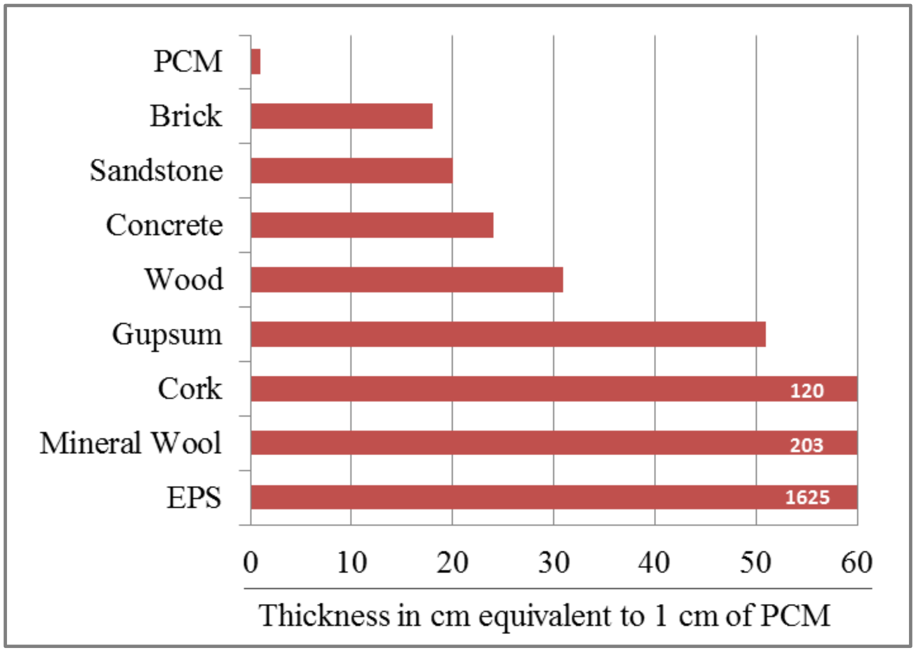

Figure (6) Necessary layer thickness of different building materials to store as much heat as a 1cm thick layer of PCM (Mehling and Cabeza 2008).

Therefore, the use of PCMs is desirable for improving building performance and creating thermal comfort with the reduction of electrical energy consumption because of the discrepancy between the indoor day temperature and the outdoor night temperature (Zalba et al. 2004). For example, in the summertime, peak heat flow crossing a painted roof deck using reflective insulations and PCMs sub-venting air channels was reduced by about 70% compared with the heat flow penetrating a conventional shingle roof (Kosny et al. 2008). This specific application clarifies the impact of PCMs can have on building performance, which subsequently affects the thermal comfort of the physical indoor environment (Kosny et al. 2008), and indicate the necessity of conducting further experimental studies to assess the effective utilization of PCMs in building enclosures and their impact on building performance.

- **PCMs in the Market and their Possibility in Building Construction**

In 2010, varieties of different PCMs were available on the market. The two most common forms were paraffin waxes and salts, which can provide a large range of melting temperatures. In 2013, the commercial market had more than 100 PCMs that were available at different melting temperatures within the range of $0^{o}C$ to $100^{o}C$ with latent heat of fusion in the range of 100 to 300 kJ/kg (Milisic 2013). In the immediate future, it is probable that the market for PCMs in construction will become affordable to local-area applications, mainly because of the PCM resources are becoming cheaper to use and more efficient to apply by conventional methods (Milisic 2013). According to a report from Mordor Intelligence LLP (2015), PCMs were valued at $563.53 million in 2014 and they are expected to extent to reach $1,674.29 million by 2020, presenting a compound annual growth rate of 19.9%.

The opportunity of reducing energy consumption and improving the indoor environment and thermal comfort of buildings is obtainable by using PCMs in building construction. However, the application of PCMs in building materials depends on climate parameters, building location, as well as the individual PCM's properties, and its actual position within different building components. Climate parameters in a building location and thermal characteristics of the building not only have an influence on building components themselves, but also on the thermal comfort of the interior space (Al-Hadithi 2011) and (Fernandes and Costa 2009). Additionally, solar radiation, cloudiness, heat absorption and reflection of the ground, wind speed, and atmospheric pressure all can have a major effect on the indoor comfort environment under natural conditions (Rimkus et al. 2007).

PCMs do not require a thicker layer of building materials as thermal mass to provide thermal comfort for buildings in hot or cold regions because of their absorbing and releasing properties from reactions using the latent heat of fusion (Vuceljic 2009). Therefore, they are mostly suitable to be used in lightweight construction because of their impact, which is similar to thermal mass in the building (Building for Change 2010). Moreover, PCMs can be used in both new building and existing buildings, but when using PCMs in existing buildings, some criteria have to be taken in consideration such sound absorption properties of surfaces or moisture control within enclosure components. Bouguerra et al. (2011) emphasize the possibility of using existing microencapsulated PCMs, which are made with paraffin waxes embedded in small spheres of polymer in building construction, by mixing them with building materials or facing wallboard. They also found that the available PCMs in the market can easily be added to plaster, and can thus be installed in new construction or during the renovation process of an existing building.

Most of the applications of PCMs in buildings focus on heating or cooling by using natural or manmade resources to match the required thermal comfort (Mehling et al. 2002). Therefore, the materials containing PCMs can absorb and release heat more effectively than most of the traditional building materials, and they can be successfully used in components of building enclosure to provide the thermal comfort for interior spaces (Madhumathi and Sundarraja 2012). For longer periods of time, PCMs can provide hours of comfort to the interior space while occupied (Manioglu and Yilmaz 2008). However, PCMs must be selected and applied very carefully, specifically in accordance with fire and other building codes following sound engineering practices.

In hot dry regions, where temperature changes during a 24-hour period are more significant, PCMs applications become an even more relevant driver, as they can reduce and absorb daytime heat gains and provide improved thermal comfort for interior building environments (Madhumathi and Sundarraja 2012). Thus, PCMs are especially suitable in arid and semi-arid areas, when the solar irradiance is maximized during the day, and the energy demand reaches the peaks because of air-conditioning loads (Nath 2012). Also, using PCMs in buildings is suitable to create thermal comfort because of their ability to adapt to the differences between indoor day temperatures and outdoor night temperatures (Zalba et al. 2004).

CONCLUSION AND FUTURE RESEARCH

This paper described in brief the existing situation of PCMs' application in different fields and the opportunity of utilizing them in building construction practices. Also, it discussed the opportunities of utilizing PCMs to improve building performance by using natural resources with less energy consumption. However, providing occupancy comfort by better maintaining desired surface temperatures as well as decreasing the overall required energy of buildings by shifting part of the heating and cooling loads to off-peak hours are perhaps the more significant parts of this study. While this first stage of a larger research agenda discussed the existing applications of PCMs in different fields and explored the possibility of using PCMs in different areas of building construction, the authors identified several areas of future research needs. First, there is a lack of practical experiments for real world assessment of applying PCMs towards energy performance in building enclosures in different climatic contexts. Second, there is a need to study and compare actual temperature distributions and latent heat storage processes in the building enclosure system, when building components contain PCMs and when they are built without PCMs, and are exposed to the same exterior and interior boundary conditions. Third, further research needs to establish performance metrics to measure and assess actual heat transfer across different wall systems and to compare the applicability of these systems for available simulation software, since ultimately designers will have to evaluate thermal performance of enclosure systems that use PCMs.

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Innovating Continuous Exterior Insulation

Theresa A. Weston, PhD.[1]

ABSTRACT

As the need to reduce energy usage and carbon consumption has increased, the need for energy efficient building envelopes has increased. The application of continuous exterior insulation in frame construction is a key technology to achieving an energy efficient building envelope. Continuous exterior insulation includes a variety of products, including insulating sheathing and insulated claddings and while these products have long been available, recent advances in the energy codes have spurred innovation in products and application techniques. This paper reviews the benefits of exterior continuous insulation, including the increase in wall effective R-value, reduction of thermal bridging, and reduction of potential for vapor condensation. The challenges of integrating exterior insulation into a wall system, including the complications of interfaces with other building components and the reduction in wall drying potential and water management will also be reviewed. Finally, this paper will describe recently introduced continuous insulation products and explore how they meet these challenges.

INTRODUCTION

Energy codes and certification have increased the interest in increasing the insulation level of opaque building envelope assemblies and spurred the development of new insulation materials and systems. One key building block in the design of energy efficient wall systems is incorporating exterior continuous insulation. Polystyrene and poly-isocyanurate foam boards have traditionally been used to provide continuous insulation, but because of their low vapor permeability they can present challenges to water management of wall systems. Integration with other building components such as windows and siding can also be an issue. As the drive to become more energy efficient increases, new insulation products have been brought to the market to address some of the deficiencies in the traditional products.

ENERGY CODE EVOLUTION

The challenges of diminishing resources and the need to reduce global climate change have led to an increased desire for energy efficiency. When residential and commercial occupancies are combined, the building sector comprises about 41% of the U.S. Energy consumption [U. S. Department of Energy].

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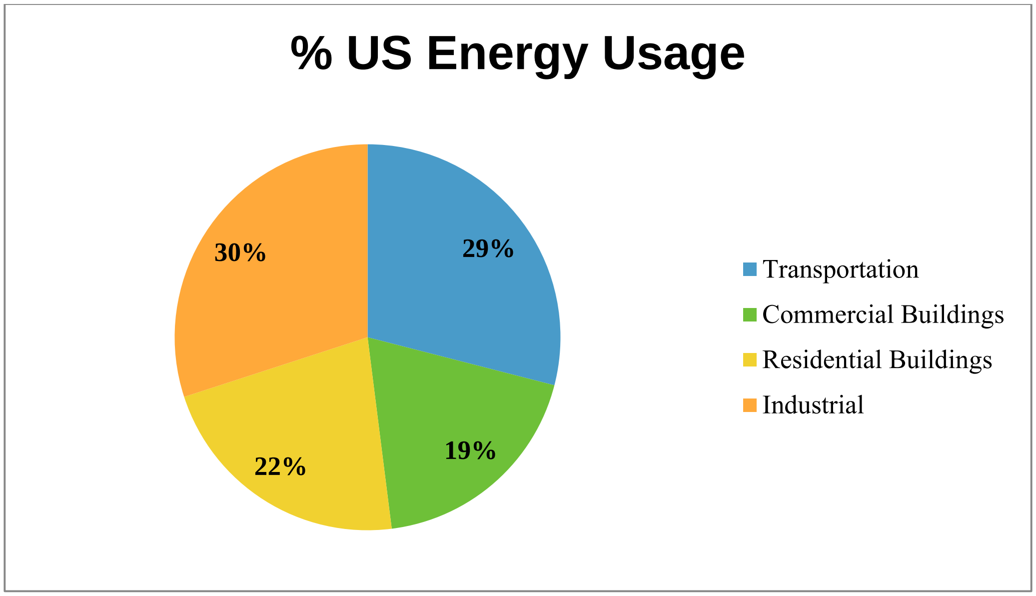

Figure 1. U. S. Energy Usage by Sector

Early energy efficiency gains had been made through utility and green building programs, most notably through the EPA's Energy Star for New Homes Program. Over the last 5 to 10 years, energy codes have picked up momentum, following the U.S. Federal government's setting of goals for improvements in both the residential and commercial energy codes. The actual energy efficiency determinations for residential energy codes versus the federal goal are shown in Table 1.

Table 1. Energy Code Determinations vs. Federal Goals

	IECC 2006	IECC 2009	IECC 2012	IECC 2015
US DOE Goal Improvement	Baseline	17%	30%	50%
US DOE Actual Determination	Baseline	14%	32%	34%

Key components in the advancement of the energy codes, have been an increase in the insulation required in opaque wall assemblies and more stringent air leakage requirements. As an example, the increase in R-value requirements in the Residential wood frame wall prescriptive path is shown in Table 2. [ICC 2006, ICC 2009, ICC 2012, ICC 2015-2] The increase in overall minimum R-values, as well as the increase in continuous insulation use, is evident.

Table 2. IECC Residential Wood Frame Wall R-value Requirements

CLIMATE ZONE	2006 IECC	2009 IECC	2012 & 2015 IECC
1	13	13	13
2	13	13	13
3	13	13	20 or 13+5
4 X-MARINE	13	13	20 or 13+5
4 MARINE	19 or 13+5	20 or 13+5	20 or 13+5
5	19 or 13+5	20 or 13+5	20 or 13+5
6	19 or 13+5	20 or 13+5	20+5 or 13+10
7	21	21	20+5 or 13+10
8	21	21	20+5 or 13+10

The development of residential air leakage requirements in the IECC provisions is shown in Figure 2. In 2006, air leakage requirements were vague and difficult to demonstrate compliance and enforce. In 2009, methods of demonstrating compliance were detailed with options for visual inspection or whole-building air leakage testing. The whole-building air leakage maximum at 7 ACH_{50}, was quite modest. In 2012 and upheld in 2015 was mandatory visual inspection and whole-building air leakage testing. The whole-building leakage maximum was reduced to much more challenging 5 ACH_{50} in climate zones 1 and 2, and 3 ACH_{50} in climate zones 3 through 8. Air leakage reduction is not only important to meet code, but it also improves the performance of insulation. The standard test method to determine R-value is conducted with no air pressure difference across the sample. In real conditions, air pressures differences from wind, mechanical systems or stack pressure can induce airflow through the insulation, resulting in reduced effective R-value. As shown in Figure 3, testing of thermal performance of wall assemblies with and without air flow demonstrates effective R-value can be reduced by more than 50% under low to moderate wind loads, especially when an air barrier is included in the wall system [Jones, 1995].

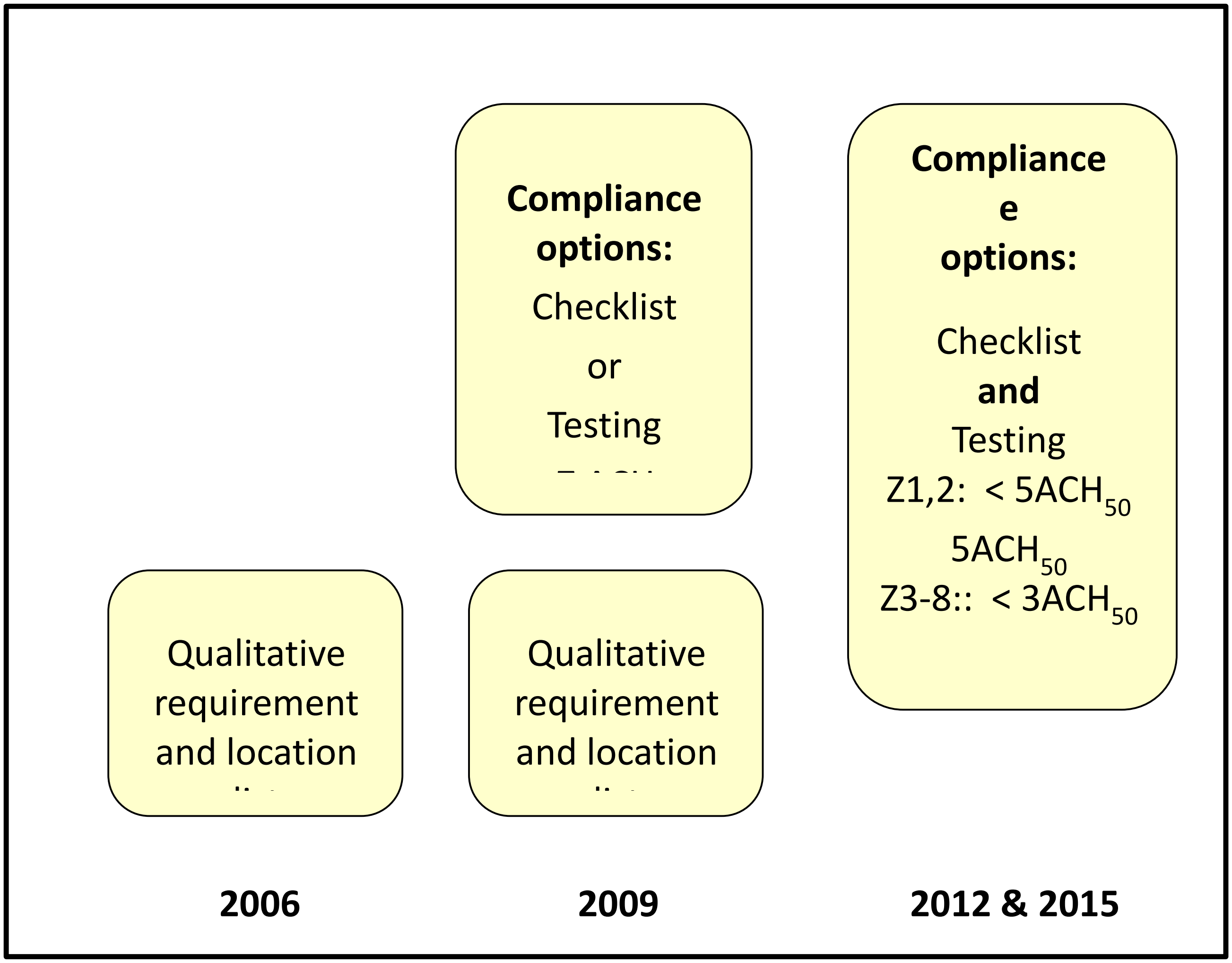

Figure 2. IECC Residential Air Leakage Requirements

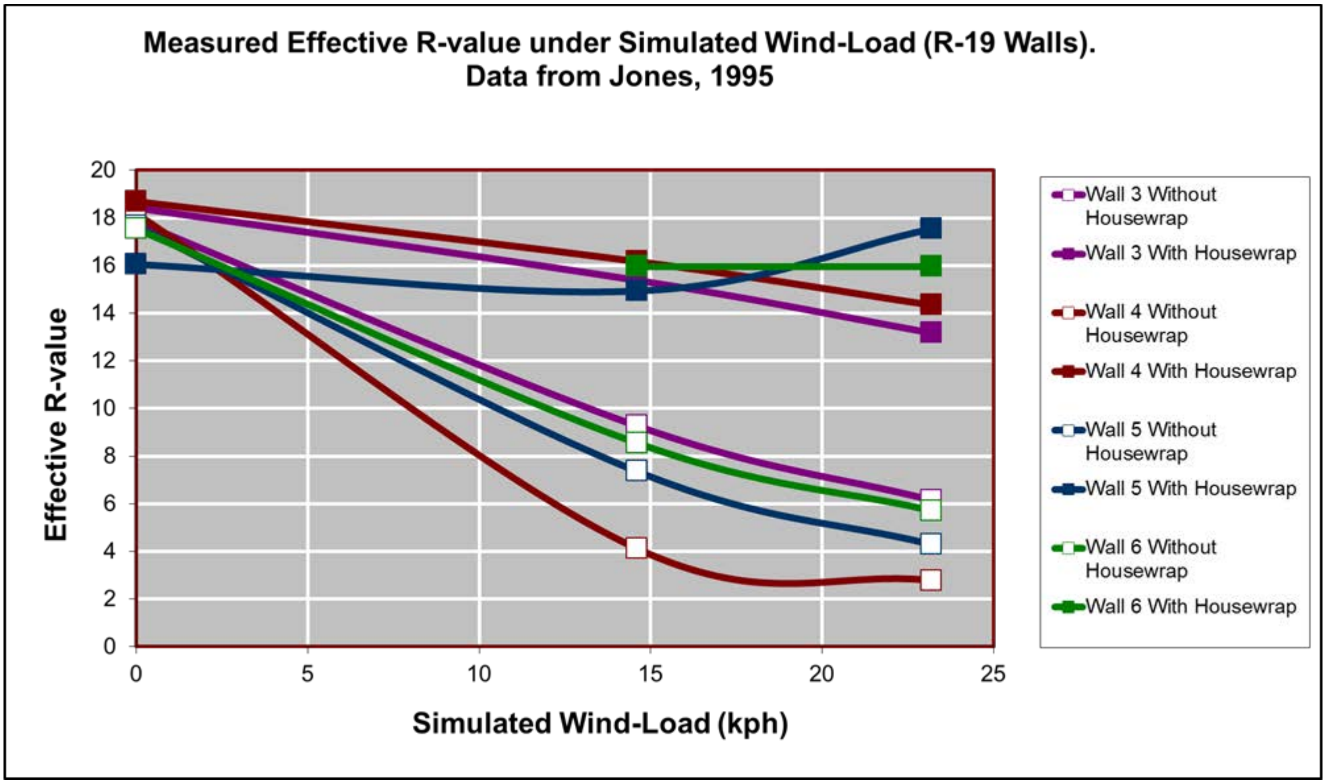

Figure 3. Wall Assembly Effective R-value as a Function of Simulated Wind Load

INSULATION DEVELOPMENT CRITERIA

Analysis of the energy code evolution showed that there was opportunity for new product development in insulation products. Key desired attributes include:

- Insulating performance: impact increased with continuous insulation performance
- Air barrier performance: provide a continuous and durable air barrier for the wall system which can be integrated with other building envelope assemblies
- Water management performance: include both the ability to be detailed and perform as a water-resistive barrier and providing forgiveness (drying) in the event of incidental water entry.

Each of these performance requirements is described in more detail in the following sections.

Insulating Performance: Benefits of Continuous Insulation. The primary benefit of continuous insulation is the reduction in thermal bridging at the studs leading to a more uniform and higher thermal resistance for the wall system. The results can easily be seen when houses with and without exterior insulation are compared using infrared (IR) photography as can be seen in Figures 4 and 5. These figures show two houses in the Columbus, OH region. The only difference in the wall system design is the inclusion of continuous exterior insulation in the house in Figure 5. Thermal bridging reduces the overall R-value of the wall system, as is quantified in the calculations shown in Table 3.

An additional benefit of exterior continuous insulation is the warming of the interior sheathing surface. This surface is a potential plane of winter-time condensation if vapor intrudes past the interior vapor/air barrier. Its warming reduces the potential for water condensing within the wall assembly.

Because of the various benefits provided by exterior continuous insulation, it should be a focus of product innovation.

Figure 4. IR Photography of house in Columbus, OH with no exterior insulation.

Figure 5. IR Photography of house in Columbus, OH with exterior continuous insulation.

Table 3. Total Calculated Wall R-value for Different Wall Assemblies

Wall Assembly Component	**2x4**		**2x6**		**2x4 + c.i.**	
	Studs	Cavity	Studs	Cavity	Studs	Cavity
Outside Air Film	0.17	0.17	0.17	0.17	0.17	0.17
Exterior Insulation	n/a	n/a	n/a	n/a	5	5
½" OSB	0.62	0.62	0.62	0.62	0.62	0.62
Stud Wood	3.71	n/a	5.83	n/a	3.71	n/a
Cavity Insulation	n/a	13	n/a	20	n/a	13
½" Gypsum Wallboard	0.45	0.45	0.45	0.45	0.45	0.45
Interior Air Film	0.68	0.68	0.68	0.68	0.68	0.68
Total	**5.6**	**14.9**	**7.75**	**21.9**	**10.6**	**19.9**
Total Wall (Standard Framing - 23%)	**10.8**		**15.4**		**16.6**	
Total Wall (Advanced Framing – 17%)			**16.7**			

Air Barrier Performance. Many materials have been used to reduce air leakage in buildings. For residential wall systems, the most common air barrier material is a continuous sheet material, sometimes referred to as a "house wrap", which is detailed as an air barrier at interfaces and connections. Performance of house wraps to provide air leakage protection was reviewed in 2006 [Weston, 2006]. This study concluded that *"Significant research has been conducted to characterize the performance of house wrap materials and their ability to control air leakage in residential construction. The research clearly shows that house wraps if installed correctly can* *significantly reduce air leakage and provide the associated energy savings."* The performance of house wraps to control air leakage was also documented in a field study on a high performance home showed that with correct detailing and installation a house wrap can provide the air barrier performance sufficient to meet the 2012 and 2015 air leakage requirements [Oberg, 2011] . Taping the seams of board products has been proposed to provide air barrier performance. However, taping of board products, such as foam sheathing, may not provide a durable air barrier. Figure 6 shows the results of air leakage testing of taped foam board and typical house wrap wall assemblies. Both assemblies were tested as built and after thermal cycling. While both assemblies met assembly air barrier requirements as-built, after thermal cycling the foam sheathing wall exhibited air leakage in excess of the maximum allowable air leakage while the house wrap wall continued to meet requirements. The data can indicate that exterior insulation wall assembly innovation should focus on insulation systems that either include a separate air barrier layer, or incorporate an air barrier layer that be integrated to provide air barrier continuity as part of the insulation product.

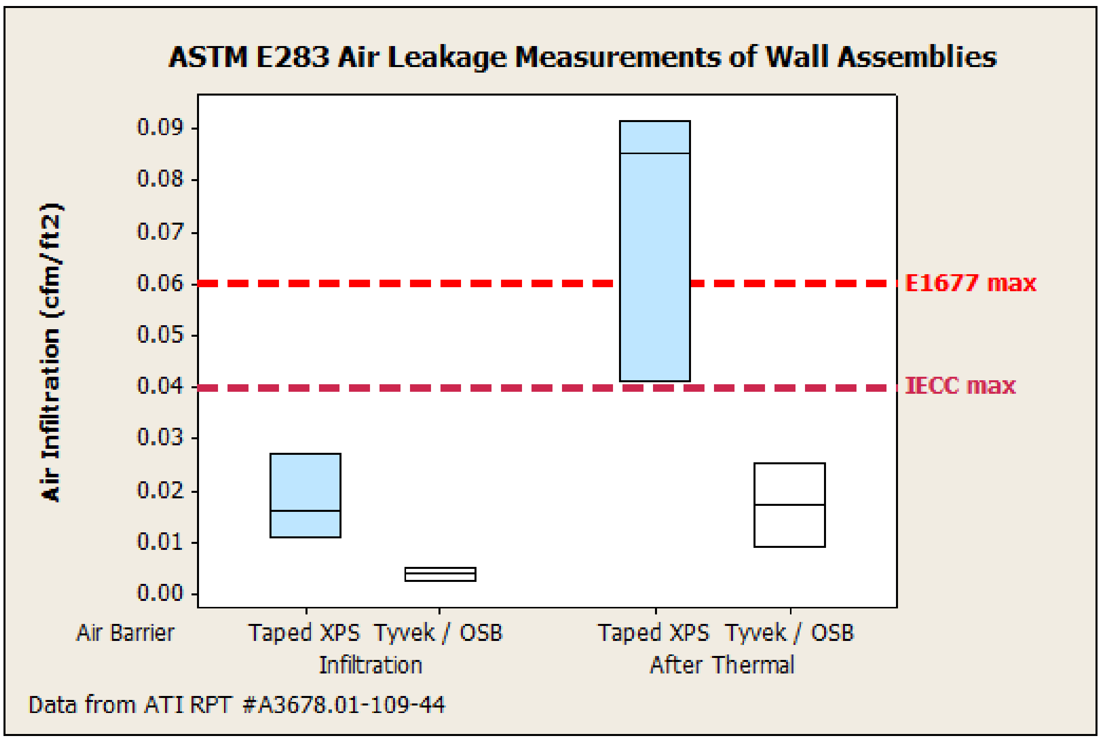

Figure 6. Air Leakage of Wall Assemblies As-Built and after Thermal Cycling

Water Management Performance. To manage water properly, a wall system must not only resist wetting it must also allow drying if there is any incidental moisture entry. The building code requirements focus on four areas of water management of wall assemblies:

- Flashing at intersections
- Water-resistive barrier

- Means of draining water
- Protection against condensation

The first three items deal with prevention of bulk water intrusion, such as from precipitation. "Protection against condensation" will be increased to some extent by any exterior insulation because the warming of the exterior sheathing surface and will be increased by air barrier incorporation.

Performance of a water-resistive barrier is dependent on both material and installation. The International Residential Code provides the basic requirements for both materials and installation [ICC 2015-3]:

> *"One layer of No. 15 asphalt felt, free from holes and breaks, complying with ASTM D226 for Type 1 felt or other approved water-resistive barrier shall be applied over studs or sheathing of all exterior walls. Such felt or material shall be applied horizontally, with the upper layer lapped over the lower layer not less than 2 inches (51 mm). Where joints occur, felt shall be lapped not less than 6 inches (152 mm). The felt or other approved material shall be continuous to the top of walls and terminated at penetrations and building appendages in a manner to meet the requirements of the exterior wall envelope as described in Section R703.1."*

The requirements invoke shingling as a traditional method of water management. Taped board products have been proposed to perform as a water-resistive barrier. These systems do not utilize shingling to allow water to drain off the assembly, but rely on the tape adhesion to prevent water entry. The tape joint is very dependent on installation conditions to perform. For examples, poor adhesion can result if the substrate surface is cold, wet, or dirty during installation. Additionally, for board products that have significant thermal expansion and contraction, the tape joint will be stressed as the assembly is subjected to normal temperature cycles. This has been noted in past studies, "*With some question as to the long term dimensional stability of insulating sheathing products, this should only be used in areas with limited rainfall and exposure, where rain water management is not as critical*" [Baker, 2006] .

To examine the performance of taped seams of foam sheathing for water intrusion, wall assemblies were tested before and after thermal cycling using ASTM E331 [ASTM, 2009] . Figure 7 shows water (dyed red) has intruded at taped foam-board interfaces.

To best prevent water intrusion, an exterior continuous insulation product would need to be flexible enough to be installed and integrated with flashings in shingled manner or to be installed with a separate water resistive barrier. For wall systems involving rigid board exterior insulation a separate water-resistive barrier is advisable.

Figure 7. Wall Specimen after Testing with E331 showing water intrusion at foam insulation board taped seams.

The second key to good water management is to allow for drying. The ability for a wall to dry will help provide for durability whether the source is bulk water, condensation from air leakage or vapor diffusion, or built-in construction moisture. The codes require interior vapor retarders in cold climates to reduce winter-time moisture condensation. Problems may occur, however, if exterior insulation has low vapor permeability. In this case, there is restricted drying at both the exterior and interior boundaries of the wall assembly. In a modeling study of different wall assemblies subjected to small amounts to water intrusion concluded that this wall assembly condition was at increased risk of moisture accumulation [Weston 2012]. Figure 8 shows the results of 3-year moisture simulations in Minneapolis climate zone with either no water intrusion, or with intrusion of 1% of the water that impacts the exterior wall surface. The results compare walls with exterior foam sheathing (vapor retarder) with walls with a vapor permeable exterior insulation. Both walls had kraft paper vapor retarder to meet the minimum code requirement. The results show year-over-year accumulation in wall total water content in the wall with foam sheathing, while the vapor permeable exterior insulation was able to manage the water intrusion with no total water content accumulation. These results indicate that a vapor permeable exterior insulation would be preferred to effectively manage water.

The need for a vapor open exterior insulation has begun to be included in code provisions. In 2015, the International Building Code included restrictions on interior vapor retarders when walls incorporate vapor impermeable exterior insulation: [ICC 2015-1]

> *" 1405.3.12 Class III vapor retarders…. Only Class III vapor retarders shall be used on the interior side of frame walls where foam plastic insulating sheathing with perm rating of less than 1 perm is applied in accordance with Table 1405.3.1 on the exterior side of the frame wall."*

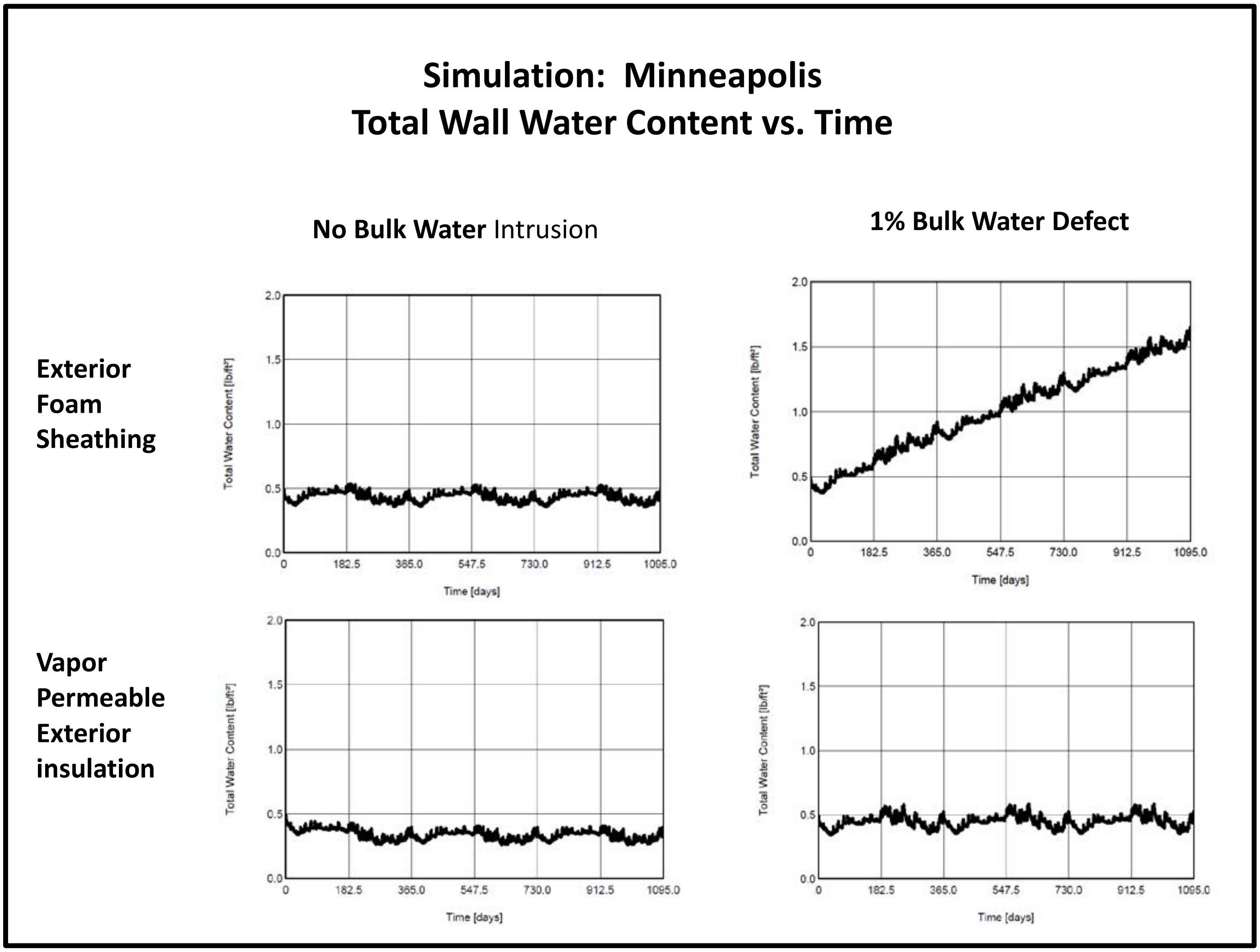

Figure 8. Moisture Simulations indicating higher moisture accumulation risk with both exterior and interior vapor barriers.

PRODUCT DEVELOPMENT RECOMMENDATIONS

Weighing the factors of thermal performance, air leakage reduction and water management, an insulation product was developed. It was a 1 ¼″ polymer fibrous batt that was faced with vapor permeable air and water-resistive barrier sheet. The product is provided in roll form with flaps of the facing that can be used to shingle over previously installed layers. This is just one possible insulation solution. Many other products of systems could be designed. The criteria described in this paper is a starting point but the choice of specific solution need to respond to constructability and cost concerns of a specific project. Constructability concerns include:

- Safety & ergonomics during the construction process
- Job-site storage requirements
- Installation dependence on environmental conditions
- Ease of installation
    - Is the new system installed in a similar way to existing products?
    - Can it be installed by existing trades?
    - Does it require a high level of specialization to install?
- Reliability & repeatability of the installation.
- Integration with other products (Can the next group of laborers work easily on top of it?)

Finally cost assessment should not be confined to first material cost. Also included should be costs of implementing a new product including costs associated with design changes and required contractor training or re-training. Installation costs should include any required environmental conditions required by the system and any adaptation needed by adjacent components. Finally, the costs associated with call-backs and long term moisture intrusion should be assessed.

SUMMARY AND CONCLUSIONS

The increasing stringency in energy and building codes is stirring interest in innovation of insulating products and systems. Product innovation should not focus on the single attribute of material R-value, but should evaluate durability and insulation effectiveness of the entire wall system. Water resistance concerns in existing systems were discussed. Product development recommendations include energy efficiency performance, moisture management performance and constructability of the system.

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Evaluation of Air Quality in Buildings Located Above TCE and Chloroform Contaminated Plume – A Field Study

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ABSTRACT

Vapor intrusion (VI) has been recognized since the 1990s as a potential pathway of concern at contaminated sites. VI is the migration of volatile organic compounds (VOCs) from the subsurface soils into overlying buildings. The major sources of organic vapors are waste disposal sites (landfills), contaminated old industrial sites, contaminated subsurface soils, and contaminated groundwater. The volatile organic compounds of concern in vapor intrusion are usually divided into two categories: chlorinated VOCs and petroleum hydrocarbons.

Several residential and commercial buildings were built on a closed old industrial site in the 1990s. Due to the presence of TCE and chloroform in a groundwater plume located under the site, VI investigation was conducted at the commercial and residential buildings located on and around the site. Sub-slab soil gas and indoor air samples were collected to determine the indoor air quality in these buildings using Summa canisters equipped with flow controls. All samples were analyzed for volatile organic compounds using the USEPA Method TO-15. The analytical data were compared with background ambient air data and the New Jersey Department of Environmental Protection (NJDEP) soil gas and indoor air screening levels.

The results indicated that chlorinated volatile organic compound including TCE and chloroform were present above the NJDEP screening levels in the sub-slab soil gas and indoor air samples collected from several buildings. To remediate the existing condition, a sub-slab depressurization system (SDS) was installed under the slab of each building with elevated levels of TCE and chloroform. After installation of the SDS, indoor air sampling was performed to determine the indoor air quality in these buildings. It was recommended that yearly inspection of the SDS and indoor air sampling be conducted.

Key Words: Vapor intrusion, indoor air, soil gas, PCE, TCE, CVOC

INTRODUCTION

The migration of volatile organic compounds from the contaminated groundwater into the indoor of overlying buildings through subsurface soils or preferential pathways (such as underground utilities) is known as vapor intrusion. VOCs of concern are usually divided into two categories: chlorinated volatile organic compounds and petroleum hydrocarbons (Tillman and Weaver, 2005)

Adults living in North America spend an estimated 80-90% of their time indoors (Orwell et al., 2004; Dales et al., 2008). Some of the VOCs identified in indoor air are considered suspected or confirmed carcinogens by the World Health Organization (WHO), an International Agency for Research on Cancer (IARC).

Vapor intrusion has been recognized since the 1990s as a potential pathway of concern at contaminated sites. It attracted national attention when news revealed human exposures to 1,1-dichloroethene (1,1-DCE) vapors from the contamination at Denver's Ridgefield rifle scope factory in 2002 (Obmascik, 2002). A number of vapor intrusion investigations have been conducted since the 1990s to determine the source of contamination in soil and groundwater, the migration of VOCs from the source into buildings, the factors affecting vapor intrusion, and how to remediate vapor intrusion (Erdogan and Hsieh, 2013; Fisher et al., 1996; Folkes and Kurtz, 2002; McDonald and Wertz, 2007; McHugh et al., 2007; Moseley and Meyer, 1992, and Sanders and Hers, 2006).

Some investigators have suggested using models with site-specific data to evaluate the VI pathway (McHugh et al., 2006; Yao et al., 2011, and McAlary et al., 2014, Diallo, et al., 2015). Models have their own additional challenges, often being either simplified and not accounting for all fate and transport processes, or complex and containing unmeasurable parameters. For screening level purposes, a simplified model may be appropriate, if it can be shown to produce a worst case prediction of current and future exposure in all cases. An example of the screening level model is the widely used Johnson and Ettinger vapor intrusion model (Johnson and Ettinger, 1991). One dimensional diffusion through the unsaturated zone and advection and diffusion through building slab are incorporated into the model, but biodegradation of organic vapors is not included (Tillman and Weaver, 2005).

Predicting whether or not vapor intrusion will occur at rates sufficient to cause health risk is extremely difficult and depends on many factors (Yao et al., 2011). Major factors to be considered during a vapor intrusion investigation include the presence and concentrations of the pollutants, distance to the contamination source, groundwater flow direction, soil type, depth to groundwater below the foundation, type of foundation, geology of the site, preferred pathways (utility lines), occupied levels, the presence of a clean water lens on top of the groundwater aquifer, weather conditions, and ventilation (Erdogan and Hsieh, 2013)

Indoor air sampling and analysis is a fairly routine procedure, yet the interpretation of the results is often difficult (Sanders and Hers, 2006). Many household building supplies and products such as household cleaners, sealants, gules, adhesives, paints, lubricants, and personal care products contain organic compounds identical to common contaminants in soil or groundwater (Sanders and Hers, 2001). The quality of the outside air may also be important because some of these contaminants may be present in the outside air. Additionally, VOCs may be emitted from wall board, ceiling, tile, carpet, and upholstery during high concentration periods (Sanders and Hers, 2006).

New Jersey Department of Environmental Protection (NJDEP) has developed a technical guidance document based on a phased approach for investigating the VI pathway (NJDEP, 2012) The NJDEP technical guidance follows the basic provisions of the USEPA VI guidance (USEPA, 2002). NJDEP's VI investigation procedure involves four stages: receptor evaluation, site investigation, mitigation, and maintenance and monitoring. It begins with evaluation of the VI receptor and assessment of the potential for VI. The second stage involves site investigation and evaluation of the analytical data. At the third stage, appropriate mitigation technologies are identified and implemented. The fourth stage is a long-term maintenance and monitoring of the mitigation system.

NJDEP has developed groundwater screening levels (GWSLs), soil gas screening levels (SGSLs), and indoor air screening levels (IASLs) to be used in the third stage. Exceedances of these screening levels will require further evaluation of VI and possible mitigation of the VI pathway (NJDEP, 2012).

The purpose of this study was to investigate VI of chlorinated volatile organic compounds (CVOC) including tetrachloroethene (PCE), trichloroethene (TCE), and chloroform at several houses located above the CVOC plume and adjacent to the contaminated site.

BACKGROUND

The contaminated site investigated in this study is located in northern New Jersey. In 1956, Ronson Metals, Inc. (RM) built a manufacturing facility at the site to produce thorium-containing metal discs and coating strips referred as getters. Discs were produced using michmetal, a mixture of rare earth elements in the lanthanide series. The facility consisted of several buildings and associated paved parking areas. The facility ceased operation in 1989 and underwent remedial investigation and remediation under the NJDEP Industrial Site Recovery Act (ISRA) formerly known as ECRA (Environmental Cleanup Responsibility Act).

The facility had a hazardous waste disposal operation (i.e., incinerator) on site. Hazardous waste was stored in 55 gallon drums. At one time, there were between 2,000 and 3,000 drums stored in one of the buildings. On October 2, 1985, NJDEP conducted a site inspection and observed that some of the drums were leaking. Record showed that the facility filed the Part B Resource Conservation and Recovery Act (RCRA) application for obtaining a hazardous waste disposal permit in 1984.

The site is situated in the Triassic lowlands of the piedmont physiographic province of New Jersey. Based on the New Jersey Geologic Survey, the near surface soil of this region is Passaic formation consisting of sandstone, siltstone, shale and conglomerates (NJGS, 2003). Soil boring and testing conducted during the study revealed the presence of 1-3 feet of fill material at the site. The fill material was underlain by brown, yellow brown and red brown silt, sandy silt and clayey silt to a depth of at least 3 feet.

In addition, the site investigation has revealed the presence of a 550 gallon underground storage tank (UST) at the site. The UST was removed on March 17, 1992 and three soil samples (T1, T2, and T3) were collected from the excavation and analyzed for total petroleum hydrocarbons (PHC), priority pollutant volatile organic compounds (PP VOCs), and lead. Lead was detected in soil samples at concentrations of 35 ppm, 630 ppm and 16 ppm. TCE was also detected above NJDEP soil remediation standards in these samples. Figure 1 shows contaminated areas that were remediated during the investigation.

Pursuant to ISRA rules and requirements, a cleanup plan was developed to investigate and remediate the site in 1992. Groundwater investigations conducted in April 1992 and May 1992 revealed the presence of CVOC beneath the site and nearby residential and commercial areas. Groundwater sampling identified a large plume of VOCs including trichloroethene, tetrachloroethene, 1,1-dichloroethene, vinyl chloride, ethylbenzene, and xylenes under the site. VOCs detected in the groundwater samples are given in Table 1.

During the investigation, soil sampling was also conducted to determine the environmental impact of facility operations on the surrounding soils and subsurface soils. The analytical data revealed the elevated levels of heavy metals including arsenic, barium, lead, and radioactive metals such as cerium and samarium, and chlorinated volatile organic compounds, specifically, trichloroethene, tetrachloroethene, and chloroform in surface and subsurface soils.

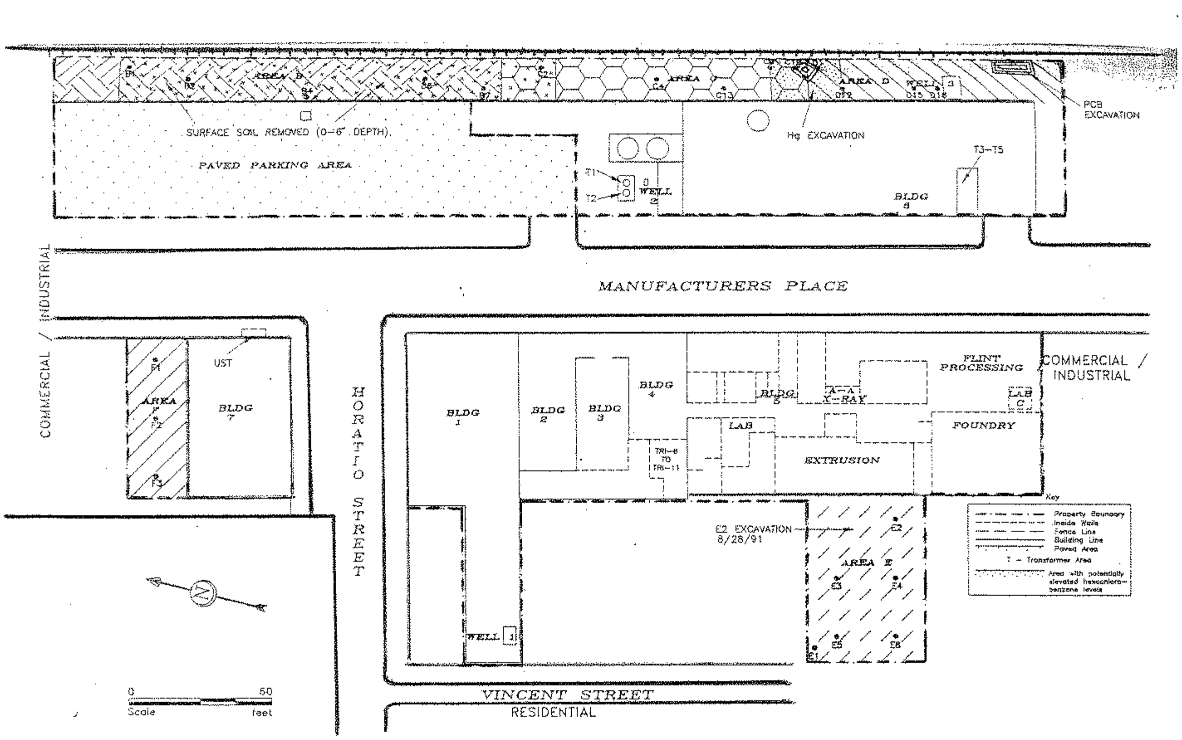

Figure 1. Contaminated and remediated areas identified at the former RM site

The site cleanup began in 1998. Hot spots containing heavy metals and radioactive materials were excavated and removed. After completion of the remediation activities, lead and TCE were the only contaminants remaining at the site above NJDEP soil cleanup standards. In order to remediate the remaining contaminated areas, engineering controls (capping) and institutional controls (Deed Note) were implemented at the site on February 19, 2002.

The cap designed for the impacted areas included six (6) inches of a clay layer, geotextile fabric and six (6) inches of a gravel layer. Clay layer was placed over the TCE impacted area and geotextile was placed over the clay layer. Six (6) inches of ¾ inch gravel was then placed on the top of the geotextile. A Deed Notice restricting use of the site was filed with township for the impacted areas.

After remediation of the impacted areas, several residential units were built at the site. This investigation was conducted to determine whether there is a potential VI into the residential and commercial buildings built at the site. Figure 2 shows the site and residential and commercial units built at the site.

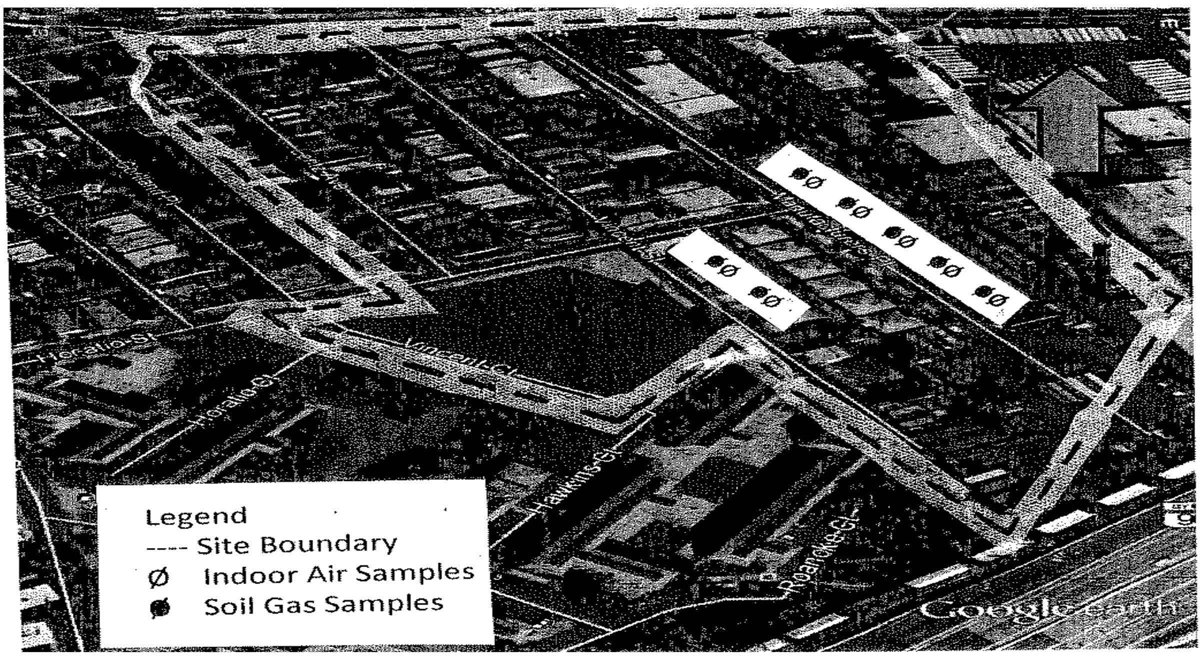

Figure 2. Former RM site and residential and commercial buildings surrounding the site

APROACH

Sub-slab soil gas, and indoor air and outdoor air samples were collected during VI investigation from the residential buildings located above the VOC plume.

To determine whether there is a potential for vapor intrusion into the nearby buildings, groundwater samples, sub-slab soil gas samples, and indoor air samples were collected from the affected buildings.

The first step was to collect groundwater samples at the site to determine the concentration of VOCs and the flow direction. On March 19, 1992, a groundwater monitoring well was installed at the site and the well was sampled on April 7 and May 14, 1992. Groundwater samples were analyzed for volatile organic compounds. Concentrations of VOC detected in groundwater are presented in Table 1.

Table 1 shows trichloroethene, tetrachloroethene, and total xylenes exceeded the NJDEP groundwater quality standards (GWQS). Concentrations of TCE exceeded the NJDEP groundwater screening levels (GWSLs) as well as the NJDEP GWQS.

Elevated levels of chlorinated volatile organic compounds and petroleum hydrocarbons in groundwater triggered a vapor intrusion investigation. The NJDEP Vapor Intrusion Technical Guidance requires that a VI investigation be conducted at structures located above or/and within 100 feet of a shallow VOC plume containing contaminants above the NJDEP GWQS or/and GWSLs. It also requires benzene, toluene, ethylbenzene, and xylenes (B TEX) sampling within 30 feet of the BTEX plume.

Table 1. Concentrations of VOC detected in groundwater

Volatile Organic Compounds (VOCs)	**NJDEP Groundwater Quality Standards (GWQS)**	**NJDEP Groundwater Screening levels (GWSLs)**	**Concentration of CVOC µg/L**	**Concentration of CVOC µg/L**
	µg/L	**µg/L**	**April 7, 1992**	**May 14, 1992**
Trichloroethene (TCE)	1	2	37	27
Tetrachloroethene (PCE)	1	31	24	12
Ethylbenzene	700	700	30	160
Xylenes (total)	40	8,600	100	215
1,1-Dichloroethene	2	260	U[5][a]	U[5]
Vinyl chloride	5	1	U[10]	10[b]

Notes:
All concentrations are in microgram per liter (µg/L)
a: U = Undetected; method detection limit [MDL]
b: Detected at levels below the MDL; estimated value

In order to determine the extent of indoor air pollution resulting from contaminated subsurface soils and groundwater, it is important to determine the background sources first. To identify potential background sources, Building Indoor Air Survey and Sampling Forms developed by the NJDEP were distributed to the residences prior to conducting sub-slab soil gas and indoor air sampling.

Sub-slab soil gas samples were collected using stainless steel 1 liter Summa canisters equipped with flow controllers. The maximum flow rate into each Summa canister was 200 millimeter per minute, which corresponds to a sample time of 5 minutes for 1 liter canisters. The canister's pressure was set at approximately -30 inches of mercury at the laboratory prior to shipment.

A minimum of one sample per 1,500 square feet of residential or commercial space was collected for indoor air. Indoor air samples were collected from the breathing zone (3-5 feet above the floor basement) using 6 liter stainless steel Summa canisters over a 24 hour period. All samples were analyzed for VOCs using the USEPA Method TO-15.

RESULTS AND DISCUSSION

Sub Slab Soil Gas Sampling

Based on the results of the groundwater investigation, site inspection was conducted to determine sampling locations, and numbers of sub-slab soil gas samples and indoor air samples.

During the period of February 23 to 25, 2013, the investigation team collected sub-slab soil gas samples at six (6) residential buildings (Building #1, #2, #3, #4, #5, and #6) located above the CVOC contaminated plume. A total of six (6) sub-slab soil gas samples, SS-1, SS-2, SS-3, SS-4, SS-5, and SS-6 (one sample from each building) were collected and analyzed for VOCs. All samples were collected using Summa canisters equipped with flow controls. Samples were sent to TestAmerica Burlington Laboratory, Inc. for the VOC analysis using USEPA TO-15 method.

The results of sub-slab soil gas samples and indoor air and outdoor air samples were compared with the NJDEP residential soil gas screening levels and indoor air screening levels. The results of sub-slab soil gas samples are presented in Table 2. Chloroform exceeded the SGSLs in four samples and TCE exceeded the SGSLs in all five samples.

Table 2 reveal the presence of elevated levels of trichloroethene (TCE) and chloroform in the sub-slab soil gas samples collected from these buildings. TCE was detected in sub-slab soil gas samples SS-1, SS-2, SS-3, SS-4, SS-5, and SS-6 at concentrations of 25,000 $\mu g/m^3$, 13,000 $\mu g/m^3$, 5,000 $\mu g/m^3$, 1,700 $\mu g/m^3$, 4,500 $\mu g/m^3$, and 2,000 $\mu g/m^3$, respectively. These concentrations exceeded both the residential and non-residential soil gas screening levels. These concentrations also exceeded 10 times the residential SGSL of 27 $\mu g/m^3$ for TCE.

Several other contaminants were also detected in the sub-slab soil gas samples. However, concentrations of these contaminants were below the SGSLs with the exception of chloroform. Chloroform was detected in sub-slab soil gas samples SS-1, SS-2, SS-4, SS-5, and SS-6 at concentrations of 37 $\mu g/m^3$, 64 $\mu g/m^3$, 49 $\mu g/m^3$, 37 $\mu g/m^3$, and 30 $\mu g/m^3$, respectively. These concentrations exceeded the SGSL of 24 $\mu g/m^3$ for chloroform.

Indoor Air Sampling

On July 23, 2013, the investigation team collected indoor air samples at the same six (6) residential buildings located above the VOC plume. A total of six (6) indoor air samples IA-1, IA-2, IA-3, IA-4, IA-5, and IA-6 (one sample from each building) were collected. In addition, an ambient air sample, IA-7 was collected outside in front of the buildings. Indoor air samples were analyzed for VOCs using the USEPA Method TO-15. Concentrations of VOCs detected in the indoor air samples are presented in Table 3.

Table 2. Concentrations of VOCs detected in sub-slab soil gas samples

Chemical	NJDEP Residential Soil Gas Screening Levels ($\mu g/m^3$)	Sub-Slab Soil Gas Samples					
		SS-1	SS-2	SS-3	SS-4	SS-5	SS-6
Acetone	1,600,000	-	240	-	120	580	120
Chloroform	24	**37**	**64**	12	**49**	**37**	**30**
Carbon disulfide	36,000	-	-	-	20	25	-
1,1-Dichloroethane	76	24	-	-	-	-	-
1,1-Dichloroethene	10,000	31	-	-	-	-	-
1,2-Dichloroethene (cis)	NA	1,900	690	-	35	160	290
1,2-Dichloroethene (trans)	3,100	230	220	-	20	110	25
n-Heptane	NA	-	-	-	34	-	-
n-Hexane	36,000	-	-	-	55	-	-
Methyl ethyl ketone	260,000	49	-	-	-	-	17
Toluene	260,000	-	-	-	-	8	16
Tetrachloroethene (PCE)	470	46	-	-	-	-	-
1,1,1-Trichloroethane	260,000	47	-	-	-	-	-
Trichloroethene (TCE)	27	**25,000**	**13,000**	**5,000**	**1,700**	**4,500**	**2,000**

Notes:
Only compounds detected at one or more sample locations above the analytical reporting limits are listed in this table.
All results are in micrograms per cubic meter ($\mu g/m^3$).
NA – A Soil Gas Screening Level is currently unavailable for this chemical.
ND - Not Detected
Bolded and shaded results identify exceedances of the applicable NJDEP Soil Gas Screening Levels.

The indoor air analytical data were evaluated using the NJDEP residential indoor air screening levels. Table 3 revealed the presence of elevated levels of TCE in indoor air samples. TCE was detected in the indoor air samples IA-1, IA-2, IA-3, IA-4, IA-5, and IA-6 at concentrations of 5 $\mu g/m^3$, 32 $\mu g/m^3$, 16 $\mu g/m^3$, 23 $\mu g/m^3$, 22 $\mu g/m^3$, and 5 $\mu g/m^3$, respectively. These concentrations have exceeded the residential IASL of 3 $\mu g/m^3$ for TCE. Other VOCs including benzene, carbon tetrachloride, chloroform, 1,4-dichlorobenzene, and ethylbenzene were also detected above the residential IASLs in some of the indoor air samples.

Benzene was detected in the sample IA-5 at a concentration of 6 $\mu g/m^3$. Carbon tetrachloride was detected in the sample IA-3 at a concentration of 5 $\mu g/m^3$. Chloroform was detected in indoor air samples IA-2, IA-3, and IA-5 at concentrations of 72 $\mu g/m^3$, 15 $\mu g/m^3$, 8 $\mu g/m^3$, respectively. 1,4-dichlorobenzene was detected in the sample IA-2 at a concentration of 5 $\mu g/m^3$. Ethylbenzene was detected in the sample IA-3 and IA-5. Concentrations of these contaminants exceeded the residential IASLs.

Sub-slab soil gas and indoor air analytical data show that the main contaminants of concern in these buildings are TCE and chloroform. Concentrations of TCE detected in the sub-slab soil gas samples are more than 10 times the residential SGSL of 27 $\mu g/m^3$ and non-residential SGSL of 150 $\mu g/m^3$ for TCE. In addition, concentrations of TCE detected in indoor air samples also exceeded both the residential and non-residential IASL of 3 $\mu g/m^3$ for TCE.

Table 3. Concentrations of VOCs detected in indoor air samples

Chemical	NJDEP Residential Indoor Air Screening Levels (µg/m^3)	Indoor air Samples					
		IA-1	IA-2	IA-3	IA-4	IA-5	IA-6
Benzene	2	2	1	2	ND	**6**	2
Carbon tetrachloride	3	ND		**5**	ND	ND	ND
Chloroform	2	**ND**	**72**	**15**	**ND**	**8**	ND
1,4-Dichlorobenzene	3	**ND**	**5**	ND	**ND**	**ND**	**ND**
Ethylbenzene	2	2		**3**	ND	**8**	ND
Trichloroethene (TCE)	3	**5**	**32**	**16**	**23**	**22**	**5**

Notes:
Only compounds detected at one or more sample locations above the analytical reporting limits are listed in this table.
All results are in micrograms per cubic meter (µg/m^3).
ND – Not Detected
Bolded and shaded results identify exceedances of the applicable NJDEP Indoor Air Screening Levels.

Chloroform was detected above the residential and non-residential IASL of 2 µg/m^3 in three of the six indoor air samples collected. Concentrations of chloroform ranged from 8 µg/m^3 to 72 µg/m^3. Chloroform is often associated with chlorinated drinking water, the common use of bleach, and leaking sewer lines.

With the exception of chloroform, none of the other contaminants, including benzene, carbon tetrachloride, and 1,4-dichlorobenzene, and ethylbenzene present in the indoor air samples, were detected in the sub-slab soil gas samples. Therefore, these contaminants are not related to the previous operations conducted at the site. They may be due to the use of household products at these houses.

The results of indoor air samples were also compared to the NJDEP residential rapid action levels (RALs). The RALs are generic indoor air numbers developed by the NJDEP to determine whether further investigation or implementation of an interim remedial measure is needed (NJDEP, 2012). Any compound that exceeds the RALs triggers a call for prompt action.

The evaluation of the VI analytical data indicated that VI pathways exist at these residences for TCE and chloroform. TCE was detected above the residential and non-residential IASL of 3 µg/m^3 in all six indoor air samples. In addition, TCE was detected above the residential and non-residential SGSLs in all six sub-slab soil gas samples. Concentrations of TCE detected in the indoor air samples also have exceeded the RAL of 4 µg/m^3. The decision flow chart developed by the NJDEP and RALs indicated that implementation of interim remedial measures are necessary in these residences (NJDEP, 2012).
At the present time the most common method of remediating VI is installation of a subsurface depressurization system. A subsurface depressurization system was installed by the NJDEP at these six houses. The subsurface depressurization system works by intercepting soil gas prior to its entry across the building foundation and directing it aboveground to the outdoor air. Perforated pipes are placed under the basement to collect soil gas. An exhaust fan pulls air

through these pipes and vents it to the atmosphere. The cracks and penetrations in the building foundation have been sealed to prevent VI.

In order to determine whether the implemented remedy is effective for preventing VI in these buildings, an indoor air sampling was conducted at these six residences on July 10, 2014. Post-remediation indoor air samples and outdoor air samples were collected and analyzed for VOCs using the USEPA Method TO-15. The data indicated that the implemented remedy is working very well and affectively removing the contaminated soil gas from beneath the basement slab of these houses. The post-remediation analytical data are presented in Table 4. As shown in Table 4, no VOCs including TCE and chloroform were detected above the IASLs in the post-remediation indoor air samples.

Table 4. Concentrations of VOC detected in the post-remediation indoor air samples

Chemical	NJDEP Residential Indoor Air Screening Levels (μg/m^3)	Indoor air Samples						Outdoor Air Sample
		IA-1	IA-2	IA-3	IA-4	IA-5	IA-6	
Acetone	32,000	20	96	110	18	31	130	ND
Benzene	2	**4**	2	2	1	2	2	1
Chloromethane	94	1	2	1	1	2	1	1
Chloroform	2	ND	ND	3	1	ND	ND	ND
Cyclohexane	6,300	0.7	0.9	1	ND	ND	1	ND
Dichlorodifluoromethane	100	ND	3	ND	3	3	3	ND
Ethylbenzene	2	4	1	ND	ND	2	1	1
n-Heptane	NA	2	1	1	ND	2	ND	ND
n-Hexane	730	5	2	4	1	3	2	2
Methylene chloride	94	3	3	ND	ND	3	3	4
Methyl ethyl ketone	5,200	2	11	7	2	8	3	4
Toluene	5,200	37	8	4	2	11	4	6
Trichlorofluoromethane	730	ND	1	1	1	1	1	1
Trichloroethene (TCE)	3	1	ND	ND	ND	ND	ND	ND
1,2,4-Trimethylbenzene	NA	2	3	ND	ND	2	ND	ND
2,2,4-Trimethylpentane	NA	7	ND	1	ND	4	1	2
Xylenes (total)	100	22	4	ND	ND	7	2	4

Notes:
Only compounds detected at one or more sample locations above the analytical reporting limits are listed in this table.
All results are in micrograms per cubic meter (μg/m^3).
NA – An Indoor Air Screening Level is currently unavailable for this chemical.
ND – Not Detected
Bolded and shaded results identify exceedances of the applicable NJDEP Indoor Air Screening Levels.

Benzene is the only compound that was detected above the IASL of 2 μg/m^3 in a post-remediation indoor air sample collected at building #2. The presence of benzene in this residence may be due to background. Paint and lawn mower were stored in the basement area of the house. Several other VOCs were also detected in the post-remediation indoor air samples at very low levels below the IASLs. Those may also be due to the background and outdoor air quality. The same compounds were also detected in the indoor air samples collected at these residences prior to installation of subsurface depressurization systems. Concentrations of VOCs detected in the outdoor air are presented in the last column of Table 4.

CONCLUSION

Vapor intrusion investigation was conducted to evaluate the impact of chlorinated volatile organic compounds detected in subsurface soil and groundwater on the quality of air in the six residences located above a CVOC plume. Soil gas data and indoor air data clearly show that those six houses were impacted by VI despite the presence of a capping system at the site. The analytical data show that the capping system have been damaged or partially removed during the construction of these residential buildings.

The post-remediation indoor air sampling confirmed that the subsurface depressurization systems were effective at improving the quality of indoor air in these residences and no VOCs including TCE and chloroform were detected above the NJDEP indoor air screening levels at these buildings.

Investigation of the company’s past history indicated that chloroform was not used in any of the previous operations conducted at the site. Chloroform could be a regional problem. It was also detected in groundwater samples collected from the up-gradient well located at the site. Chloroform has been attributed to the background condition.

Based on the results of VI investigation conducted in these homes, vapor intrusion study was expanded to include other residential and commercial buildings located on the site or adjacent to the site. This VI investigation has been completed at the site in June 2015.

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Concepts for High Temperature Furnace Testing of Scaled Building Members and Connections under Axial Load

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Abstract:

Fire can have one of the most damaging and harmful exposure conditions on building components throughout their life-cycle. Recent developments in building materials and designs, such as new architectural trends in sustainable, green, and energy-efficient focused materials and components, have introduced new fire scenarios. Lack of adequate understanding of the behavior of new and emerging materials under fire and high temperature conditions can lead to unpredicted property damage or injury of building occupants. One objective of this paper is to review documented full-scale fire tests on building components and identify potential constraints and conditions that will yield suitable alternative testing options at the small scale. Reduced cost and time and safety considerations make fire testing of small-scale specimens a desired alternative to full-scale fire testing. In the current study, the use of a scaled-down model and full-scale, but small-size connections are considered for small-scale electric lab furnace as alternatives to conventional, full-scale fire testing. This elevated temperature testing approach allows developing a better understanding of the behavior of certain materials and connections when exposed to high temperature under structural load by more convenient and affordable means.

Keywords: *Scale-down model; experimental fire test; lab furnace; building components; envelope and connections; high temperature testing; fire safety.*

1. Introduction

Governing building fire codes generally address design and specification of fire safe related features focused on smoke detection and fire alarm installations in new buildings. However, new architectural trends focused on sustainable, green, and energy-efficient building systems and facilities may in many instances increase the risk of fire incidents because of the modern materials and building components underpinning these design trends. Fires in residential buildings (e.g., single-family dwellings and multi-family apartment buildings) remain a serious concern for governmental agencies (Mierley and Baker 1983, Istre et al. 2001, Karter 2013). This can be seen in an official report from The China Fire Services where they indicated that in a populous society, 39.7% of fire incidents occurred in residential buildings (Yung and Beck 1995, Wang and Fan 1997, Zhong et al. 2004, Xin and Huang 2013, Xin and Huang 2014).

In the past decade, developments in innovative building materials and components desirable for green and sustainable properties have been on the rise. As a result, an urgent need exists for better understanding of the behavior of these new materials and components under high temperature and direct fire exposure. One of the most critical aspects of building safety is thermal behavior of structural and non-structural components when exposed to fire or high temperature. Thermal performance investigations of certain materials used in a building often lead to selection of different strategies and options for fire safety systems (Lo et al. 2008) and to inspection and maintenance of old fire protection devices (Lo 1999). Harper (2004) states the importance of adequate understanding of the behavior of building components and materials under fire and high temperature in order to develop proper fire disaster prevention strategies. Generally, fire codes are considered as the best reference when selecting materials subjected to fire. However, developing fire code provisions for new materials for each new cycle is a lengthy process. In many cases, the outcome of experimental tests and feedback from users about new materials' probable shortcomings will be important for such provisions. This long process for issuance of new material fire code provisions along with competitive material and product market issues often necessitates conduction of fire or high temperature product performance certification testing. Therefore, interest has increased in carrying out experimental tests on new materials in fire research labs (Jatheeshan and Mahendran 2015, Le Dréau et al. 2015, Wang et al. 2015, Roszkowski and Sulik 2016). Nguyen et al. (2009) conducted a full-scale fire test on a concrete frame infilled brick wall to evaluate thermal performance of masonry. Their results indicate that a restrained brick wall in a frame buckles at high temperature. Gunalan et al. (2013) employed full-scale fire testing to explore weak points of light wall panels fabricated with cold-formed steel when exposed to fire. Pascual et al. (2015) used a full-scale fire test to determine thermal behavior of blind-bolted connections for hollow and concrete-filled steel tubular columns. The first formal record of a fire test of a full-scale steel structure occurred at the Building Research Establishment Cardington between 1995 and 1996 (Martin and Moore 1997). Cardington fire test is one of the biggest full-scale fire tests in the history of experimental study on fire. The Cardington test utilized seven, real-scale thermal tests at altered positions inside an eight-story steel structure.

Despite noteworthy outcomes from full-scale fire tests, the number of reported tests is limited. Fire testing history has shown that this type of experimental study is accompanied by high expenses, long lead times and fire hazards. Perhaps these are the most serious disadvantages of full-scale fire testing and are also the main reasons for the limited number of reported tests. In the present study, scaled-down specimens and isolated connection tests are proposed for effective, manageable, and affordable experimental tests. Scaled-down tests use scaling laws to infer full-scale fire test results by testing reduced-scale specimens in small-scale facilities. Figure 1 shows an overview of the proposed scaling method for planning small-scale fire tests. Alternatively, full-size connections with dimensions appropriate for the small-scale, lab furnace can be tested. For both approaches, the specimens can be studied under simultaneously application of elevated temperature and axial load profiles.

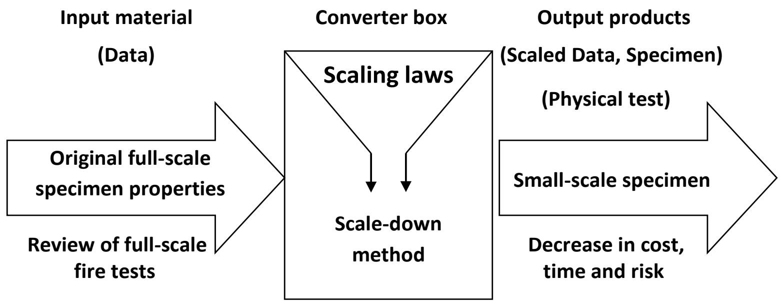

Figure 1. Overview of the proposed method for applying scaling laws in the planning of small-scale fire tests

2. Review of full-scale, furnace fire tests

A brief summary of relevant full-scale fire tests in the literature at this point is useful for framing the subsequent discussion of scaling methods applicable to small-scale fire testing. Nguyen et al. (2009) conducted a full-scale fire test on a 3 m high x 3 m wide unloaded infill wall constructed with 45 terra cotta, hollow blocks laid with conventional mortar. The block wall was confined inside a concrete frame and subjected to fire on one face, while out-of-plane horizontal displacements were measured at various locations on the unexposed face. Nguyen et al. found that the restrained brick wall could buckle when exposed to fire. Gunalan et al. (2013) conducted experimental fire testing to investigate thermal and structural performance of load-bearing cold-formed, steel stud wall systems with varied insulation schemes subjected to fire conditions. Eleven, full-scale specimens were tested in a test facility that used six, gas-fired burners mounted on a carriage with wheels. The burners applied heat to the specimen in a manner that would allow the specimen temperature to follow the AS 1530.4 standard fire curve during testing. Cold-formed steel stud wall systems with external insulation provided higher fire resistance ratings than conventional cavity insulated wall systems in these tests. Chen et al. (2012) used a modern, full-scale furnace to conduct fire tests on load-bearing, cold-formed steel stud walls sheathed with different types of fire-resistant wall board. Five, full-scale, cold-formed steel stud wall panels sheathed with double layers of three different fire-resistant panels on both sides, including fire-resistant gypsum plasterboard, magnesium board and calcium silicate board were exposed to loading and fire in a gas-fired furnace test facility following the ISO 834 standard time-temperature curve. The testing indicated that the fire performance of magnesium board was superior to that of the fire-resistant gypsum plasterboard and that the calcium silicate board exhibited undesirable explosive spalling. The steel studs experienced buckling in the middle third. Kodur and Mcgrath (2003) examined fire endurance of high strength concrete columns by full-scale test methods. Fire-resistance tests on six, reinforced concrete columns under service load were performed. Columns were heated in a gas-fired furnace custom-fabricated for fire testing loaded columns. Columns were subjected to a constant load, and the furnace temperature followed the ASTM E119 standard time-temperature curve. The steel framework of the furnace was external to the furnace chamber. Aggregate type, concrete strength, load intensity, and detailing and spacing of ties have were found to influence the fire-resistance of the tested columns. Conventional (large) column tie spacing led to extensive buckling of column bars and severe spalling of concrete and loss of concrete core. On the other hand, specimens with closer tie spacing showed significantly better performance due to the confinement effect of ties.

3. Scale-down Approach

Scaled-down testing apparatus offers an attractive alternative to full-scale fire testing facilities. The appeal of small-scale fire testing is that it is in general more manageable, economical and safer than full-scale testing. Scaling methods attempt to preserve correct relations between all main aspects, e.g., geometric proportions of a full-scale model during the conversion to small-scale as shown in Figure 1. Testing of a properly scaled model, can allow estimation of full-scale behavior.

Scaling laws are used to establish the full-scale to small-scale conversion formulas for parameters. For instance, the volume of a body varies with the cube of its length scale (l^3) and its surface area varies in terms of l^2. Hence, the ratio of surface area to volume of a smaller object is larger than that for a larger object of the same geometrical shape. There are two types of scaling laws applicable to this discussion. If all parts of an object scale in a similar geometric way with size, the scaling is termedisometric. In contrast, when different components of an object with different functionalities do not scale in a similar way; e.g., the shape of an object changes as its size changes, the scaling is termedallometric (Ghosh 2011).

When miniaturizing a full-scale specimen or component for fire testing, one must, for example, consider the possible consequences from the reduction of both volume and surface area. The rules of geometric scaling are well-known; e.g., perimeter (*P*), area (*A*) and volume (*V*) are defined with l, l^2 and l^3, respectively, where l is the length scale. Scale models often are represented in geometric scale terms, e.g., S_L (L referring to length); and in general, the scale of any quantity *i* is $S_i = i_p/i_m$ where i_p and i_m are the quantity value of the prototype, or item at full-scale, and the scale model, respectively. Physical Dimensions and scale factor relationships for various quantities considered in structural analysis and modelling are given in Table 1.

Table 1. Scale factors for prototype and scale models (Harris and Sabnis 1999)

Quantities	Scale factor	Dimensions
Stress	S_E	FL^{-2}
Modulus of elasticity	S_E	FL^{-2}
Specific weight	S_E/S_l	FL^{-3}
strain	1	-
Linear dimension	S_l	L
Linear displacement	S_l	L
Area	S_l^2	L^2
Moment of inertia	S_l^4	L^4
Concentrated load	$S_E.S_l^2$	F
Uniform distributed line load	$S_E.S_l$	FL^{-1}
Moment	$S_E.S_l^3$	FL
Shear force	$S_E.S_l^2$	F

3.1 Example for scale-down method

A simple example illustration of the scale-down method is the scale-down of a load case for a full-scale steel beam in order to fit within the size of small-scale laboratory test facilities. In this example, the full-size beam under load is 8000 mm long, has a solid rectangular cross section, roller and pin supports, and is subjected to a 200 kN, mid-beam point load (Figure 2a). The beam has a cross-sectional area, A = 400×500 = 2×10^5 mm^2, and a modulus of elasticity, E = 210 kN/mm^2. If in this example an assumption is made that a small lab can only test such beams with a maximum length of 2000 mm in this manner, scaled dimensions for fabrication of a small-scale specimen beam with a length of 2000 mm for test must be determined. In accordance with Table 1, the point load of 200 kN is scaled to 12.5 kN, and the cross-sectional area is scaled to 1.25×10^4 mm^2 as shown schematically in Figure 2b. Table 2 presents a brief comparison between geometry and loading quantities resulting from the scale-down method and the well-known beam equations for this example. The comparison suggests the feasibility in this example of straightforward scaling of full-scale testing to fit small-scale laboratory facilities.

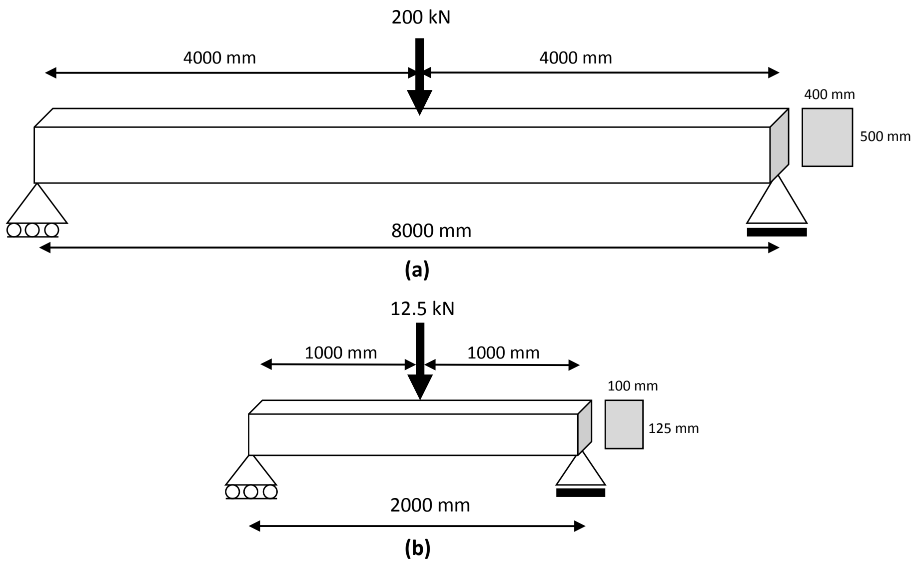

Figure 2. Sketch of: a) the prototype or full-scale beam, and b) the scaled-down beam (not to scale)

Table 2. Comparison between beam equations and scale-down method

Geometry and loading quantities	From Beam's Equations				From Scale-down method			
	Equation	Prototype model (p)	Scale-down model (m)	$\frac{m}{p}$	Recommanded Scale factor	SE	SI	Scale factor
Deflection (δ) at midpoint (mm)	$\frac{FL^3}{48EI}$	2.438	0.6095	0.25	S_l	1	0.25	0.25
Moment (M) at midpoint (kN.mm)	$\frac{FL}{4}$	400000	6250	0.015625	$S_E.S_l{}^3$	1	0.25	0.01563
Shear (V) at end (kN)	$\frac{F}{2}$	100	6.25	0.0625	$S_E.S_l{}^2$	1	0.25	0.0625
End Slope (θ)	$\frac{FL^2}{16EI}$	0.0009143	0.0009143	1	1	1	0.25	1

4. BCERL small-scale, high temperature test facility

The Building components and Enclosures Research Laboratory (BCERL) at Penn State has developed small-scale fire test facilities for conducting scaled-down tests under varied, time-temperature and load profiles. The MTS Systems 110-kip electrohydraulic load frame shown in Figure 3a. is being retrofitted with an electric furnace capable of applying the time temperature curve found in ASTM E119 standard (ASTM 2012) to the furnace control volume. The design intent was to have a customizable test facility for small-scale fire testing on a wide range of specimens. The load frame is capable of performing axial tensile, compression, and cyclic tests up to 0.5 Hz at the maximum actuator stroke of +/- 3 in. The tall, double-column load frame structure allows for a wide range of specimen lengths to be tested on this machine. The load frame is controlled by a MTS FlexTest 40 Controller.

Mechanical wedge grips with 67-kip capacity and liners for flat or round specimens and rated for a temperature range of -200˚F to 600˚F are used to hold the specimen or adapters to the specimen during tensile and cyclic tests in the load frame. When used in conjunction with the furnace, the grips are placed on the outside of the furnace allowing the specimen to run through the entire length of the furnace as shown schematically in Figure 3b. Placing the grips externally will ensure that the grips will not be subjected to the high temperatures of the furnace.

A high temperature (to 2900˚F) axial extensometer with ceramic rods designed to engage the specimen under test and chilled water cooling means is one technique used to measure test specimen strain within the furnace. This extensometer is configured with a gauge length of 2.0 inches and a +50% to -10% measuring range. The extensometer frame is mounted external to the furnace and passes through designated holes on the furnace. Type S thermocouples are one means used to monitor the temperature inside the furnace and at the surface or within the specimen. A custom, split tube furnace designed for steady-state and transient high temperature tests is shown in Figure 3. This split tube furnace has a 29 in. outside diameter and 40 in. outside height. The internal dimensions of the furnace are about 12 in. diameter by 30 in height. The end openings in the top and bottom of the furnace are adjustable to a maximum diameter of 12 in. to accommodate specimens with maximum width of 12 in. The end openings are made adjustable using stackable end plugs.

The furnace is capable of replicating the time-temperature curve in the ASTM E119 standard (ASTM 2012). Figure 4 shows this curve along with a number of other common time-temperature relationships used for fire testing at full-scale and small-scale. A significant capability in this furnace as compared to typical load frame furnaces is its ability to replicate the initial ramping that is seen within the first 10 minutes of the E119 curve. There are three independently-controlled zones in the furnace for improved control of the temperature uniformity or gradient within the furnace control volume.

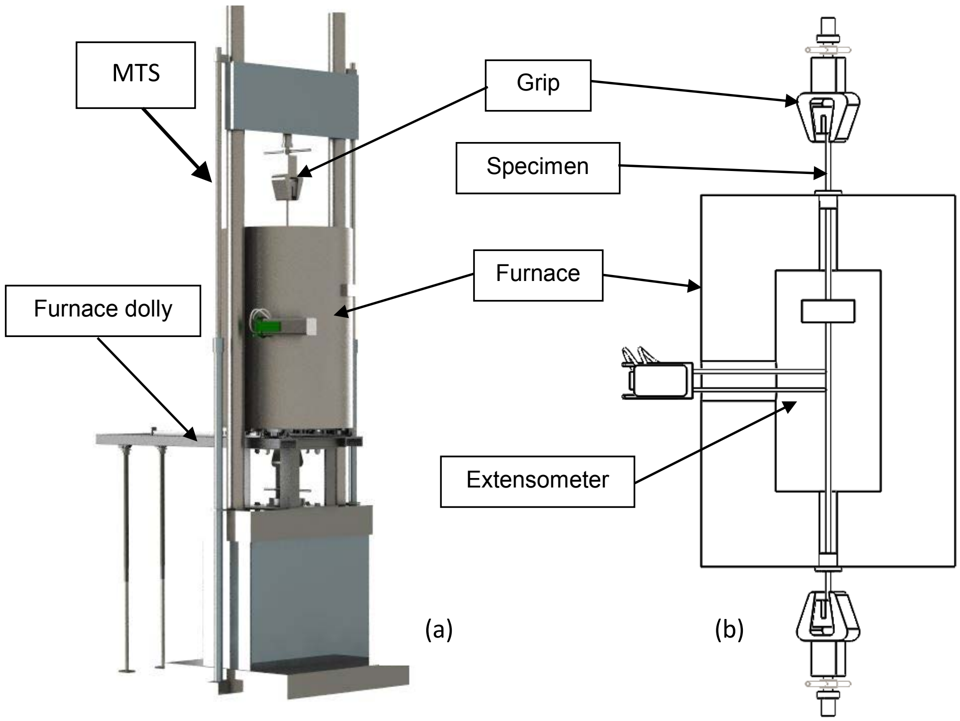

Figure 3. a) BCERL small-scale, high temperature test facility, b) 2D cross-section of furnace

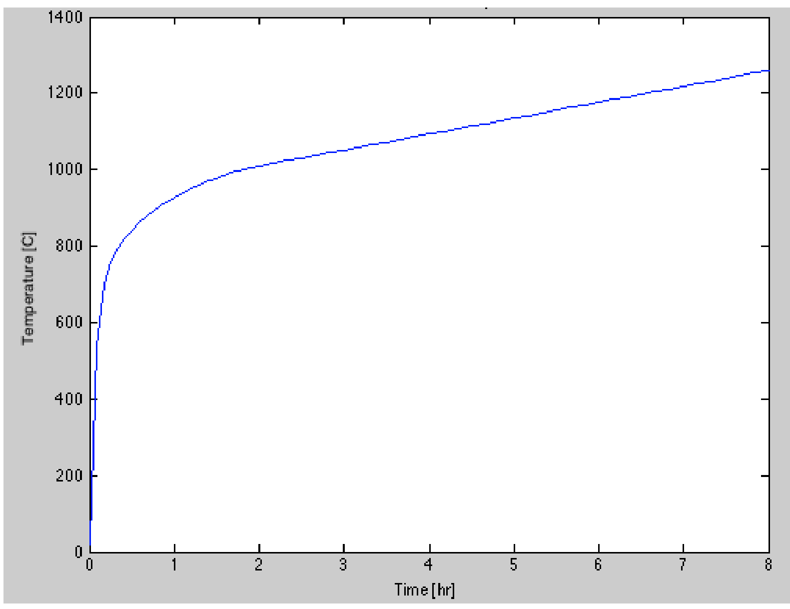

Figure 4. Typical time-temperature profiles used for full-scale and small-scale fire and elevated temperature testing (ASTM 2012)

For in-lab transportation of the furnace, the custom furnace dolly shown in Figure 3a has been designed and fabricated to fit with not only the MTS load frame, but two other custom load frames in BCERL to further increase the range of testing capabilities with the furnace. Linear slides have been mounted on the top side of the dolly to allow for 39 in. of travel across the length of the slide to allow the furnace to be pulled out of the load frame crosshead area between tests.

5. Projected small-scale fire test projects

In this section, scale-down techniques are presented for use of the BCERL small-scale, high temperature test facility to conduct small-scale tests with higher throughput and substantially reduced cost compared to typical full-scale testing. For conducting a full-scale fire test it is often necessary to fabricate an industrial furnace based on the actual size and loading of a member in buildings or with very large overall dimensions in order to accommodate a wide-range of full-scale fire tests. Typical components of the furnace compartment for a full-scale facility shown schematically in Figure 5 generally include: external structural framing, refractory walls, gas distribution and metering system, access doors and panels, load application system, environmental controls, specialized sensors and actuators, and a furnace data acquisition and control system. Existing dimensions and properties of the component(s) under test in a full-scale test help determine a logical relation between a scaled-down specimen that will fit the BCERL facilities and real-scale members. Fire testing on a scaled concrete column is one of the potential fire test projects that is expected to adapt well to the BCERL small-scale furnace. For instance, it is assumed that the real-scale circular concrete column with height H and cross-sectional area, πR^2 is exposed to fire and concentrated load *P* as depicted in Figure 5. With the aim of decreasing cost and increasing parametric variations to study, the use of scale-down techniques (Ghosh 2011) yield small-scale conversions of the real-scale column height and diameter to 0.2 H and 0.4R, in order to fit the testing inside the BCERL lab furnace as depicted schematically in Figure 6. The scaled concrete column also requires scaling of P based on the new specimen size. Fire tests on scaled-down concrete column specimens with variations in specimen size, cross-section and reinforcement under different loading profiles is considered to be a good match for the BCERL furnace.

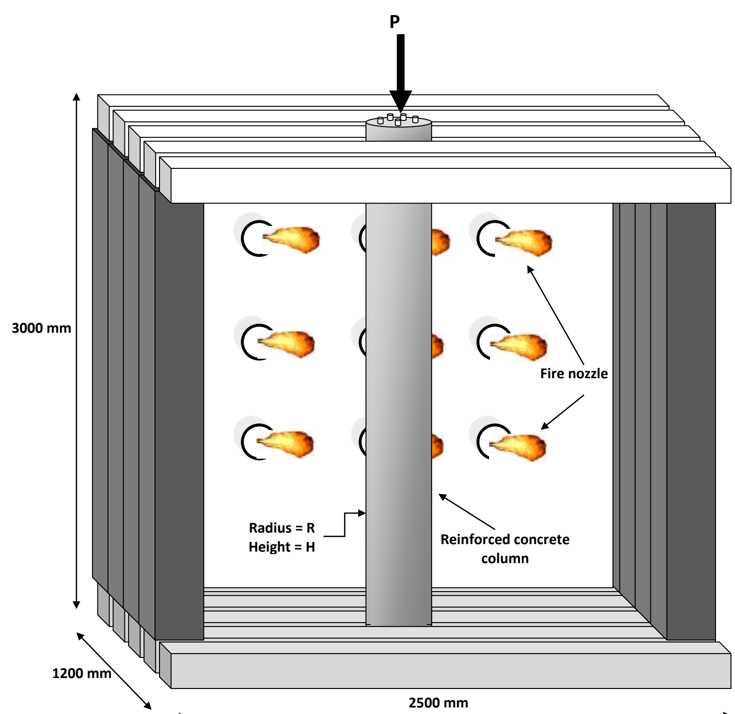

Figure 5. Schematic of a furnace and test setup for a full-scale fire test on a reinforced concrete column

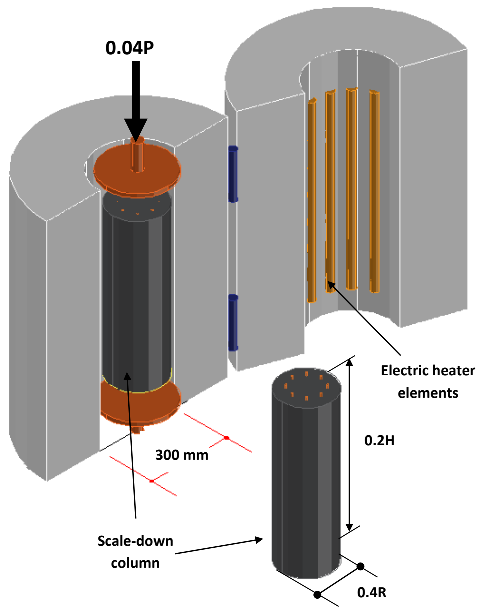

Figure 6. Scaled-down fire test of a real-scale concrete

Despite the widespread use of cold-formed steel in light-frame buildings, poor performance at high temperature is considered to be a serious weakness in many of cold-formed steel construction applications. Conducting scaled-down fire tests on cold-formed steel members and connections can lead to improvements in the thermal performance of cold-formed steel in construction. Figure 7 shows a shear connection that is widely used in cold-formed members as scaled-down to fit the BCERL furnace. Using a small-scale lab furnace, high temperature tests on cold-formed steel member connections and even connections of cold-formed steel to different materials will be of great value in the evaluation of potential failure modes of connections and fasteners and in the evaluation of concepts for mitigation of these failure modes.

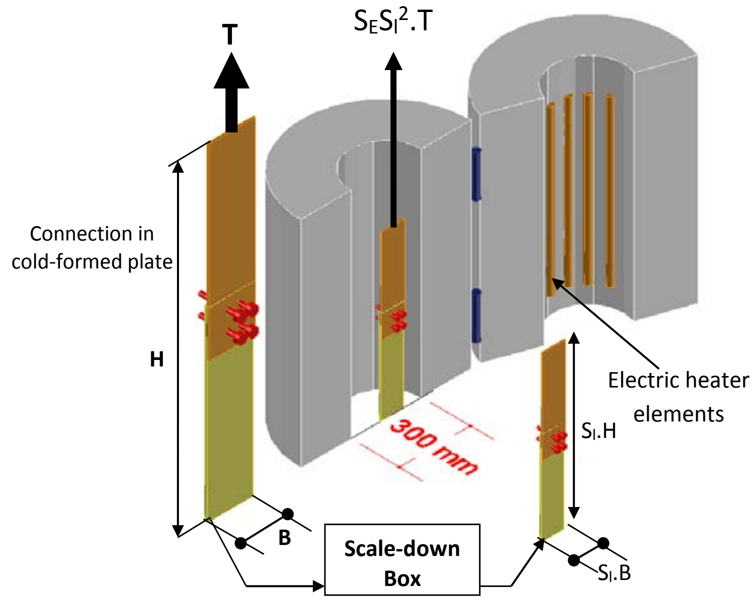

Figure 7. Fire tensile test of connection in cold-formed plates

After masonry walls are built, various types of anchors are used to attach other structural or nonstructural components to them. Masonry walls often reach high temperatures when exposed to direct flame or heat generated in surrounding spaces during fires. Hence, concern exists about the potential for failure of masonry anchorage. Figure 8 shows a standard masonry brick with a common masonry anchor detail scaled down to fit the BCERL furnace in order to subject the detail to high temperature tensile or shear testing. High temperature testing will help better understand shear and tensile capacities of masonry anchors (mechanical and chemical) and embedded or adhered fasteners at elevated temperature. In a similar fashion, anchorage and embedded fastener details for other wall and substrate materials can be scaled for testing in the BCERL furnace.

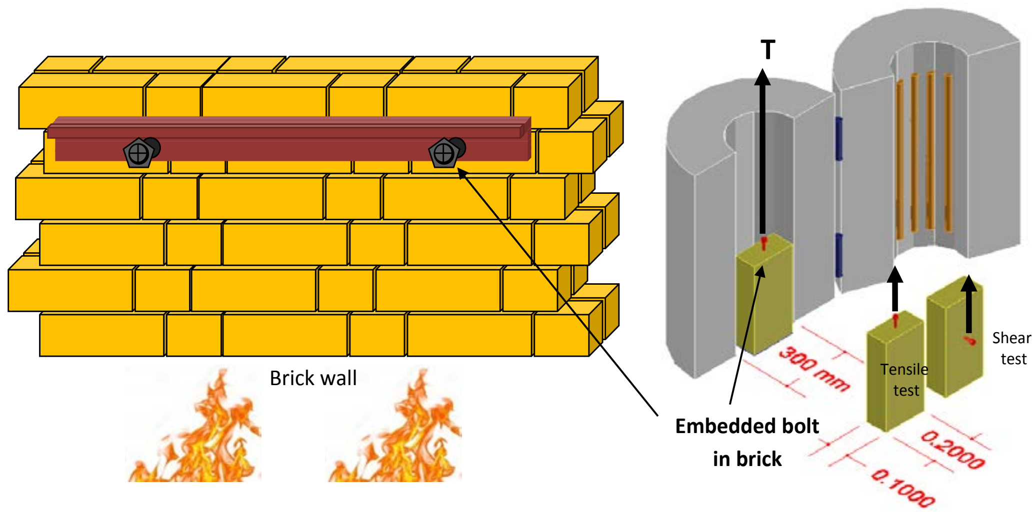

Figure 8. Fire tensile test of embedded bolt in brick

Fiberglass Reinforced Plastic (FRP) is often used to retrofit deteriorated concrete structures to satisfy new code requirements. In many cases, FRP is used in conjunction with concrete beams and columns to improve structural stability. However, FRP does not perform nearly as well at high temperatures as it does at ambient conditions. Two common methods of joining concrete members and FRP are FRP strip embedment in the concrete, or FRP attachment to the face of the member. Figure 9 shows two scaled-down FRP details fitted to the BCERL furnace in order to subject the details to high temperature tensile testing. In one detail, an FRP strip is embedded, and in the other an FRP strip is bonded to the face of a masonry element. Tensile loading will yield important information about rupture or pullout of the FRP strip in the first case, and bond failure in the second case.

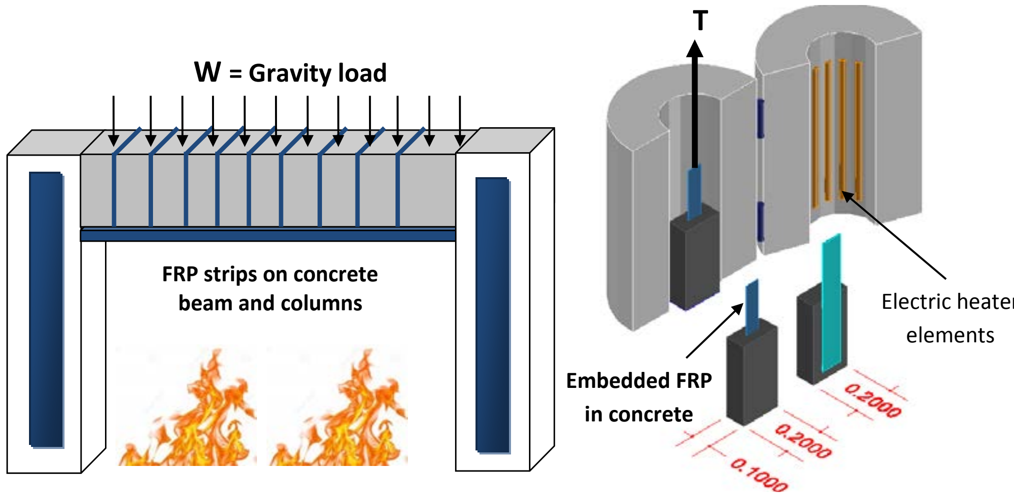

Figure 9. Fire test on the FRP strips in concrete members

6. Summary and Conclusion

A review of a number of full-scale fire tests on building components amenable to scaling down to fit testing in small-scale laboratory furnaces has identified many of the challenges and shortcomings inherent in full-scale fire testing, such as high cost, long lead times, low throughput, and safety issues. Examples of affordable scaled-down testing alternatives to these full-scale tests at small-scale have been suggested and described. Scale-down specimens and full-scale, but small dimension specimens able to fit in a relatively small laboratory furnace offer many opportunities to investigate high temperature testing of materials, components or connections using minimal space and existing facilities in research labs such as BCERL at Penn State. General design details for adapting a larger-than-typical laboratory furnace to an electrohydraulic load frame have been presented. Simultaneous high temperature and structural load testing of scaled-down specimens in smaller furnaces such as the BCERL lab furnace is expected to be of great value to construction material manufacturers, especially manufacturers of connection, anchorage and fasteners details products.

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CONDITION SURVEY OF ASSEMBLED CONCRETE BLOCKS (DOX PLANK)

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Abstract

Condition surveys can be challenging for existing floor and roof slabs constructed of assembled concrete blocks, also known as Doc's Blocks and Dox Plank, used in existing construction. Assembled concrete blocks that were manufactured in the 1940's, 1950's, and the 1960's, remain widely in use today throughout the Midwest and the East Coast in schools, motels, apartments, nursing homes, offices, churches, and single family homes. Historical data, design theory, and basis information on the manufacturing process of assembled concrete blocks are not readily available, but these are an important part of the condition survey. Assembled concrete blocks are machine-made, prefabricated, modular units of pre-cast concrete, with light weight aggregate, made of low strength, hollow core block, bonded together using deformed steel bars grouted into preformed voids (i.e., hollow cores). Some blocks have tongue and groove edges and also grooves along the top corners to aid in composition action. Unfortunately, applying the current state of practice in pre-stressed concrete planks will give misleading results. This paper aids designers, building officials, and the forensic architect/engineer in conducting a condition survey of assembled concrete blocks in service. It provides a resource on the early developments in precast concrete construction, period design guides, reference standards, patents, technical manuals, product catalogs, and design theory, with tips on conducting a condition survey.

Introduction

Past performance of floor and roof slabs in service can be an indicator of future performance. However, when past performance alone is insufficient to evaluate serviceability, or when changing the building use or adding dead loads, further investigation and analysis may be warranted. Often the first step is a condition survey. However, the condition survey can be challenging, if not incomplete, without a basic understanding of the original design theory, material properties, manufacturing process, and installation methods that were in use at the time of construction. This paper provides a resource on the early developments in pre-cast concrete construction, period design guides, reference standards, patents, technical manuals, product catalogs, and design theory, with tips on conducting a condition survey.

Background

In the 1920's, the American Concrete Institute (ACI) formed Committee 711 on the practice and construction methods used in pre-cast concrete joists with superimposed concrete floors and also to make recommendations for minimum standard requirements.

On July 25, 1929, Committee 711 submitted its initial report to ACI. The report was titled, "Precast Joist Concrete Floor Systems." ACI published its report in January 1940 (ACI 711-1940).

In the 1940's and 1950's, assembled concrete blocks gained popularity as an economical alternative to wood and light steel joists for relatively light loads, but were not included in ACI 711 report. Assembled concrete blocks emerged in an effort to eliminate or to minimize the cost of carpentry that was otherwise necessary in formwork used in cast-in-place concrete. They had the advantage of being manufactured in the shop, with greater supervision, quality control, and uniformity than would otherwise be available on the jobsite. They were also well suited for residential and light commercial construction, such as schools, motels, apartments, nursing homes, offices, churches, and single family homes, but were not recommended for roofs or floors with heavy loads or moving machinery due to the potential for impact forces and vibrations.

It wasn't until November 1952 that Committee 711 introduced standards that were specific to assembled concrete blocks. Manufacturers had already introduced proprietary systems and patents.

By the 1950's, the subsequent production of high strength steel reinforcement, especially wire strands, and the increased compressive strength of concrete lead to the use of pre-stressed concrete, which improved upon many of the disadvantages of conventionally reinforced concrete. By the late 1960's, the introduction of pre-cast hollow core, pre-stressed planks captured the market formerly dominated by assembled concrete blocks, which naturally led to their decline and discontinuation.

Plank Description

Assembled concrete blocks are manufactured of lightweight hollow core concrete. They are formed by placing individual blocks end to end in a row to form a plank (Fig. 1). The lightweight aggregate and preformed void space, also known as hollow cores (D), reduced the overall weight of the plank.

Typically, during manufacture the plank is placed upside down on a work table. In some cases, shims (E) may be placed between blocks to form camber within the plank. The blocks within the plank are compressed by an external means using approximately 20,000 pounds of clamping force applied to the ends of the plank. Once the plank is compressed reinforcing steel bars (C) are laid into the aligned channels and grouted into place (B). Once the grout cures, the external means of compression is then removed, thereby forming a minimally pre-stressed plank.

Later variations in the manufacture of planks used tongue and groove edges (A) for shear transfer and longitudinal grooves (F) cast into the upper corners of the blocks to increase composite action, with a thin concrete topping usually up to 2 inches in thickness.

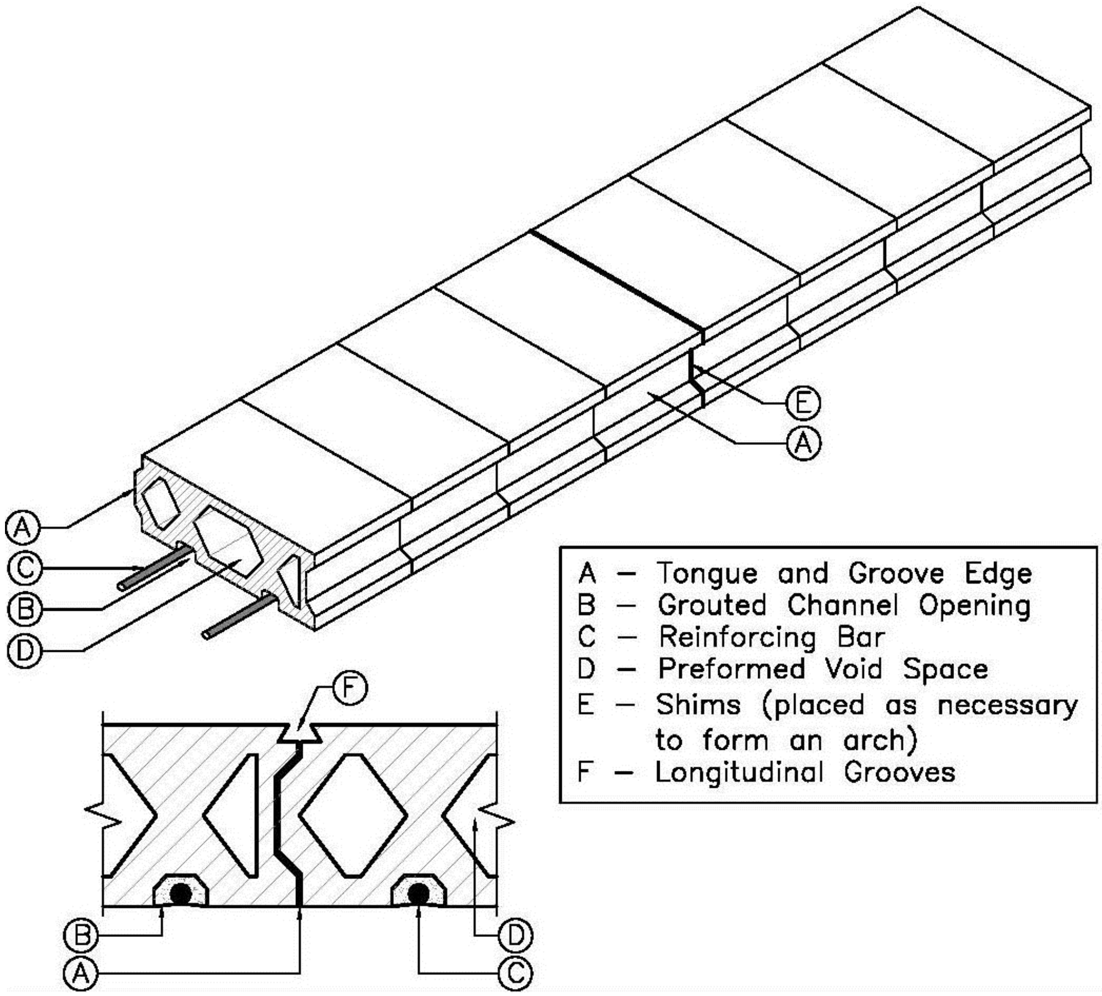

Fig. 1. Typical Assembled Concrete Blocks

Variations in proprietary assembled concrete blocks generally consisted of differences in the external clamping action, grouting process, external tensioning, camber, block shapes, and the manufacturing apparatus. Most of these variations are structurally insignificant and cataloging the variations between proprietary systems is outside of the scope of this paper.

Among the proprietary systems that attracted the most attention was Dox Plank, initially known as "Doc's Blocks." It was named for its inventor Mr. Bernard A. "Doc" Vander Heyden, who patented improvements in the planks and in the methods of manufacture in 1954 and 1965. He founded the Dox Plank Manufacturers Association, which licensed approximately 25 manufacturers across the eastern United States in the 1950's and 1960's. Although Dox Plank is just one variation on assembled concrete blocks, it came to represent the industry.

Once the planks are delivered to the jobsite, they are able to be hoisted quickly into position and laid side by side to form a floor or roof slab. Once in place the slab served as a working platform. The hollow cores could be used as conduits for utilities or as air ducts. The undersides of the planks formed a flat ceiling which may, or may not, have been plastered.

Standard plank sections were manufactured in 4, 6, 8, and 10 inch depths and 16 inch widths. Planks are designated using a three digit numerical code, followed by a "T" to indicate a topping slab, if present. For example, a standard section 856T indicates an 8 inch deep plank, with 1-No. 5 bar and 1-No. 6 bar and a topping slab.

Patents

On December 14, 1954, Patent No. 2,696,729 was granted to Mr. Vander Heyden for improvements to the manufacture of "pre-stressed" planks using concrete blocks that are supported at their ends (Vander Heyden, 1954). The patent identified 13 claims distinguishing it from other patents using concrete and clay tile block. The patent's stated objective was,

> *To provide a strong but light and porous cementitious plank combining great strength with a high thermal and acoustical insulation factor, which together with its light weight, adapts it for making of roofs and floors, and the like.*

The patent claims that the manufacturing process provides a means for grinding the face of individual blocks, aligning the channels and also the preformed voids/hollow cores within a row of blocks, using shims between individual blocks to create a camber/arch in the plank, placing reinforcing bars at pre-determined positions in the plank, using reinforcing bars that are not threaded nor do they extend beyond the end blocks, compressing the assembly of blocks, grouting the reinforcing bars while the assembly of blocks remains in compression, grouting the reinforcing bars throughout the length of the plank so as to distribute the compressive stress to individual blocks rather than concentrating it within the end blocks, and transferring compressive stress in the blocks through the bond with the reinforcing bars thereby forming a minimally pre-stressed plank.

On March 9, 1965, Patent No. 3,172,932 was granted to Mr. Vander Heyden for additional improvements to the method of manufacturing a concrete plank. It identified 10 claims pertaining to pre-fabricated or drilled access ports for pressure grouting in special blocks provided at pre-determined intervals along the length of the plank and to provide a step by step process for grouting (Vander Heyden, 1965).

Specifications and Design Data

The Dox Plank Manufacturers Association licensed those manufacturers that complied with Patent No. 2,696,729. Each manufacturer produced its own technical manual which included standard specifications, design assumptions, design tables, and installation details (Dox Plank Manufacturers Association, 1960 est.).

The standard specifications in effect in the 1940's, 1950's and 1960's indicated that the design was performed in accordance with the prevailing building regulations (i.e., ACI 318-41, ACI 318-51, ACI 318-56, ACI 711-46, ACI 711-53, and ACI 711-58). Table 1 provides the allowable unit stresses in concrete, taken from ACI 711-58.

Table 1. Allowable Unit Stresses in Concrete

Description		Allowable Unit Stresses, (psi)				
		For Any Strength of Concrete as Fixed by Test in Accordance with ACI 711 Section 302	When Strength of Concrete is Fixed by the Water-Content in Accordance with ACI 711 Section 302			
			Compressive Strength, $f'_c\,(psi)$			
			2,000	2,500	3,000	3,750
		$n = \frac{30{,}000}{f'_c}$	$n = 15$	$n = 12$	$n = 10$	$n = 8$
Flexure, f_c Extreme fiber stress in compression	f_c	$0.45\,f'_c$	900	1,125	1,350	1,688
Shear, v Flat slabs at distance, d, from the edge of column capital or drop panel	v_c	$0.03\,f'_c$, but not to exceed 75 psi	60	75	75	75

Note: Allowable unit stresses shown were based upon ACI 711-58.

The specifications also indicate that the compressive strength of all concrete is generally 2,500 pounds per square inch, or greater. The maximum tensile stress of reinforcing steel is 20,000 pounds per square inch. The ratio of net area to the gross area of a typical plank is approximately 0.55. The concrete topping, if provided, is reinforced with welded wire fabric. On roof slabs and other areas where no concrete topping is provided, a grout coat with a 1 to 3 cement to sand mix ratio is swept into the top surface of the plank after being placed. The bearings are a minimum of 3 inches on masonry and concrete beams and 2-1/2 inches on structural steel.

Design Theory

The design of simple span planks under a uniformly distributed load using the prevailing Working Stress Design method derived from a T-beam section in accordance with the ACI Reinforced Concrete Design Handbook (ACI 317-55) yielded the following standard formula used in the original plank design:

$$M_s = A_s f_s j d \quad (1)$$

$$M_c = f_c \left(1 - \frac{t}{2 k d}\right) b t j d \quad (2)$$

$$V_c = v_c b' j d \quad (3)$$

$$V_u = u \sum o j d \quad (4)$$

$$V_h = \frac{U_h I}{2 (kd - 1)} \quad (5)$$

$$j = 1.0 - \left[\frac{\left(k - \frac{2t}{3d}\right)}{\left(2k - \frac{t}{d}\right)} \text{ x } \frac{t}{d} \right] \quad (6)$$

$$k = \frac{\frac{n A_s}{b t} + \frac{t}{2 d}}{\frac{n A_s}{b t} + 1.0} \quad (7)$$

The values of j and k are illustrated in Fig. 2,

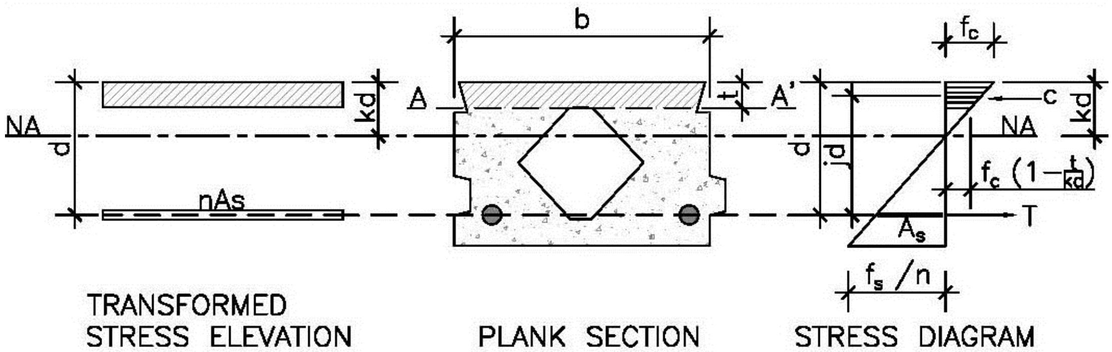

Fig. 2. Stress Diagram

Additional Load Capacity Considerations

Assembled concrete blocks essentially behave as a collection of simply supported beams. The cross section of a typical plank is comparable to a box beam with top and bottom flanges and side web elements.

In a plank, the primary flexural compression element (i.e., the bonded concrete topping, if present) and the primary flexural tension element (i.e., the reinforcing bars grouted in the bottom channel openings) are continuous over the entire span length. Thus, the demands sustained by these elements are similar to the demands sustained in a conventional cast-in-place or precast concrete beam, and the flexural capacity of plank can be established using typical flexural design principles. However, plank must be treated differently in shear. This is due to the regular, closely spaced, web discontinuities at the unbonded butt joints between the ends of adjacent planks along the span length. These discontinuities alter the distribution of shear stresses as compared to that which would be sustained in a continuous beam web. Fig. 3 illustrates a free body diagram of a single plank.

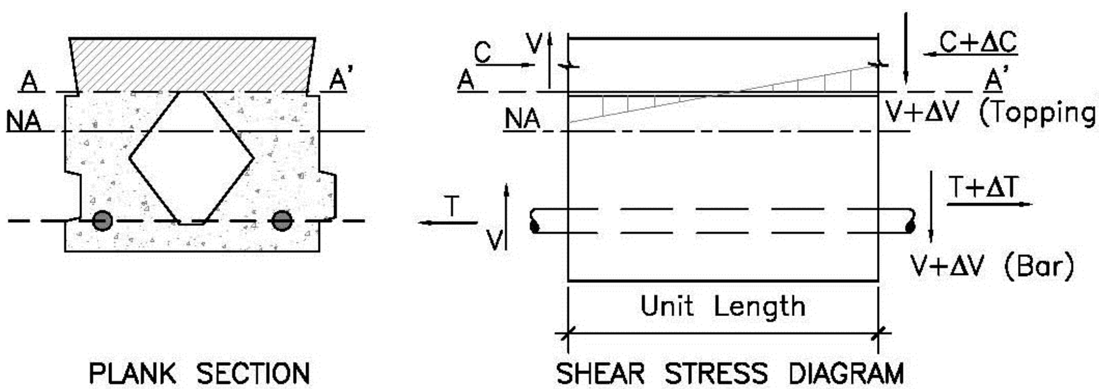

Fig. 3. Free Body Diagram

On the cross-section of the plank below Plane A-A' in Fig. 3, the only external forces are the net horizontal force in the reinforcing bar (ΔT) and the small fraction of the total shear taken by the bar at each end ($\Delta V\ bar$). Unless the reinforcing bar carries most of the interface shear, which is not realistic, summing the moments about the center of the block will result in significant moment associated with vertical flexural stresses in the web of the plank. If the tensile stress levels are high enough, web failure can compromise plank capacity. In a member with a continuous web, this does not occur.

The presence of significant web tensile stresses of the type shown in Fig. 3 is a characteristic of flexural members with closely spaced web discontinuities. In this manner, the plank is comparable to Sheffield Tile Deck System (Hill, 2003). The magnitude of these tensile stresses relative to the tensile strength of the concrete used to fabricate the plank must be evaluated to establish the true flexural strength of the plank. In some instances, these stress levels will control the ultimate capacity. Although manufacturer load tables given in the Technical Manuals of the Dox Plank catalogs provide guidance regarding the capacity of a plank, their development did not include consideration of the local stress mechanism described above.

Therefore, the effect must be evaluated to ensure that the appropriate limiting strength is established.

Use and Application

Assembled concrete blocks were well suited for schools, apartment buildings, nursing homes, offices, churches, and single family homes where load bearing walls are uniformly placed along main corridors and between quest rooms, offices, and classrooms. Figs. 4-7 illustrate typical building construction using planks in the floors and roof systems. At the time of construction, the planks could be quickly placed and serve as cover to the floor below and as a working platform above.

Tips for Conducting a Condition Survey

Based upon the historical data, original design theory, material properties, manufacturing process, and basic installation methods used at the time of manufacture and construction presented above, below are a few tips on conducting a condition survey.

Past surveys of assembled concrete blocks in service reveal that the planks are prone to cracking in the webs (Figs. 8-9); corrosion of embedded steel reinforcing (Figs. 10-11); open joints and the separation between adjacent planks and differential settlement between planks (Figs. 12-13).

Area of Reinforcement: Each plank contains two embedded reinforcing steel bars. These maybe the same diameter or vary by one bar diameter. For example, a single plank may contain 2-No. 5 bars, or 1-No. 5 bar and 1-No. 4 bar, or 1-No. 5 bar and 1-No. 6 bar. These planks are designated 855, 854, or 856, respectively. Therefore, the bar size is not readily known without investigating the size of both bars in each plank.

Conventional Reinforcement: Reinforcement used in assembled concrete blocks is mild steel. The pre-compression forces are of the magnitude of 20,000 pounds with incidental pre-stress force transferred to the reinforcement. Despite the early claims that the assembled concrete blocks are pre-stressed concrete planks, the planks are more accurately conventionally reinforced concrete, with incidental pre-stressing. Applying the current state of practice in pre-stressed concrete planks to assembled concrete blocks will give misleading results.

Simple Span Planks: Assembled concrete blocks were generally intended in simple span construction, with a pair of reinforcing bars at the bottom of the section, and wire mesh in the topping slab. Negative moment bending is contrary to the original design. Therefore, the placement of intermediate partition walls below the planks need to be investigated to determine whether the partition walls engage the planks and provide unintended bearing, which may cause stress reversals.

Load Capacity: Original designs of assembled concrete blocks typically used the lightest possible planks to resist the design loads resulting in minimal reserve load capacity. Therefore, subsequent alterations to floors and roofs with assembled concrete blocks need to be investigated to ensure that the planks have sufficient capacity to resist any additional loads.

Lightweight Aggregate: The assembled concrete blocks are made with lightweight aggregate giving the blocks an extremely low modulus of elasticity. Manufacturer's technical design data indicates that the modulus of elasticity of the block is 1,666,667 pounds per square inch. As with other low modulus concretes, deflection and in particular creep can become problematic. Therefore, the investigation of creep and differential deflection between adjacent planks needs to be investigated.

Water Intrusion: The concrete blocks are touted as being porous in part to improve the acoustical properties of the underside of the plank. However, high porosity is correlated with low resistance to carbonation and low resistance to water penetration. Therefore, the exposure of the concrete blocks to water intrusion from leaks in the roofs, overhangs, and balconies can result in corrosion of the embedded steel reinforcement.

Fig. 4. Floors and balconies constructed using assembled concrete blocks.

Fig. 5. Floors of nursing home constructed using assembled concrete blocks.

Fig. 6. Floors of offices constructed using assembly concrete blocks.

Fig. 7. Roof of school gymnasium constructed using assembly concrete blocks.

Fig. 8. Cracks viewed from within the hollow core.

Fig. 9. Cracks viewed from within the hollow core.

Fig. 10. Spalled concrete cover with exposed reinforcement.

Fig. 11. Close-up of corrosion and section loss on exposed reinforcement.

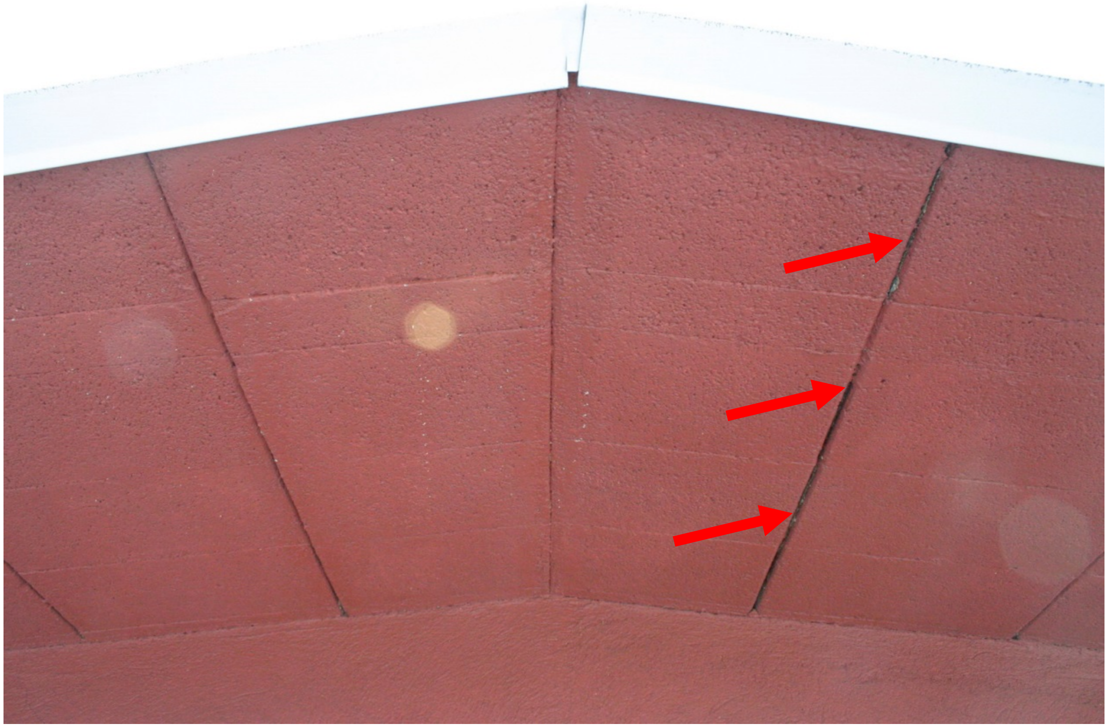

Fig. 12. Open joints between adjacent planks (arrow).

Fig. 13. No grout between joints (arrow) and no topping slab.

Summary and Concluding Remarks

This paper aids designers, building officials, and the forensic architect/engineer in conducting a condition survey of assembled concrete blocks in service. Notable takeaways include the following:

1. Embedded reinforcing steel bars maybe the same diameter or vary by one bar diameter.

2. Despite the early claims that the assembled concrete blocks are pre-stressed concrete planks, the planks are more accurately conventionally reinforced concrete, with incidental pre-stressing.

3. Assembled concrete blocks were generally intended for simple span construction, and so negative bending over partition walls is generally contrary to the original design may cause unintended stress reversal and cracking in the negative moment regions.

4. The addition of post-construction topping slabs, flooring, and roof overlays on assembled concrete blocks necessitates the need for an available reserve capacity.

5. Assembled concrete blocks are vulnerable to deflection and creep due to their low modulus of elasticity.

6. The condition of an existing topping slab may adversely affect the composition action of the plank.

7. The porous nature of assembled concrete blocks make then vulnerable to water intrusion and corrosion of embedded reinforcing steel.

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ANALYTIC SOLUTIONS FOR BIO-BASED RENEWABLE CONSTRUCTION PANELS MANUFACTURED WITH NON-RIGID BONDING

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ABSTRACT

Under the immense pressure of environmental, energy, economic, and other modern problems, many new materials have been scientifically developed. There is a wide range of renewable materials developed from natural and manmade resources as polymers and composites. Yet, the state of scientific advancements apparently lags behind their applications in the buildings sector. One may argue that there is a gap between the discovery of those materials and the state of residential construction. The needed knowledge about these materials for the engineering designs may shed light on that gap. To elaborate, structural insulated panels have been successfully used nationwide but why renewable components such as green adhesives and biodegradable foams have not been applied as load bearing elements in modular and panelized buildings?

This paper is the result of an in-progress effort to close the gap between the scientific development of materials and their applications. It will present accurate analytic models developed for panels manufactured with non-rigid bonding and subjected to various loads. The models are useful to ascertain the effects of the finite values of bonding stiffness on the performance and responses of the panels. Numerical and experimental results indicated that the customary assumption of perfect bonding should not be used beyond a certain level of stiffness. This discovery also provided an answer to what constitutes perfect bonding.

Keywords: Buildings, construction, laminated/sandwich panels, residential, SIP.

GENERAL

The demanding needs of the construction industry have inspired the creation of innovative building systems. Laminated and sandwich panels constructed from renewable products have been applied successfully in various construction projects (1 to 4, 6 to 8, and 10). They balance the engineering of light weight components with mechanical and thermal properties with the engineering of a useful system that possesses satisfactory properties while in service. Prominent organizations such as the EPA foster research in the area of alternative sustainable buildings made of composites from natural, biodegradable, and recyclable materials. The concept of combining different materials with different physical and chemical properties to produce products that are stronger than the individual components is not new. However, the use of cellulosic and synthetic fibers in new composite products is progressing at a very rapid pace. The new generation of products possess what the residential sector require in designs such as durability, high strength-to-weight ratios, energy saving, flexibility in design, and indeed became a category in the LEED system. The composite-based products are in each residence nowadays in varies applications including flooring and roofing, utility, bathrooms and kitchens, doors/windows/light panels, interior and exterior architecture as decking and fencing, HVAC, rain systems such as drains, etc. With this very wide popularity of composites in residential construction, their application in integrated load-bearing panels is not as noticeable. For example, green adhesives and biodegradable foams are available in the market but somehow not listed by the SIP as used materials.

Although the use of adhesives is unavoidable in manufacturing laminated and composite panels, the literature lacks adequate studies on their effects on the structural performance. The existing analytic and experimental methods of analysis laminated panels have invariably assumed perfect bonding between layers. Nevertheless, interlayer interactions occur because of the finite bonding stiffness; and environmental effects. These interactions may answer many unanswered questions related to problems such as delamination of renewable panels. This paper aims at the essential material in manufacturing these panels, i.e. the bonding. The broad impacts of this study include responding to the calls for construction systems that are recyclable; the reduction in construction demolition waste disposal in landfills; and the production of building materials with low hazardous impacts on the environment.

RENEWABLE PANELS IN THE HOUSING CONSTRUCTION

According to the EPA (10), residential and commercial buildings account for about 40% of the total annual energy consumption in the United States of America, they produce 35% of the total carbon dioxide emissions, and attribute 40% of landfill wastes. The building industry is also a large consumer of non-renewable materials and this trend has escalated dramatically over the past century. Building systems that included renewable materials have proven their potentials to reducing energy consumption, pollutant emissions and non-renewable material.

The rapidly rising and widely spreading of these materials in the buildings industry is pushing the boundaries in a heavily demanding markets towards residential composites systems. Structural panels composed of thick core bonded to two rigid sheathing materials are commonly applied in the residential construction for walls, floors, roofs, and foundations. The core is generally light weight foam, and the faces could be made a wide variety of materials such as oriented strand boards, plywood, composite panels, and of metal sheets.

The concept of such composite panels meet the functional and performance requirements of integrated designs such as structural, energy, acoustic, fire safety, constructability, maintainability, durability, aesthetics, and economy.

DESCRIPTION OF TECHNICAL PROBLEM

The effects of bonding on the structural response of renewable panels have been tackled using the fundamentals of theory of elasticity (9). Generally, equations are set up to define the equilibrium of the separate skins and of the core and to prescribe the necessary continuity between the faces and the core. The result is a set of differential equations, which may be solved for the quantities of interest as stress. Because this kind of analytic investigation is inherently complex and depends on the applied loading, only the edge loading case is presented here in details. The solutions of other cases could be obtained from the author of this paper. However, numerical results and the impacts of adhesives on the structural performance have been presented for various loading cases.

A Selected Formulation: Edge Loading

Consider a panel composed of three layers bonded together and made of orthotropic materials. The dimensions of the panel are a and b in the x and y directions, respectively. The faces or outer layers are of equal thickness t_f. The core or middle layer, of a thickness 2 t_c, has a modului of elasticity, E_{cx} and E_{cy} usually significantly less than those of the faces E_{fx} and E_{fy}. However, its shear modului G_{cxy}, G_{cxz} and G_{cyz} should be high enough to develop the interaction required between the layers. The adhesive between the faces and core has finite stiffness K_x and K_y. The extent of this kind of composite action depends on the relative stiffness of the constituent materials as will be shown subsequently. The stress state in the faces and core elements is shown in Figure 1. The equilibrium of the face element requires that

$$\frac{\partial \sigma_{fx}}{\partial x} + \frac{\partial \tau_{fyx}}{\partial y} - \frac{q_x}{t_f} = 0$$

$$\frac{\partial \sigma_{fy}}{\partial y} + \frac{\partial \tau_{fxy}}{\partial x} - \frac{q_y}{t_f} = 0$$

in which

σ_{fx}, σ_{fy}	=	Normal stress components in faces;
τ_{fxy}, τ_{fyx}	=	Shear stress components in faces;
q_x and q_y	=	Interlayer shear stress;
t_f	=	The thickness of the face;
f	=	Subscript denoting face;
x, y	=	Coordinate axes.

The state of stress in the core must satisfy the following equilibrium equations.

$$\frac{\partial \sigma_{cx}}{\partial x} + \frac{\partial \tau_{cyx}}{\partial y} + \frac{\partial \tau_{czx}}{\partial z} = 0$$
$$\frac{\partial \sigma_{cy}}{\partial y} + \frac{\partial \tau_{cxy}}{\partial x} + \frac{\partial \tau_{czy}}{\partial z} = 0$$

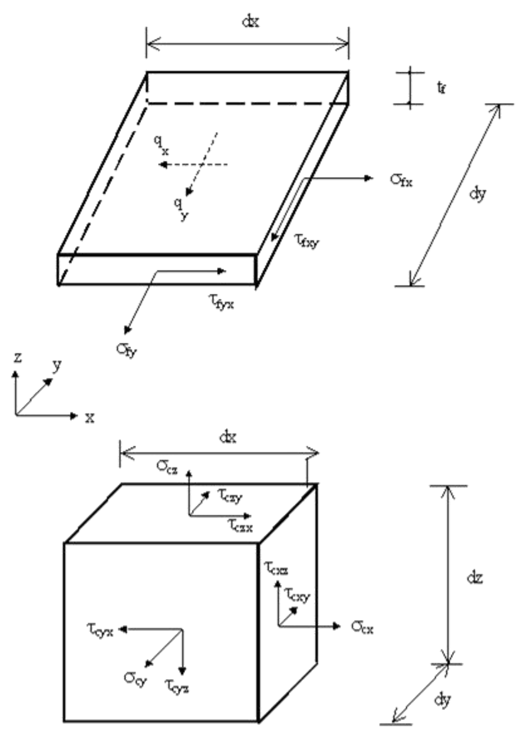

Fig 1. Stress State in Skin and Core

in which

σ_{cx}, σ_{cy}, σ_{cz}	=	Normal stress in the core;
τ_{cxy}, τ_{cyz}, τ_{czx}	=	Shear stress in the core;
c	=	Subscript denoting core.

At the interfaces between the core and the skins, the stresses and strains must be compatible. The compatibility equations in terms of stresses are

$$q_x = \tau_{czx}\Big|_{z=\pm tc}$$

$$q_y = \tau_{czy}\Big|_{z=\pm tc}$$

In terms of strains, the compatibility equations are written as

$$\frac{\partial \Delta_x}{\partial x} = \varepsilon_{fx} - \varepsilon_{cx}\Big|_{z=\pm t_c}$$

$$\frac{\partial \Delta_y}{\partial y} = \varepsilon_{fy} - \varepsilon_{cy}\Big|_{z=\pm t_c}$$

$$\gamma_{fxy} = \gamma_{cxy}\Big|_{z=\pm t_c}$$

in which

ε and γ = Normal and shear strain, respectively;
Δ_i = Interlayer deformation in the i direction, where i = x or y;
= $\frac{q_i}{K_i}$;
K_i = Stiffness of adhesive in the i direction.

Solutions to the problem must satisfy the above equilibrium and compatibility equations, in addition to the following boundary conditions:

1. At the panel edges, no normal or shear stresses should exist in the core and the face normal stress must equal the applied in-plane stress, thus

   at x = 0, 2a $\quad \sigma_{fx} = \sigma_{fxo} \quad \sigma_{cx} = \sigma_{cxo}$
   at y = 0, 2b $\quad \sigma_{fy} = \sigma_{fyo} \quad \sigma_{cy} = \sigma_{cyo}$

2. For symmetrical loading about the panel middle plane and centerlines, the shear stresses vanish and no in-plane displacements occur, thus

   at x = a $\quad \tau_{fxy} = \tau_{cxy} = 0 \quad u_c = u_f = 0$
   at y = b $\quad \tau_{fyx} = \tau_{cyx} = 0 \quad v_c = v_f = 0$

   in which

   σ_{fxo} = p_{fxo} / t_f
   σ_{fyo} = p_{fyo} / t_f
   u and v = Displacements in the x and y directions, respectively.

A solution for normal stress components in the core satisfying the above boundary conditions is considered as (5 and 9)

$$\sigma_{cx} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} A_{mn}\, \phi_x\, S_x\, S_y + \sigma_{cxo}$$

$$\sigma_{cy} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} C_{mn}\, \phi_y\, S_x\, S_y + \sigma_{cyo}$$

Using these equations, expressions for the displacement of the core are derived from Hooke's law as follow

$$u_c = -\frac{1}{E_{cx}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \frac{A_{mn}\phi_x\, C_x\, S_y}{\alpha_m} + \frac{\nu_{cxy}}{E_{cy}} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{C_{mn}\, \phi_y\, C_x\, S_y}{\alpha_m} + (x - a)\left(\frac{\sigma_{cxo}}{E_{cx}} - \frac{\nu_{cxy}\, \sigma_{cyo}}{E_{cy}}\right)$$

$$v_c = -\frac{1}{E_{cy}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \frac{C_{mn}\phi_y\, S_x\, C_y}{\beta_n} + \frac{\nu_{cyx}}{E_{cx}} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{A_{mn}\, \phi_x\, S_x\, C_y}{\beta_n} + (y - b)\left(\frac{\sigma_{cyo}}{E_{cy}} - \frac{\nu_{cxy}\, \sigma_{cxo}}{E_{cx}}\right)$$

An expression for the shear strain and stress in the core are obtained by properly differentiating the above displacement equations; thus

$$\gamma_{cxy} = \frac{1}{E_{cx}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} A_{mn}\phi_x\left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx}\frac{\alpha_m}{\beta_n}\right) C_x\, C_y + \frac{1}{E_{cy}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} C_{mn}\, \phi_y\left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy}\frac{\beta_n}{\alpha_m}\right) C_x\, C_y$$

$$\tau_{cxz} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \int_{z=0}^{z} \phi_x\, dz\, A_{mn}\left[-\alpha_m + \frac{G_{cxy}}{E_{cx}}\beta_n\left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx}\frac{\alpha_m}{\beta_n}\right)\right] C_x\, S_y + \frac{G_{cxy}}{E_{cy}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \int_{z=0}^{z} \phi_y\, dz\, C_{mn}\, \beta_n\left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy}\frac{\beta_n}{\alpha_m}\right) C_x\, S_y$$

$$\tau_{cyz} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \int_{z=0}^{z} \phi_y \, dz \, C_{mn} \left[-\beta_m + \frac{G_{cxy}}{E_{cy}} \alpha_m \left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy} \frac{\beta_n}{\alpha_m} \right) \right] S_x C_y +$$

$$\frac{G_{cxy}}{E_{cx}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \int_{z=0}^{z} \phi_x \, dz \, A_{mn} \, \alpha_m \left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx} \frac{\alpha_m}{\beta_n} \right) S_x C_y$$

The continuity conditions require the interlayer stresses to be the same as the core shear stresses at the interfaces, thus

$$q_x = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \left(A_{mn} \lambda_{gn1} + C_{mn} \lambda_{gn2} \right) C_x S_y$$

$$q_y = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \left(C_{mn} \lambda_{gk1} + A_{mn} \lambda_{gk2} \right) S_x C_y$$

Similarly, the cores and face shear strains must be the same at the interfaces, thus

$$\tau_{fxy} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} A_{mn} \left[\frac{G_{fxy}}{E_{cx}} \phi_x \Big|_{z=t_c} \left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx} \frac{\alpha_m}{\beta_n} \right) + \frac{G_{fxy} \beta_n}{K_x} \lambda_{gn1} + \frac{G_{fxy} \alpha_m}{K_y} \lambda_{gk2} \right] C_x C_y +$$

$$\sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} C_{mn} \left[\frac{G_{fxy}}{E_{cy}} \phi_y \Big|_{z=t_c} \left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy} \frac{\beta_n}{\alpha_m} \right) + \frac{G_{fxy} \beta_n}{K_x} \lambda_{gn2} + \frac{G_{fxy} \alpha_m}{K_y} \lambda_{gk1} \right] C_x C_y$$

The obtained solutions for the face shear stress and interlayer stresses in conjunction with the equilibrium equations of the face element lead to the following expressions for the face stresses

$$\sigma_{fx} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \left[A_{mn} \lambda'_{z1} + C_{mn} \lambda'_{z2} \right] S_x S_y + \left(\sigma_{xo} + \sigma_{cxo} \frac{t_c}{t_f} \right) \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{2}{a \alpha_m} \frac{2}{b \beta_n} S_x S_y$$

$$\sigma_{fy} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \left[A_{mn} \lambda'_{z3} + C_{mn} \lambda'_{z4} \right] S_x S_y + \left(\sigma_{yo} + \sigma_{cyo} \frac{t_c}{t_f} \right) \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{2}{a \alpha_m} \frac{2}{b \beta_n} S_x S_y$$

At this stage, A_{mn} and C_{mn} are the only unknowns. They were determined using the compatibility equations of interlayer displacements as

$$A_{mn} = \frac{\dfrac{\lambda_{y3}}{\lambda_{y2}} - \dfrac{\lambda_{y6}}{\lambda_{y5}}}{\dfrac{\lambda_{y1}}{\lambda_{y2}} - \dfrac{\lambda_{y4}}{\lambda_{y5}}}$$

$$C_{mn} = \frac{\dfrac{\lambda_{y3}}{\lambda_{y1}} - \dfrac{\lambda_{y6}}{\lambda_{y4}}}{\dfrac{\lambda_{y2}}{\lambda_{y1}} - \dfrac{\lambda_{y5}}{\lambda_{y4}}}$$

in which

$$\phi_x = \theta_x \left(2\,\theta_x \cosh\theta_x z + z\,\theta_x^2 \sinh\theta_x z - t_c\,\theta_x^2 \coth\theta_x t_c \cosh\theta_x z\right) - \frac{\alpha_m^2}{2} k_{\phi x} \cos\alpha_{\phi x} z$$

$$\phi_y = \theta_y \left(2\,\theta_y \cosh\theta_y z + z\,\theta_y^2 \sinh\theta_y z - t_c\,\theta_y^2 \coth\theta_y t_c \cosh\theta_y z\right) - \frac{\beta_n^2}{2} k_{\phi y} \cos\alpha_{\phi y} z$$

$$\lambda_{z1}' = \lambda_{z1}\left(1 - \frac{2}{b^2 \beta_n^2}\right) - \frac{2\int_0^{tc} \phi_x\, dz}{t_f\, b^2 \beta_n^2}$$

$$\lambda_{z2}' = \lambda_{z2}\left(1 - \frac{2}{b^2 \beta_n^2}\right)$$

$$\lambda_{z3}' = \lambda_{z3}\left(1 - \frac{2}{a^2 \alpha_m^2}\right)$$

$$\lambda_{z4}' = \lambda_{z4}\left(1 - \frac{2}{a^2 \alpha_n^2}\right) - \frac{2\int_0^{t_c} \phi_y\, dz}{t_f\, a^2 \alpha_m^2}$$

$$\lambda_{z1} = \frac{G_{fxy}}{E_{cx}} \left.\phi_x\right|_{z=t_c} \frac{\beta_n}{\alpha_m}\left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx}\frac{\alpha_m}{\beta_n}\right) + \frac{\lambda_{gn1}}{\alpha_m}\left(\frac{G_{fxy}\beta_n^2}{K_x} + \frac{1}{t_f}\right) + \frac{G_{fxy}\,\lambda_{gk2}\,\beta_n}{K_y}$$

$$\lambda_{z2} = \frac{G_{fxy}}{E_{cy}} \left.\phi_y\right|_{z=t_c} \frac{\beta_n}{\alpha_m}\left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy}\frac{\beta_n}{\alpha_m}\right) + \frac{\lambda_{gn2}}{\alpha_m}\left(\frac{G_{fxy}\beta_n^2}{K_x} + \frac{1}{t_f}\right) + \frac{G_{fxy}\,\lambda_{gk1}\,\beta_n}{K_y}$$

$$\lambda_{z3} = \frac{G_{fxy}}{E_{cx}} \left.\phi_x\right|_{z=t_c} \frac{\alpha_m}{\beta_n}\left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx}\frac{\alpha_m}{\beta_n}\right) + \frac{\lambda_{gk2}}{\beta_n}\left(\frac{G_{fxy}\alpha_m^2}{K_y} + \frac{1}{t_f}\right) + \frac{G_{fxy}\,\lambda_{gn1}\,\alpha_m}{K_x}$$

$$\lambda_{z4} = \frac{G_{fxy}}{E_{cy}} \left.\phi_y\right|_{z=t_c} \frac{\alpha_m}{\beta_n}\left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy}\frac{\beta_n}{\alpha_m}\right) + \frac{\lambda_{gk1}}{\beta_n}\left(\frac{G_{fxy}\alpha_n^2}{K_y} + \frac{1}{t_f}\right) + \frac{G_{fxy}\,\lambda_{gn2}\,\alpha_m}{K_x}$$

$$\lambda_{gn1} = \int_{z=0}^{z} \phi_x \, dz \Big|_{z=t_c} \left[-\alpha_m + \frac{G_{cxy}}{E_{cx}} \beta_n \left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx} \frac{\alpha_m}{\beta_n} \right) \right]$$

$$\lambda_{gn2} = \frac{G_{cxy}}{E_{cy}} \int_{z=0}^{z} \phi_y \, dz \Big|_{z=t_c} \beta_n \left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy} \frac{\beta_n}{\alpha_m} \right)$$

$$\lambda_{gk1} = \int_{z=0}^{z} \phi_y \, dz \Big|_{z=t_c} \left[-\beta_n + \frac{G_{cxy}}{E_{cy}} \alpha_m \left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy} \frac{\beta_n}{\alpha_m} \right) \right]$$

$$\lambda_{gk2} = \frac{G_{cxy}}{E_{cx}} \int_{z=0}^{z} \phi_x \, dz \Big|_{z=t_c} \alpha_m \left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx} \frac{\alpha_m}{\beta_n} \right)$$

$$\lambda_{y1} = \frac{\lambda'_{z1}}{E_{fx}} - \frac{\nu_{fxy} \lambda'_{z3}}{E_{fy}} - \frac{\phi_x \big|_{z=tc}}{E_{cx}} + \frac{\alpha_m \lambda_{gn1}}{K_x}$$

$$\lambda_{y2} = \frac{\lambda'_{z2}}{E_{fx}} - \frac{\nu_{fxy} \lambda'_{z4}}{E_{fy}} + \frac{\nu_{cxy} \phi_y \big|_{z=tc}}{E_{cy}} + \frac{\alpha_m \lambda_{gn2}}{K_x}$$

$$\lambda_{y3} = \frac{2}{a\alpha_m} \frac{2}{b\beta_n} \left[\frac{\sigma_{xo} + \sigma_{cxo} \frac{t_c}{t_f}}{E_{fx}} - \nu_{fxy} \frac{\sigma_{yo} + \sigma_{cyo} \frac{t_c}{t_f}}{E_{fy}} + \frac{\sigma_{cxo}}{E_{cx}} + \nu_{cxy} \frac{\sigma_{cyo}}{E_{cy}} \right]$$

$$\lambda_{y4} = \frac{\lambda'_{z3}}{E_{fy}} - \frac{\nu_{fyx} \lambda'_{z1}}{E_{fx}} + \frac{\nu_{cyx} \phi_x \big|_{z=tc}}{E_{cx}} + \frac{\beta_n \lambda_{gk2}}{K_y}$$

$$\lambda_{y5} = \frac{\lambda'_{z4}}{E_{fy}} - \frac{\nu_{fyx} \lambda'_{z2}}{E_{fx}} - \frac{\phi_y \big|_{z=tc}}{E_{cy}} + \frac{\beta_n \lambda_{gk1}}{K_y}$$

$$\lambda_{y6} = \frac{2}{a\alpha_m} \frac{2}{b\beta_n} \left[\frac{\sigma_{yo} + \sigma_{cyo} \frac{t_c}{t_f}}{E_{fy}} - \nu_{fyx} \frac{\sigma_{xo} + \sigma_{cxo} \frac{t_c}{t_f}}{E_{fx}} + \frac{\sigma_{cyo}}{E_{cy}} + \nu_{cyx} \frac{\sigma_{cxo}}{E_{cx}} \right]$$

$$k_{\phi x} = -\frac{\theta_x t_c}{\sinh \theta_x t_c} + \theta_x t_c \cosh \theta_x t_c \qquad k_{\phi y} = -\frac{\theta_y t_c}{\sinh \theta_y t_c} + \theta_y t_c \cosh \theta_y t_c$$

$$\theta_x = \alpha_m \sqrt{\frac{E_{cx}}{G_{cxz}}} \qquad \theta_y = \beta_n \sqrt{\frac{E_{cy}}{G_{cyz}}}$$

$\alpha_{\phi x} = \dfrac{m\ \pi}{2\ t_c}$ $\qquad\qquad$ $\beta_{\phi y} = \dfrac{n\ \pi}{2\ t_c}$

ν_{cxy}, ν_{cyx} = Poisson's ratio in the x plane and y-direction, and the y-plane and x-direction, respectively;

S_x, S_y, C_x, C_y = $\sin \alpha_m x$ and $\sin \beta_n y$, $\cos \alpha_m x$ and $\cos \beta_n y$, respectively;

α_m, β_n = $\dfrac{m\ \pi}{2\ a}$ and $\dfrac{n\ \pi}{2\ b}$, respectively, and m and n are integers;

σ_{cxo}, σ_{cyo} = Edge stresses in the core, if any, in the x and y directions, respectively. σ_{xo}, σ_{yo} are edge stresses in the skins;

m, n = Integers.

Effects of Adhesive on the Structural Performance

Case 1: Edge Loading

Consider a panel with the following properties: a = b = 20 in., t_f = 0.04 in.; t_c= 1.0 in., $E_{fx} = E_{fy}$= 10^7 psi, $\nu_{fxy} = \nu_{fyx}$= 0.33, $E_{cx} = E_{cy}$= 2 x 10^6 psi, $G_{cxy} = G_{cxz} = G_{cyz}$ = 10^4 psi, and $\nu_{cxy} = \nu_{cyx}$ = 0.20. Two loading cases are considered. In the first case, a biaxial uniformly distributed stress of intensity $f_{xo} = f_{yo}$ = 210 psi is used. In the second, case a uniaxial uniformly distributed stress of intensity f_{xo} = 210 psi is applied. In each loading case, the load is applied independently first to the face and core, and then concurrently to face and core. The face normal and shear stresses are calculated for a chosen range of bonding stiffness from $K_x = K_y = K = 10^3$-10^4 psi/in. The selected range for K-values covers a broad spectrum of adhesives from a non-rigid to excessively rigid for practical purposes. This range was needed for conducting a parametric study on the effects of adhesives. The normal stress in the faces at the panel center and the shear stress in the faces at the panel corner are shown graphically in Figures 2 to 7.

It is seen that the face normal stress shows greater sensitivity to the variation of bond stiffness value when the latter is in the lower range; and beyond a certain level of stiffness, the adhesive can be practically considered as rigid. A change in K-value for example from 10^3 to 2 x 10^3 psi/in induces a stress decrease almost 6 times in the uniaxial case and 5 times in the biaxial case greater than when K changes from 9 x 10^3-10^4 psi/in. The changes are 24% and 27% due to uniaxial core and combined edge loads, respectively, 32% and 22% due to biaxial core and combined edge loads, respectively. In all load cases, the face shear stress is practically independent of bonding stiffness.

This analysis has also detected an important point. By using existing theories, stress components in laminated panels may be determined only at high values of bond stiffness with a small margin of error, otherwise the K values must be included in the analysis.

Another important point was revealed by this analysis. By common sense, it can be felt that a very stiff adhesive would be unnecessary if the core was too soft, and the converse would be unwise. This is quantitatively shown in Figures 2 to 7 which show that the ratio of core stiffness to bonding stiffness is one of the main parameters influencing the behavior of laminated panels.

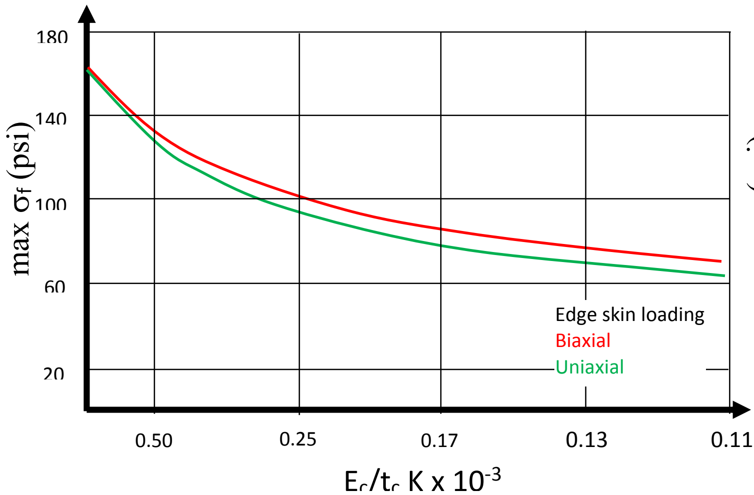

Fig. 2. **Effect of Bonding Stiffness on Skin Normal Stress Due to Skin Edge Loading**

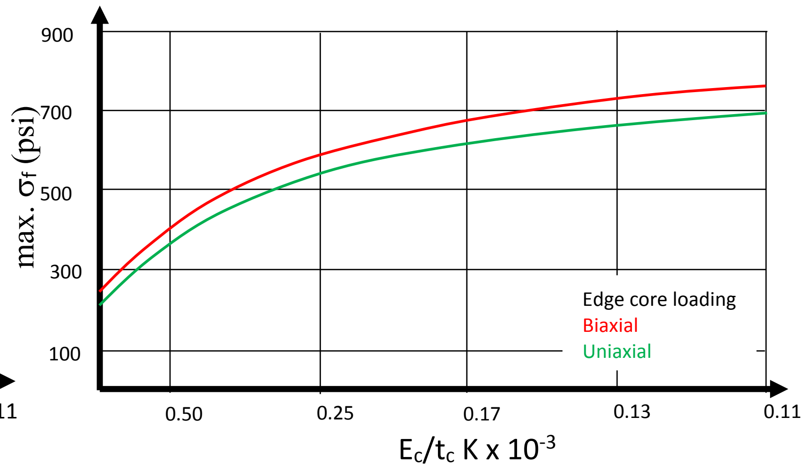

Fig. 3. **Effect of Bonding Stiffness on Skin Normal Stress Due to Core Edge Loading**

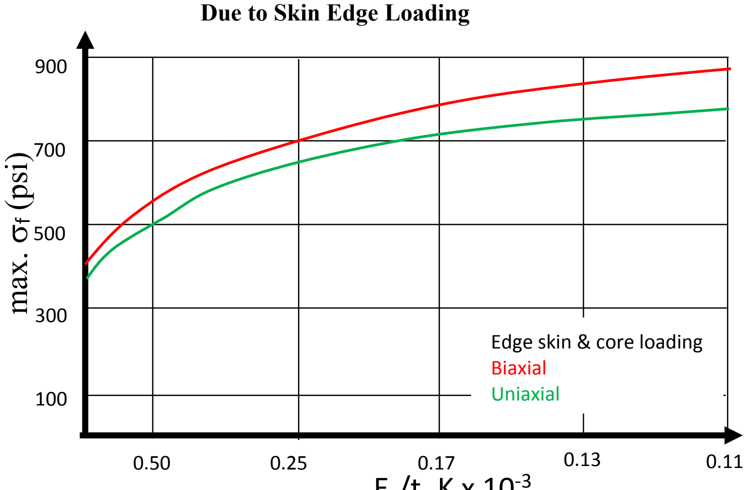

Fig. 4. **Effect of Bonding Stiffness on Skin Normal Stress Due to Skin and Core Edge Loading**

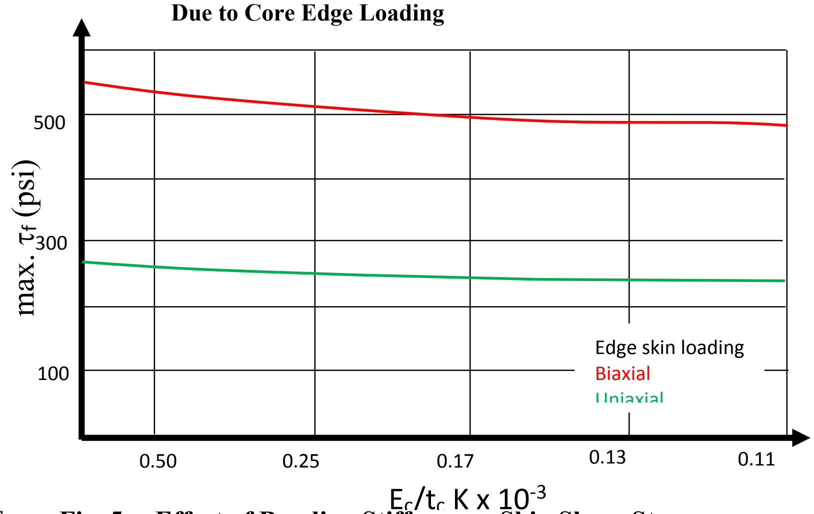

Fig. 5. **Effect of Bonding Stiffness on Skin Shear Stress Due to Skin Edge Loading**

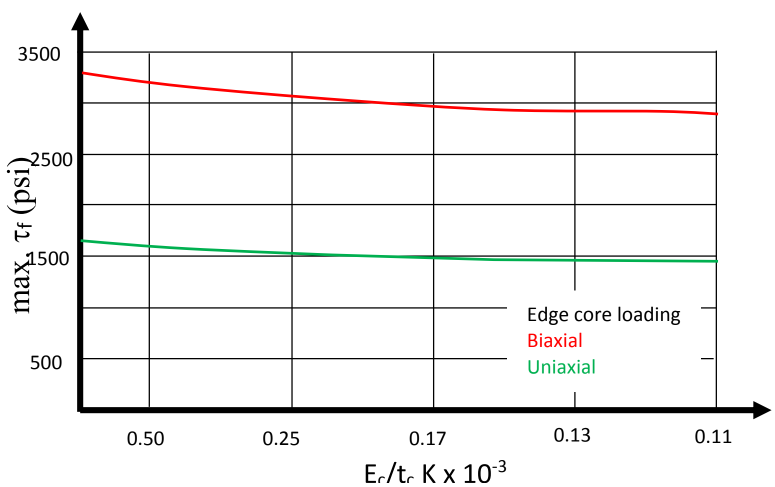

Fig. 6. **Effect of Bonding Stiffness on Skin Shear Stress Due to Core Edge Loading**

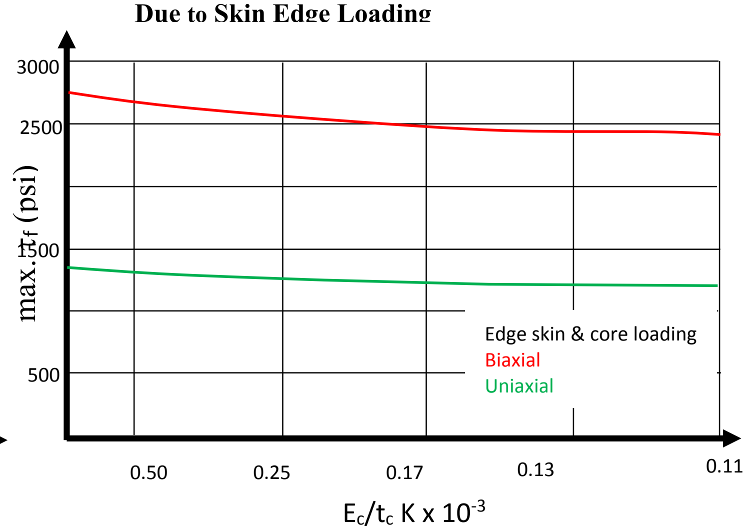

Fig. 7. **Effect of Bonding Stiffness on Skin Shear Stress Due to Skin and Core Edge Loading**

Case 2: Transverse Loading

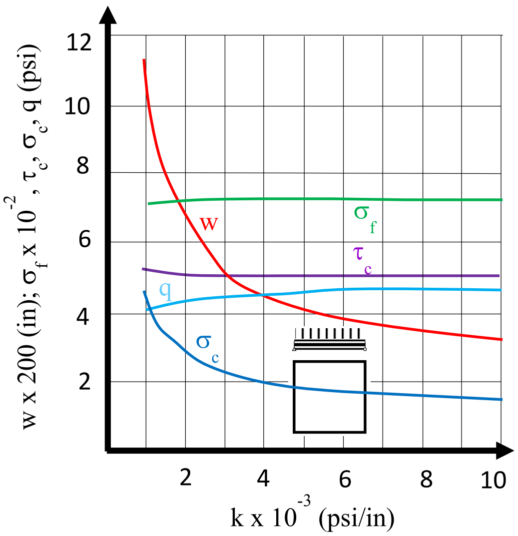

Fig. 8. Effect of Bonding Stiffness Due to Transverse Uniform Loading

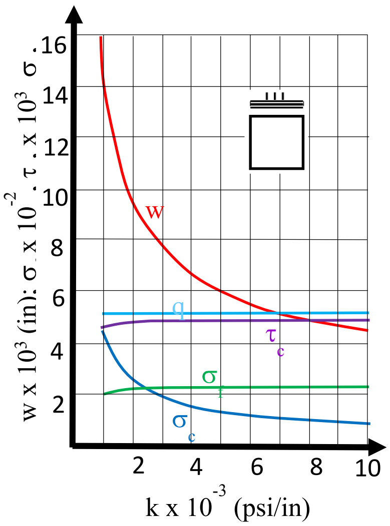

Fig. 9. Effect of Bonding Stiffness Due to Transverse Partial Uniform Loading

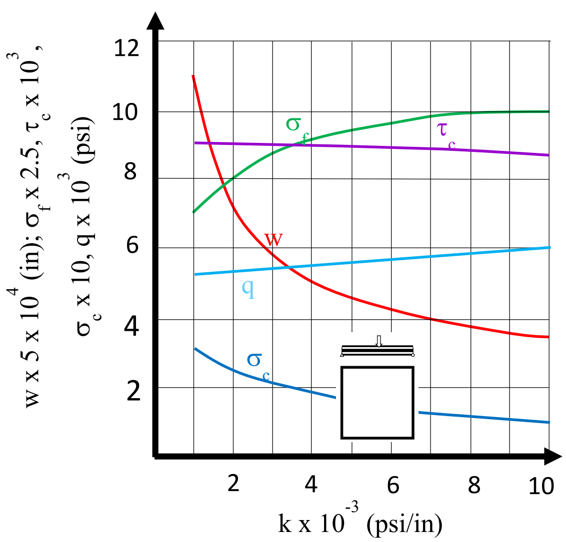

Fig. 10. Effect of Bonding Stiffness Due to Transverse Concentrated Load

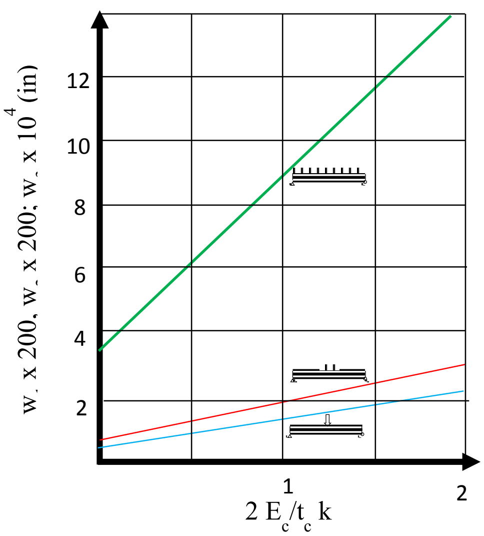

Fig. 11. Effect of E_c/t_c K on Maximum Deflection

To demonstrate the effects of bonding, three panels were investigated under three transverse loadings: uniformly distributed load, partial load on a central square area, and a concentrated load. In each case, the maximum normal stresses in the facings and core, the maximum in-plane shear stress in the facings, the maximum transverse shear stress in the core, and the maximum deflection were calculated for a range of bonding stiffness from 10^3-10^4 psi/in. The results are shown in Figs. 8 to 11.

It is seen that the deflection shows greater sensitivity to the variation of the K value when the latter is in the lower range; and beyond a certain level of bonding stiffness, the bonding can be practically considered as rigid. An increase in the K value is accompanied by a decrease in the normal stress of the core and an increase in the face's normal stress.

The results brought up an important point. By assuming perfect bonding, normal and shear stresses in the facings, and the transverse shear stress in the core may be determined using classic plate theories with a small margin of error. The bonding stiffness should be included in the analysis whenever the deflection is the quantity of interest.

Another important point has also been discovered. The results led to answer an un-answered question in the literature; i.e. what constitute perfect bonding? This question is best answered in terms of the ratio of the core stiffness to the bonding stiffness, rather than on the individual constituent material. By common sense, it can be felt that a very stiff bonding would be unnecessary if the core were too soft, and the converse would be unwise. This is quantitatively shown in Fig. 11, which shows that the ratio of core stiffness to adhesive stiffness is one of the main parameters influencing the behavior of the panels.

It should be noted that the complexity of the mathematical formulation and obtained solutions hinder their applications in real world practices. To resolve this problem, a knowledge-based computer client was developed using Windows architecture. In this way, any practitioner could easily analyze and design panels made of any materials.

SUMMARY AND CONCLUSIONS

In recent years, the world has experienced unprecedented environmental, energy, economic, and other challenges. To meet these challenges, a wide range of renewable materials developed from natural and manmade resources as polymers and composites. Yet, the state of scientific advancements apparently lags behind their applications in the buildings sector.

In the literature, very few papers have been published which deal with the effects of bonding on the structural response of laminated panels. Realistically, the core and bond in these panels are rigid enough to make a significant contribution to the overall structural integrity of the panels, yet flexible enough to permit shear deformations. In light the development of new biobased materials including adhesives and their applications in various industries including residential buildings, these deformations and their effects can't be ignored.

This paper presented an analysis of laminated panels taking into consideration the effects of the finite bonding stiffness. The solution satisfies the equilibrium equations of the face and core elements, the compatibility equations of interlayer stresses and strains, and the boundary conditions.

The numerical results have shown that the bonding stiffness, up to a certain level, has a strong effect on the structural response. Beyond that level, the usual assumption of perfect bonding is acceptable. The answer to what constitute "perfect" bonding is best answered in terms of the ratio of the core stiffness to the bonding stiffness, rather than on the individual constituent materials.

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VIBRATION BASED APPROACH FOR STRUCTURAL HEALTH OF IN RETROFITTING OR REHABILITATION OF CONSTRUCTION BUILDINGS

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ABSTRACT

Reports after reports have documented the fragility state of many buildings and called for the urgent attention because of their critical disrepair state due to aging and degradation. Delaying prompt actions implies a high risk of catastrophic failures and probable human loss. Retrofitting and rehabilitation provide remedies to reduce the vulnerability of those systems. Almost always, data about the structural health of the components in a building being considered for retrofitting or rehabilitation is required for any engineering calculations. Nonetheless, the true structural condition is challenging to the practitioners in many projects because of the complexity of geometry, framing systems, detailing of connections, workmanship, etc. This paper is an attempt to deal with these complexities in an easy to apply procedure yet leading to reliable and fast outcomes. It will present a novel approach to assess the stiffness of joints of aged members based on the rigorous vibration fundamentals that have been proven reliable. The procedure requires a widely available and affordable signal conditioner, and an algorithm that can be easily developed in a spreadsheet. The method has been successfully evaluated via numeric results obtained.

Keywords: Buildings, Connections, Nondestructive, Rehabilitation, Retrofitting, Stiffness, Structures, Vibration

GENERAL

The need for structural rehabilitation or retrofitting of buildings is motivated by the following circumstances:

- The existence of visible defects in the building.
- Damage after a particular event, like an earthquake, that affects its stability.
- The change of the use of the building.
- Requirement imposed by new codes.

The assessment of its actual condition is a necessary step in the structural rehabilitation or retrofitting projects. This step is complex because of the aesthetical and architectural configurations, the structural system of the building, the weak or damaged areas in the building, and the types of structural components. These factors interact with each other and influence the structural performance of the components and the entire system. This in turn presents many technical challenges for diagnosticating, analysis, and rehabilitation or retrofitting tasks. For remedial solutions, practitioners rely on engineering calculations that require the assessment of the true structural condition of the building and its components.

The assessment of the actual condition of a building can comprise in-situ tests, laboratory tests, field tests, and other procedures and protocols as described by the authority in charge of the

projects. In general, tests are expensive and not simple to perform. From this perspective, non-destructive approaches have been adopted for fast yet reliable outcomes.
The remedial work is not sufficient in any retrofitting or rehabilitation project. Once the repair part is completed, the monitoring of the building during a certain period of time begins to help the elaboration of the retrofitting strategy. Monitoring procedures collect and store the acquired data and transmit it to a designated station. By comparing the results obtained from the monitoring of the building with the results obtained from its engineering modelling, it will be possible to either refine the modelling or modify the repair work. The monitoring phase could also be expensive and cumbersome. Thus, non-destructive approaches lend practical ways to overcome these obstacles.

The basic human needs include shelters to protect humans from environmental and other effects. Residential buildings meet this particular need. References 1, 2, 4 and 5 represent selected pertinent sources that depict the state of deteriorated buildings including residential and the methods used for assessing their structural health. One could see in these sources and many others the complexity of the technical tasks involved in the retrofitting and rehabilitation projects.

DESCRIPTION OF TECHNICAL PROBLEM

As described previously, remedial and monitoring activities require data obtained from tests performed on the building in rehabilitation or retrofitting projects. In general, the data is integrated with the engineering modelling of the building to render stresses, critical zones, the design of the eventual strengthening, etc.

The structural models of buildings incorporate the set of structural components used to represent the structural functioning of the building. Beams, columns, slabs, walls, are examples of the typical components. Using calculation methods and theories that are readily available, the model should adequately simulate the structural behavior of the building, as accurate as possibly accepted by the personnel involved in the project.

The modelling of existing buildings is, in general, more difficult and less reliable than in the case of new buildings. This is due to several factors, such as:

- The difficulty in adequately modelling its structural configuration.
- The uncertainties related to the characteristics of the materials and the components in the building system.
- The influence of past events such as earthquakes.
- The imperfect knowledge or available information about past repairs made.

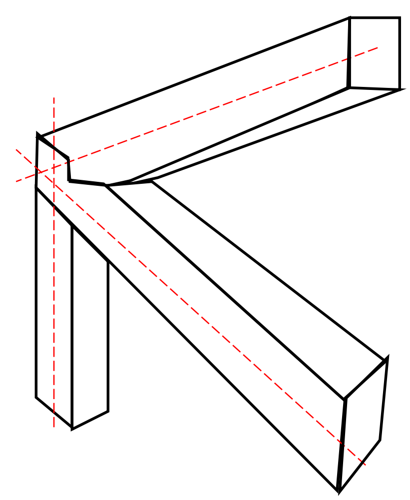

Fig. 1 A typical Structural Joint

Additional factors that compound the analytic modeling include the need for great experience and intuition about the structural behavior of building systems, local damages such as cracks, the actual constituent relationships; the alterations over time such as the creation of openings or the removal of components (headers, walls, etc.) or the increase in the height of some spaces, etc. These factors, individually or combined, affect the static and dynamic characteristics of the components and their assembly, thus complicate the engineering tasks involved in retrofitting or rehabilitation projects.

To elaborate, what should the characteristics of the connection shown in Fig. 1 be for engineering calculations? Is it a pin, rigid, or something else? What should be the answer if the connection is reinforced with binding strip, internal bolt, stirrup, or tension ties?

VIBRATION BASED APPROACH TO ASSESS THE STIFFNESS OF STRUCTURAL CONNECTIONS

The connection between beams and columns in framed structures are commonly assumed either pined or rigid. In reality, the actual stiffness is neither and fall somewhere between these two extreme cases. Flexible connections are thus suitable to represent actual connections. Flexible connections provide moment capacity within the pin to rigid range.

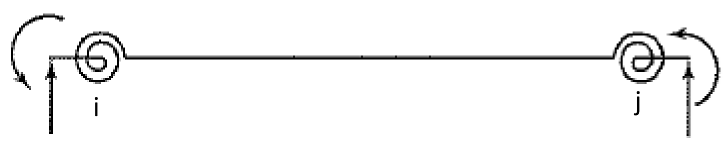

Fig. 2 Frame Element with Semi-Rigid Connections

Consider a frame element of length L and cross-sectional moment of inertia I with flexible joints at its ends with stiffness K_i and K_j, where I and j designate the ends, as shown in Figure 2. The explicit forms of the stiffness $[K]_{6x6}$ and consistent mass $[M]_{6x6}$ matrices are available in many references. It should be noted that the elements of these matrices include the following connection parameter C_i

$$C_i = \frac{L\,K_i}{E\,I + L\,K_i} \tag{1}$$

In which L is the member length and E is the modulus of elasticity of the element material. The equation of motion for free vibration of this element is

$$[M]\,\{\ddot{x}\} + [K]\,\{x\} = 0 \tag{2}$$

Where x is the displacement. The vibration characteristic value equation is thus

$$|[K] - \omega^2 [M]| = 0 \qquad (3)$$

In which ω denotes the natural frequencies of vibration.

The vibration signals of frame elements can be measured in field tests using portable and affordable signal conditioners like the one shown in Fig. 3. This type of conditioner is USB operated thus works with any computer hardware such as laptops or similar portable devices. There is also free or relatively cheap yet proven reliable software for recording the signals.

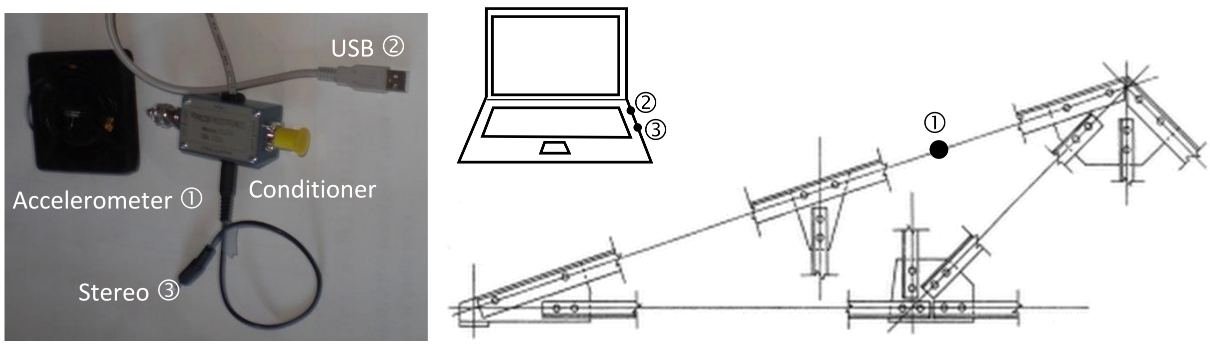

Fig. 3 A USB Signal Conditioner and Field Set-up

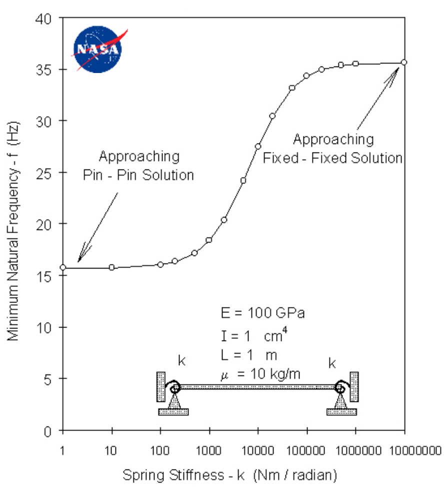

Fig. 4(a) Frequency-Stiffness (NASA)

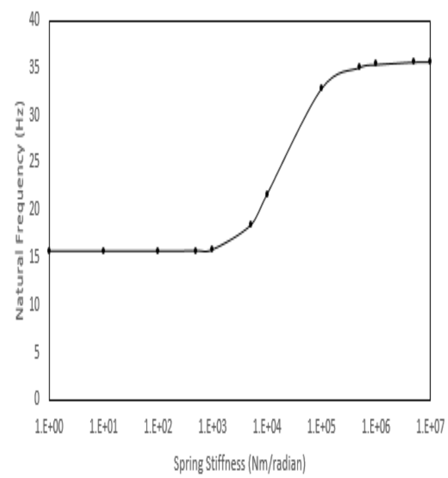

Fig. 4(a) Frequency-Stiffness (Paper)

Each recorded signal can then be analyzed using FFT from which the fundamental frequency ω is determined. The FFT algorithm is also available in many mathematic software or could easily be developed using any programming language.

Equation 3 can now be solved using iterative techniques for the connections stiffness K_i and K_j. In this paper, the solution of Equation 3 is conducted backward to obtain an input that would result in the measured input. Given the state and objective of the equation, a search is provoked to reduce the difference between the two. The iterative search is performed on the initial state to produce a new state, and the process is recursively applied to this new state and the objective state. In general, a solution is found through trial and improvement iterative procedures.

Putting the described direct, easy to perform, and inexpensive procedure together, this paper suggests the following complete protocol for the structural assessment of the joint stiffness of an actual frame member in a building under rehabilitation or retrofitting:

1. Determine the cross-sectional geometric and the material properties of the member.
2. Use a USB conditioner connected to a laptop to detect the vibration of the member.
3. Analyze the recorded signal to determine the natural frequency.
4. Solve Equation 3 iteratively for K_i and K_j.

The above described procedure has successfully been tested using a number of selected problems with known analytic solutions. Using the Finite Element Method, NASA (3) investigated the broad spectrum of joint stiffness from pin to rigid using the ratio of the rotational stiffness to the flexural stiffness of structural members as shown in Fig. 4a. NASA's data was used to run the method proposed in this paper and the results are shown in Fig. 4b. It is seen that the results from NASA and the proposed method are in agreement with insignificant differences. This success is considered as a first step of an in-progress long project. In residential buildings, the proposed method is useful to assess the joints of wood, metal such as steel and light gage, and concrete framing systems such as trusses. In addition, the presented approach has been used in other applications such as non-destructive assessment of defective utility poles. In these two developments, the intent is to provide means to deal with the vulnerability of aging infrastructure exposed to unprecedented and no longer predictable environmental and man-made loadings.

CONCLUSIONS

This paper proposed a novel approach to assess the stiffness of structural frame members using nondestructive vibration-based procedure. The procedure is useful for rehabilitation and retrofitting aging buildings. The field application of the method includes the four steps described in the paper and its analytic validity was checked by comparison with available methods like that from NASA (3). Once the vibration signals from a member are measured and analyzed, a reverse engineering procedure could be applied to solve the vibration characteristic equation for the stiffness. The required signal conditioner and software are readily available and inexpensive.

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Shear wall Design in Residential Construction: A Comparison of Methods

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Current building codes and standards for residential construction are complex and easily misunderstood when it comes to the requirements pertaining to wood shear walls that act as the lateral load resisting system. These walls fall under two categories: engineered or prescriptive in regards to design. This paper will discuss a comparison of provisions and guidelines between the IBC, IRC, NDS, and WFCM. Details will focus on the differences, limitations, and general processes necessary to conduct wood shear wall designs. The results will give designers and builders a better understanding of the complexity of shear wall code provisions and how to go about designing and constructing shear walls through clarifying code intent. Other propriety systems or uncommon engineering-critical solutions will also be discussed and how to approach those projects.

Introduction

The architectural style common in today's residences may be characterized by highly perforated and offset wall surfaces with the inclusion of a large opening to accommodate garage doors at the front of the residence (McMullin and Merrick 2002; Barnes 2006). Complicating this design style is the interior spaces that are frequently open, both horizontally and vertically over one- and two-story spaces resulting in reduced building stiffness of the lateral system (Minor 2002). Protecting this investment from natural disasters such as high wind and earthquakes is an important task for builders/engineers. The performance of the home under such events depends largely on the performance the main lateral force resisting system (Ni et al. 2010; Shirazi and Pang 2012). Fortunately, wood generally performs very well during many external environmental conditions/events over the lifespan of the project, thus its applicability and usage for 80% to 90% of all residential structures in the United States. The lateral load resistance of light wood-frame buildings is generally provided by sheathed braced walls, often more commonly called shear walls (Ni et al. 2012).

The style of modern architectural homes is often in opposition to many code prescribed requirements that permit the average builder without an engineering licensure to design them. Furthermore, current building codes and standards for residential construction are complex and easily misunderstood when it comes to the requirements pertaining to wood lateral systems. Whether they are engineered or prescriptive, the design intent is often misunderstood which has the potential to result in improper construction of walls that can lead to poor performance and failure (both aesthetically and structurally).

This paper was part of a research project whose main research goal was a comprehensive review of the current available opportunities for shear walls in residential homes. Herein, this paper provides an examination of the current International Residential Code (IRC), National Design Specification for Wood Construction (NDS), International Building Code (IBC), and American Wood Council Wood Frame Construction Manual (WFCM) for One- and Two-Family Dwellings. The depth here will provide discussions and relative code provisions for wood shear wall design.

Residential Wall Types and Configurations

Most residential and light commercial construction is based on a "box" design. Three types of loads can be imposed on walls for such designs. First are out-of-plane loads (i.e., perpendicular to the wall). These loads result primarily from wind but can also result from seismic activity. All exterior walls are exposed to these out-of-plane forces. Secondly, vertical loads (i.e., axial loads) are transferred into some walls from the roof or upper-story walls. The vertical loads can be downward-acting gravity loads that result from the weight of the structure and occupancy or upward-acting (uplift) loads from wind or seismic events. Lastly are in-plane horizontal loads (i.e., parallel to the wall). These loads typically result from lateral forces imposed on building. For this last type of loading the walls that are needed to resist these loads are called "shear walls" or "shear panels" or "braced walls." Figure 1 shows a hierarchy of factors relating to different aspects of a wall system that can affect performance. It will be observable later that many of these factors appear in the limitations and code provisions.

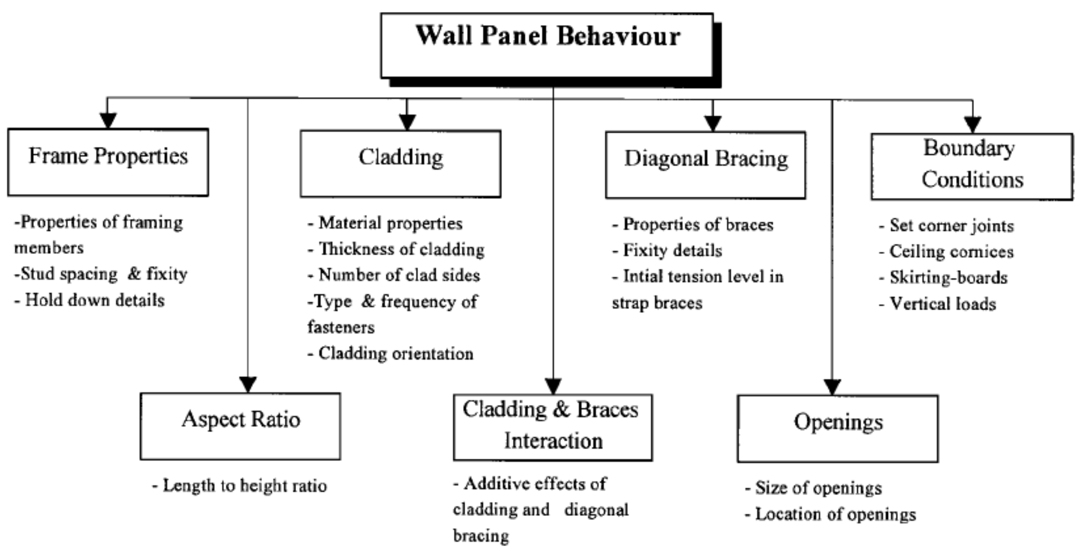

Figure 1: Factors Affecting Lateral Behavior of Shear Walls

Lateral force resistance to wind and seismic loads in wood frame structures is provided by shear walls in the majority of homes (Shirazi and Pang 2012). In this configuration, shear walls resist forces by allowing the sheathing panel to rotate, essentially racking the wall horizontally in shear (Yeh et al. 2009). In box design, horizontal diaphragms (e.g., roof and floor systems) work in conjunction with vertical shear walls to support gravity loads, resist lateral loads, and provide structural stability. The required minimum length of a shear wall panel generally ranges from 4' to 8' of wall with no openings.

For the design of shear walls with openings, the designer has the option of using the segmented, perforated, or force transfer around openings classifications. Of the classifications analyzing shear walls discussed two are the most often adopted. Segmented shear walls are full-height, fully sheathed wall segments that function independently to resist lateral loads. Perforated shear walls contain framed openings for windows and doors. Perforated shear walls rely upon continuous structural elements over windows and door openings to make the shear wall function as a single unit. These elements are called “drag struts.” Generally, greater lengths of perforated shear walls are needed to resist lateral loads than segmented shear walls. Also, in perforated shear walls, more attention in the detailing and design is needed above doors and windows, where framing functions as drag struts. The benefit of perforated shear walls is that they only need to be anchored at their ends while the ends of each segment of a segmented shear wall need to be anchored. There are 16 methods in the IRC (IRC Table R602.10.4) to select from for lateral resistance options as listed here:

- Portal Frame with Hold-downs
- Portal Frame at Garage
- Continuously Sheathed Wood Structural Panel
- Continuously Sheathed Wood Structural Panel adjacent to Garage Openings
- Continuously Sheathed Portal Frame
- Continuously Sheathed Structural Fiberboard
- Let-in Bracing
- Diagonal Wood Boards
- Wood Structural Panel
- Wood Structural Panel with Stone or Masonry Veneer
- Structural Fiberboard Sheathing
- Gypsum Board
- Particleboard Sheathing
- Portland Cement Plaster
- Hardboard Panel Siding
- Alternate Braced Wall

Because of the relative complexity of choosing and analyzing braced-wall sections per the IRC, the Engineered Wood Association (APA) published *A Guide to the IRC Wood Wall Bracing Provisions* (APA 2009). This publication walks the designer through the basic wall provisions in a step-by-step manner and greatly simplifies applying these provisions in a residential structure design. Shear walls may also be constructed with masonry, concrete, ICF (Insulated Concrete Forms) and with structural insulated panels (typically referred to as SIP). SIPs consist of wood structural panels which sandwich a rigid insulation core, which is typically polystyrene (although urethane is also used). Engineered homes with large openings may use moment frames to resist lateral loads in addition to shear walls. Alternatives to moment frames can include:

- Move or re-size window or door opening to meet the wider braced-wall requirements.
- Hire a design professional to provide an engineered solution.

- Use a code listed shear wall product that meets the intent of the code while providing a narrow wall solution such as a Simpson Strong-Tie® Wood Strong-Wall® or Steel Strong-Wall®.

Building Codes and Standards

To design shear walls (both prescriptive and engineered), various codes and specifications designers must take into account when designing Wood Framed (WF) systems. To design a WF residential structure, the design professional must be familiar with the following codes and design standards (Memari et al. 2014):

- International Residential Code (IRC) (ICC 2015b)
- International Building Code (IBC) (ICC 2015a)
- American Wood Council (AWC) National Design Specification for Wood Construction (AWC 2015)
- AWC Wood Frame Construction Manual (WFCM) for One- and Two-Family Dwellings (AWC 2012)
- American Forest and Paper Association (AFPA) Special Design Provisions for Wind and Seismic (SDPWS) (AWC 2015)

The building codes give Building Officials the authority to approve alternate materials, designs and methods of construction that comply with the intent of the provisions of the code and are at least the equivalent to those prescribed in the code. It is imperative that designers of residential structures using wood framing systems become familiar with the IRC, IBC, NDS, WFCM, and SPDWS codes and standards to assure that efficient and structurally sound design solutions are achieved. Each has a unique set of design-related information but they are all compatible. It is also important that designers use the latest editions of these documents because they are continually updated with new design information based on ongoing research. When residential structures are beyond the limitations set forth by the IRC and WFCM, the design must be engineered. This could include designing connection systems for high-wind areas, tornado-prone regions, or high–seismic risk categories. The NDS provides all the requisite information for the design of these systems.

IRC

The IRC (ICC 2015) is deemed a prescriptive code for one- and two-family dwellings with no more than three stories. It also applies to townhouses with no more than three units. The IRC applies to the large majority of residential construction in the United States. The IRC provides extensive prescriptive design information in the form of tables and figures for WF construction using sawn lumber for roofs, floors, walls, and wood foundations. It also recognizes the use of engineered wood products, including prefabricated wood I-joists, glued laminated timber (glulam), and structural composite lumber (SCL) for joists, rafters, beams, and headers. But each of these "engineered" components must be designed using engineered-design procedures, as set forth in other referenced documents. The IRC also recognizes the WFCM as an alternate design standard. In addition, the IRC provides separate bracing requirements for homes which are continuously sheathed with OSB, plywood or structural fiberboard (except seismic controlled) with masonry veneer conditions.

Exterior walls of WF construction shall be designed and constructed in accordance with the provisions of Chapter 6 in the IRC or in accordance with AF&PA's NDS. Within the IRC many tables exist that relate to design provisions for shear walls. Table 1 in this paper lists the relevant tables for designing shear walls based on main categories and topics with the appropriate code table in the IRC. Where the conditions are not within the parameters of the tables, the design is required to meet the NDS. The most relevant design tables within the IRC for shear wall sizing are R602.10.3(1), R602.10.3(3), and R602.10.5.

Table 1: Relevant Tables in the IRC for Designing Shear walls.

Category	Topic	Table Designation
Bracing methods	Applicable Methods for Shear walls	R602.10.4
Wood studs	Size, height and spacing	R602.3(5) R602.3.1
	Fastener schedule for structural members	R602.3(1-3)
Dimensions & Proportioning of Shear walls	Minimum length of braced wall panels	R602.10.5
	Braced wall line spacing	R602.10.1.3
	Minimum number of bracing units on each side of the circumscribed rectangle	R602.12.4
	Method BV-WSP wall bracing requirements	R602.10.6.5
Design Forces and Values	Bracing requirements based on wind speed	R602.10.3(1) R602.10.3(2)
	Bracing requirements based on seismic design category	R602.10.3(3) R602.10.3(4)
	Minimum hold-down forces for method ABW braced wall panels	R602.10.6.1
	Tension strap capacity required for resisting wind pressures perpendicular to method PFH, PFG and CS-PF braced wall panels	R602.10.6.4

For IRC Wind and Seismic Design Categories (SDC) A-C, braced wall panels should be installed near the ends of the braced wall line up to 12'-6" from the end. The IRC limits the total combined end distance for the outer most panels in a braced wall line to no more than 12'-6". For SDC D0-D2 the IRC states that braced wall panels may begin no more than 8'-0" from each end of the braced wall line. Panels shall be spaced no more than 25' on center along the braced wall line. It is also allowable to take up to a 4' offset and still maintain the same braced wall line. An offset is when there is a break in the wall line, for example, for a porch and front door, or a bay window. If there is more than a 4' offset, the code states that you must start a new braced wall line, which means additional braced wall panels.

Continuous sheathing methods require structural panel sheathing to be used on all sheathable surfaces on one side including areas above and below openings and gable end walls. The IRC specifies minimum wall-sheathing thickness and fastening requirements for structural panels, cellulosic fiberboard, and gypsum sheathing. Wall sheathing are be fastened directly to framing members and, when placed on the exterior side of an exterior wall, shall be capable of resisting the wind pressures. Braced walls need to have gypsum wallboard installed on the side of the wall opposite the bracing material. An approved interior finish material with an in-plane shear resistance equivalent to gypsum board is permitted. Furthermore, gypsum wall board must be at least a 1/2 inch (12.7 mm) thick and be fastened with nails or screws. Interior finish material are not be glued in Seismic Design Categories D0, D1 and D2. All panels must be identified for grade, bond classification, and performance category by a grade mark or certificate of inspection issued by an approved agency and will conform to the requirements in the IRC.

IBC

The IBC (ICC 2015) is essentially an engineered design code, although several prescriptive tables are in the document, such as for wood shear walls and diaphragms, which are included in Chapter 23. The IBC is used when the residence exceeds the scope of the IRC. Chapter 23 provides the basic design information for wood but refers extensively to the National Design Specification (NDS) (AWC 2015) and SPDWS (AFPA 2015) standards for more extensive design information. Panels complying with ANSI/APA PRP-210 shall be permitted to use design values for Plywood Siding in the AFPA SDPWS. For species not Douglas Fir-Larch or Southern Pine, the specific gravity for species of lumber in NDS must be used instead.

The IBC permits the combination of engineered elements/systems with conventionally specified systems as long as the limits of Sections 2308.1 and 2 are met. For elements not described within the IBC, these elements or systems shall be designed in accordance with accepted engineering practice and provisions in the IBC. Within the IBC the main provisions are for walls fastened with staples and not nails. Here the IBC enforces that such designs satisfy the requirements and limitations of SDPWS. Within the IBC many tables exist that relate to design provisions to shear walls. Table 2 in this paper lists the relevant tables for designing shear walls based on main categories and topics with the appropriate code table in the IBC 2015.

Table 2: Relevant Tables in the IRC for Designing Shear walls.

Category	Topic	Table Designation
Bracing methods	Applicable Methods for Shear walls	2308.6.3(1-5)
Wood studs	Size, height and spacing	2308.5.1
	Fastener schedule for structural members	2304.10.1
Dimensions & Proportioning of Shear walls	Wall bracing requirements	2308.6.1
	Min thickness of Wall Sheathing	2308.5.11
Design Forces and Values	Allowable shear values	2306.3(1) 2306.3(2) 2306.3(3)

The most relevant design tables within the IBC for shear wall sizing are 2306.3(1), 2306.3(2), and 2306.3(3). The IBC has provisions for WF shear walls sheathed with gypsum board, and lath and plaster. These systems need to be designed and constructed in accordance with Section 2306.3 and are permitted to resist wind and seismic loads.

Gypsum and plaster wood framed wall assemblies are not be used to resist loads imposed by masonry or concrete walls according to IBC. Values in the IBC are for short-term loading due to wind or seismic loading.

IBC 2015 has special provisions / additional requirements for conventional wood framed construction for seismic Design Category D or E. While in the IBC 2012 these provisions were in Section 2308.12 and its subsections, the requirements for Seismic Design Category B or C are in Section 2308.11. In the 2015 version of the IBC, these provisions have been reorganized into their respected areas of lower SDC categories. Structures of conventional light-frame construction and assigned to Seismic Design Category D or E shall not exceed one story above grade plane. Spacing between interior and exterior shear wall lines cannot exceed 25 feet. The sum of lengths of braced wall panels at each braced wall line are required to conform to the required percentage of wall length necessary to be braced per braced wall line. Panel sheathing joints are to occur over studs or blocking. Sheathing needs to be fastened to studs, top and bottom plates and at panel edges occurring over blocking. Wall framing to which sheathing used for bracing is applied is permitted to be nominal 2-inch-wide or larger members. An additional requirement is that no wall sheathing cannot be attached to framing members by adhesives. Conventional light-frame construction is not to be used in irregular portions of structures assigned to Seismic Design Category D or E. Such irregular portions of structures are permitted to be designed to resist the forces to the extent such that the irregular features do not affect the performance of the conventional framing system.

NDS/SPDWS

The NDS (AWC 2015) is the primary reference for the engineered design of wood structures. In addition to setting forth the design procedures for components, such as bending members and compression members, it provides the extensive information needed for the design of connections in WF structures. The 2015 IBC references the 2015 NDS as the required design standard in those jurisdictions adopting the 2015 IBC. The supplement to the NDS provides allowable stress values for virtually all grades and sizes of sawn lumber and timbers as well as for most combinations of glulam. Design values for proprietary products, such as wood I-joists, must be obtained from the manufacturer's code evaluation reports. As shear walls function as the mechanism to resist wind and seismic forces, the Special Design Provisions for Wind and Seismic (SDPWS) Section of the NDS applies. The SPDWS (AFPA 2015) standard provides detailed information for the engineered design of structures exposed to wind and seismic loads. The SDPWS covers materials, design, and construction of members, fasteners, and assemblies. The main shear wall sections of the SDPWS are in Chapter 4. In addition to providing detailed lateral load design guidelines, the SPDWS also provides some prescriptive tables for shear walls and diaphragms similar to those in the IBC. The lateral load resisting system must be proportioned, designed, and detailed to all chapter provisions.

Tables are provided for shear walls unit (nominal) shear capacity in a combination format for wind and seismic. Column A of Tables 4.3 A, C, B and D are for seismic, while column B of Tables 4.3 A, C, B and D are for wind. In shear wall capacities, the sheathing material can be similar or dissimilar. When they are the same material the capacity of a single side of sheathing may be doubled. When the materials are different on each side of the wall, Section 4.3.3.2 states that the values are not cumulative. Instead it is 2 times the smaller value or 1 time the larger value. The larger of these two values is used. There is one exception to this and that is for wind design. If the framing is shear walls with a combination of wood structural panel, siding, or fiberboard on one side and gypsum on the other a sum may be taken for exterior walls. Unblocked walls are permitted when framed in accordance with Table 4.3.3.2 and the strength is adjusted with an unblocked factor that ranges from 0.4 to 1.0 depending on nail spacing and stud spacing. Unblocked walls however cannot exceed 16' in height.

When w/h ratios are greater than 2:1, the nominal capacities need to be adjusted by 2bs/h. The aspect ratio factor (WSP) shall also be used = 1.25-0.125h/bs, which is applicable to shear walls with an aspect ratio greater than 2:1. A common misunderstanding of the 2bs/h factor is that it represents an actual reduction in unit shear capacity for high aspect ratio shear walls. The actual strength reduction associated with high aspect ratio shear walls is less severe in the new 2015 Version. The 2bs/h factor accounts primarily for stiffness compatibility of the high aspect ratio segment. Where 2bs/h is used to comply with load distribution requirements of Section 4.3.3.4.1, the strength reduction adjustments of Section 4.3.4.2 for high aspect ratio shear wall segments need not be applied.

Perforated shear wall capacities are taken as the tabulated nominal unit shear capacity multiplied by the sum of the shear wall segment lengths. An additional adjustment factor (Co) is applied. The Co factor can range from 0.36 to 1.0 and is dependent on percentage of full height sheathing and Max opening height. Perforated walls exceeding a 3.5:1 ratio are not permitted to use the sum of shear wall segments. Provisions for accounting for the strength contribution of high aspect ratio shear wall segments within a perforated shear wall were revised in the 2015 Version. Where a high aspect ratio for perforated shear wall segments (h/bs>2:1) was considered in the calculated strength of the perforated shear wall, the shear capacity of the overall perforated shear wall requires adjustments by the 2bs/h factor. Because the more severe 2bs/h factor is used, unit shear values of high aspect ratio shear wall segments within a perforated shear wall are not required to be adjusted by the aspect ratio factors defined in Section 4.3.4.2. While this revised method will generally permit increases in design strength of perforated shear walls incorporating high aspect ratio segments, there are cases where there is little change such as perforated shear walls comprised entirely of identical high aspect ratio perforated shear wall segments

Sheathing is to be attached to members using nails or other approved fasteners. Often other approved fasteners include wood screws and adhesives. Adhesive can only be used with SDC A-C and must have a secondary system for wood structural panel shear walls. Tables 4.3 A, C, B and D make recommendations for nailing patterns (and screws for drywall) that affect the shear strength. The SDPWS makes additional upper bounds for the limitations in the spacing of fasteners. To use Tables 4.3 A, C, B and D you need to know several values beyond if you are in wind or seismic. These include: min. nominal panel thickness, min fastener penetration, fastener type, and panel edge fastener spacing. Before you can use these tables, you need to know which table to use. Here these are based on the sheathing materials. Table 4.3A is for wood based panels, Table 4.3B is for wood panels applied over gypsum, Table 4.3C is for gypsum and Portland cement plaster only, and lastly Table 4.3D is for lumber sheathing. Tables are provided for lateral loads and withdrawal loads.

Staples are beyond the scope of the NDS, and Evaluation Service Report (ESR) 1539 (ICC Evaluation Service 2005). The International Staple, Nail, and Tool Association (ISANTA) provides the necessary design information for staples. This report also provides tables for converting the nailing schedules published in the IRC and WFCM to other equivalent types and sizes of nails.

WFCM

The WFCM (AWC 2012) is a companion document to the IRC. It is limited to one- and two-family residences having no more than three stories. WFCM has applicable limitations, which outline building dimensions and load assumptions as the WFCM provisions are intended primarily for detached one-and two-family dwellings similar to the IRC requirements. Wind provisions for sizing of wall sheathing, fastening schedules, uplift straps, shear anchorage, and shear wall lengths are included in the WFCM and are applicable for other use groups within the load limitations of the WFCM tables (Showalter et al. 2015). The WFCM provides extensive tables for floors, walls, and roofs for both the prescriptive and engineered design methods for framing using sawn lumber. Applications outside the scope of the WFCM tabulated requirements are beyond the applicability of the WFCM and must be designed in accordance with accepted engineering practice. This parallels the approach taken in Section R301.1.3 of the IRC, which permits unconventional elements of one and two-family dwellings to be designed per the IBC and NDS.

Engineering design detailed in the 2015 WFCM provides the minimum load for the purpose of establishing specific resistance requirements for buildings that meet the scope of the WFCM document. In engineering design, the wood shear walls approach is much more generic and open ended as compared prescriptive. The prescriptive approach can be broken down two ways. The first is by wall type, either segmented or perforated. The second is by wind and seismic loadings. In both cases there are limitations for when the prescriptive approach is permitted by the WFCM.

Engineering Design Approach

Engineering design is separated by wind and seismic loadings based on Section 2.4.4.2. Engineering design does not specify which walls must provide shear resistance but does state that walls parallel to the applicable load shear provide the required shear resistance at each level and that the sum of all individual walls must meet or exceed the sum of the total collected horizontal diaphragm loads from above. Among the provisions for engineering design, there exists many tables in Chapter Two to aid the design of shear walls. Table 3 in this paper lists the most relevant tables needed for designing engineered shear walls in the WFCM.

In both wind and seismic design, the WFCM Section 2.4.4.2, describes that the total shear loads shall be calculated using tables. For wind design, tabulated values for wind are found in Tables 2.5A and 2.5B. The tables are structured in such a fashion that the value generated by the tables is the unit lateral load on the diaphragm above the level you are designing. To use the tables you need to know the following: 3-second gust mph (available range 110-195), roof pitch (0:12 to 12:12) and the roof span dimension (available dimension 24'-60' in 12' internals). Table 2.5A gives you the load for parallel to the ridge and Table 2.5B gives perpendicular to ridge. Both tables have the same necessary criteria. Other wall heights and exposure categories are permitted and are adjustable. The trend of short walls and small roof pitches gives a greater reduction of length. For different exposure categories the values in the tables need to be multiplied by adjustment factors in Section 2.1.3.1. For different wall heights, the values in the tables have to be multiplied by the following factor (H+1)/11.

Table 3: Relevant Tables in the WFCM for Designing Engineered Shear walls.

Category	Topic	Table
Loads	Lateral Framing Connection Loads from wind	2.1
	Uplift Connection Loads from wind	2.2A
	Wind load loads	2.5A 2.5B
	Lateral Loads from Seismic	2.6

For seismic design, Table 2.6 gives the lateral loads. Tabulated values do not specify a numerical load like the wind tables do. Here, the story shear is based on an equation for each level and the seismic weight of the floor. To be able to calculate the values you need to know: floor weight, wall weight (parallel and perpendicular), roof weight, and partition weights. You need to further know what the seismic factors S_{ds} and R are for your particular system. The equations from Table 2.6 are based on the assumption that the building is rectangular, seismic weight is based on mid-story heights, and you need to include 20% of the ground snow in the roof weight where it exceeds 30 psf. If it is 50 and 70 psf, roof weight is increased by 10 and 14 psf, respectively.

Prescriptive Design Approach

Prescriptive design procedures have limitations for usage based upon how the provisions in the WFCM were formulated. External walls must be considered shear walls. However the entire external walls permitted need not meet shear wall requirements unless needed for strength. If external walls are not sufficient then internal walls are permitted to be used. As part of this, shear walls must be placed within the structure in two orthogonal directions. This is often not an issue to locate sufficient areas unless the house has non-traditional design attributes. Among the provisions for prescriptive design, there exists many tables in Chapter Three to aid the design of shear walls. Table 4 here lists the most relevant tables needed to design shear walls from the prescriptive approach for solid segmented and perforated walls by in the WFCM.

In the WFCM, tabulated values for wind and seismic are given but often are adjusted based on an adjustment factor for different materials, roof pitches, lengths, aspect ratios, and nailing patterns. Looking at the adjustment factors they range from 0.35 to 1.58 for wind and 1.0 to 1.6 for seismic which makes sense based on seismic weight.

Table 4: Relevant Tables in the WFCM for Designing Prescriptive Shear walls.

Category	Topic	Table
Connections	Nailing Schedule	3.1
	Foundation connection resisting lateral loads	3.2A-C 3.3
Sheathing requirements	Wall Sheathing requirements	3.13A
	Wall cladding requirements	3.13b
	Segmented sheathing requirements for wind	3.17A
	Segmented sheathing requirements for EQ	3.17C
Capacities and Design	Shear walls resisting uplift and shear	3.4B
	Unit shear capacities	3.17D
	Perforated Shear wall height adjustments	3.17E
	Segmented and Perforated Shear wall hold down capacity	3.17F

Segmented Design

The prescriptive design approach has provisions that account for the behavior of segmented formulations. In both wind and seismic design, the WFCM Section 3.4.4.2 has the shear wall lengths tabulated based upon a standard shear wall for each load type. The tables are structured in such a fashion that the value generated by the table is the minimum length of a full height shear wall perpendicular to the building dimension. To use the table you need to know the 3-second gust mph (available range 110-195) and the building dimension (available dimension 12-80 with up to 40’ in 4’ internals and beyond in 10’ intervals). Exposure B and C are provided in Tables 3.17A.

Tabulated values for seismic are found in Table 3.17C. The tabulated sheathing lengths are based on 10’ walls and 10’ top plate to ridge heights. The table is further broken down based on the story location you are considering for design. Other materials are permitted and are modified based on an adjustment factor. Adjustment factors for variations on standard shear wall construction are provided in Table 3.17C footnotes and Table 3.17D. The tables are structured in such a fashion that the value generated by the table is the minimum length of a full height shear wall. To use the table, you need to know the following: SDC (A-C only), minimum building dimension (available dimension 12-36’ in 4’ internals), building length to width ratios (1 to 3 in 0.5 internals), the level you are designing in the building, and lastly the ground snow load (30, 50 and 70 psf are available).

Perforated Design

Section 3.4.4.2.2 in the WFCM contains criteria needed for constructing perforated shear walls. This section states that an adjustment factor is applied to Table 3.17A and 3.17C values are conducted. The adjustment factors found in Table 3.17E are based upon the size (height) of the framed openings (windows or doors), the wall height (8, 9 or 10 ft), and the percentage full height sheathing on segment shear wall (10-100% in 10% intervals). These give way to adjustment factors between 1.00 to 2.50.

Summary and Comparison of Codes

To achieve a simplification for a non-engineering professional to design residential structures that are common, many of these codes have limitations based upon their formulation and intent to aid designers. Each code has different limitations which makes for a more difficult time switching from one format to another. Table 5 was created to show the comparison of the different assumptions and limitations these individual codes.

Table 5: Comparison of Limits and Assumptions for the Codes

Limitation Type	IBC	WFCM		IRC	SDPWS
		Engr.	Persc.		
Mean Roof Height	Not Limited	33'	33'	Function of wall	N/A
No. of Stories	3	3	3	3	N/A
Building Dimensions	Not Limited	80	80	Function of capacity	N/A
Shear wall line offset	4'	4'	4'	4'	N/A
Shear wall floor offset	Not allowed	Not allowed	Not allowed	Not allowed	N/A
Segment Aspect Ratio	N/A	See SDPWS	Table 3.17D	N/A	Table 4.3.3 Up to 3.5:1
Studs Spacing	16"-24"	16"-24"	16"-24"	8" - 24"	16"-24"
Wind	Speeds of 85-150 mi/h Exposures B-D	Speeds of 110-195 mi/h Exposures B-D		Speeds of 110-130 mi/h Exposures B-D	Not Limited
Seismic	All	Seismic design Categories A, B, C, D0, D1, and D2		Seismic design Categories A, B, C, D0, D1, and D2	Not Limited

SDPWS and NDS are the most robust and comprehensive codes as they are tailored towards an engineering professional utilizing these documents. The WFCM does not include a comprehensive engineering analysis that would be performed by a licensed engineer, instead it was meant to be a time saving device. In addition, WFCM limits the building width and length to 80 ft and 3 stories which covers most residential homes. Further the complexity is broken into prescriptive design of residential structures and engineered design each of which are different as was discussed.

Limitations in prescriptive designs are stricter as compared to engineering design based conservative notions to simplify options for non-trained engineers conducting the design.

Regardless of the code (except the SDPWS), three conditions must be met. The first is the shear wall line offset, here a line of shear walls cannot shift in plan more than 4'. The second is the shear wall story offset, here shear walls must be stacked on top of one another unless you meet the specific exception in Section 2.1.3.3d of the WFCM which focuses on proper detailing and ensuring a continuous load path. No walls, including shear walls, can have a stud spacing greater than 24" o.c. in any of the codes discussed. Lastly, note that the shear wall segment aspect ratios can be a limiting factor and vary across several of these codes. The ratio cannot exceed a 2:1 ratio unless you apply the NDS's SDPWS Section 4.3.3.4.1 exception 1 and 2 which will permit a ratio of 3.5:1.
The IRC follows closely to the WFCM but has less wind speed ranges as compared to the WFCM and its supplemental documents covering higher areas. IBC provisions permit shear walls to be designed and constructed in accordance with the SDPWS and the applicable provisions of Sections 2305, 2306 and 2307. The main difference here is that the values and provisions given directly in the IBC are for stapled walls.

Structural design for shear walls within these code documents varies as was discussed. When it comes to capacities for walls to resist in plane wind loads and seismic loads, the procedures change but so does the values the different codes give for designing. Table 6 was developed for two reasons. The first was to identify the unit for selecting the proper wall. The second was for comparing the permitted capacities for different materials across codes. Of all the codes, only the IRC provides capacities based on a minimum length and not a unit shear value. This makes sense as the IRC provides simplifications but it also limits designs as these lengths can be large.

We can see that across the different types of materials in Table 6 that the shear capacities change. This is expected as materials can have vastly different capacities. What is surprising is the variability of unit shear capacity from code to code. Often the more simplified codes have lower values but in some cases significantly. Additionally, the WFCM for engineered design reverts back to the SDPWS code. Lastly it needs to be noted that if you intend to use a specific material a careful choice of code will be needed as not all the codes cover the same materials.

It is known from research in shear wall design that the nailing patterns and fastener type can have a large impact of the shear capacity of the shear wall. Nail spacing is varied from 2-12" o.c. and is different for perimeters and interiors of a sheathing panel. Depending on the materials these values vary. Each code identified earlier has different limitations, as such these limitations also affect the nailing requirements. Table 7 here highlights for several different materials used for sheathing the prescribed nailing requirements. The SDPWS provides the most detail while the WFCM also references manufacturer specifications for certain types of products. The IBC provides the least amounts of provisions related to material type while focusing specifically on stapling requirements.

Table 6: Comparison of Shear Capacity Ranges Permitted in Walls.

Sheathing Type for Wall	WFCM			IBC	IRC*	SDPWS	
	Engineered	Prescriptive		Wind & E.Q.	Wind & E.Q.	E.Q. Range	Wind Range
	Wind & E.Q.	Wind	E.Q.				
Wood structural panels: structural 1	Refer to SDPWS	308-1260	221-902	155-475	Lengths	400-1740	560-2435
Wood structural panels: sheathing	Refer to SDPWS			N/A	Lengths	360-1740	505-2435
Plywood siding	Refer to SDPWS	N/A	N/A	140-430	Lengths	280-820	390-1150
Particleboard	Refer to SDPWS	N/A	N/A	N/A	Lengths	240-1040	335-1455
Structural fiber board	Refer to SDPWS	297-397	212	150-325	Lengths	340-520	475-730
Gypsum wallboard, gypsum base for veneer, water resistant gypsum backing	Refer to SDPWS	75-100	75-100	75-250	Lengths	150-500	150-500
Gypsum sheathing board	Refer to SDPWS			75-175	Lengths	150-400	150-400
Gypsum lath	Refer to SDPWS	N/A	N/A	100	Lengths	200-360	200-360
Expanded metal woven wire lath with Portland cement	Refer to SDPWS	N/A	N/A	180	Lengths	360	360
Horizontal lumber sheathing	Refer to SDPWS	N/A		N/A	Lengths	100	140
Diagonal lumber sheathing	Refer to SDPWS	N/A		N/A	Lengths	600	840
Double diagonal lumber sheathing	Refer to SDPWS Refer to SDPWS	N/A		N/A	Lengths	1200	1680
Vertical lumber sheathing	N/A	N/A		N/A	Lengths	90	125

* For the IRC shear capacities are not given, instead wall lengths and the amount of walls needed are given.

Table 7: Comparison of Sample Nailing Pattern Requirements

Panel type	SDPWS	WFCM	IBC	IRC
Wood structural panel	6" o.c. at panel edges 6" o.c. interior if panel is ≥7/16" or studs < 24" o.c. then 12" o.c. interior	6" o.c. at panel edges 12" o.c. else	6" o.c. at panel edges 12" o.c. else	6" o.c. at panel edges 12" o.c. else
Particleboard	6" o.c. at panel edges 6" o.c. interior if panel is ≥3/8" or studs < 24" o.c. then 12" o.c. interior	See manufacturer	N/A	6" o.c. at panel edges 12" o.c. else
Structural fiberboard	4" o.c. at panel edges 6" o.c. interior	3" o.c. at panel edges 6" o.c. else	N/A	3" o.c. at panel edges 6" o.c. else
Gypsum wallboard	6" o.c. at panel edges	7" o.c. at panel edges 10" o.c. else	Staples provisions given	7" o.c. at panel edges 7" o.c. else

Conclusions

As discussed in this paper, the design of wood framed shear walls to resist in plane wind and seismic forces resulting in lateral loads is variable depending on the code selected. The WFCM and IRC provide a more simplified version, particularly tailored towards those who are not engineering professionals. Whereas the SDPWS along with the NDS are intended for those individuals who wish to use a more detailed approach and are the most robust but also the most complex. Here, we attempted to help peel back the complexity to provide a broader picture comparison for approaching the use of these documents.

An additional takeaway from this paper, and part of the funded research sponsored by the PHRC was to look at where the codes can be advanced. We can see in several of the Tables given that not all codes cover the same material or some lack certain types of systems. A potential list for where the authors feel the codes can be refined in successive editions to be more useful and easier to compare is provided.

- Ensure all codes cover the same material types for sheathings including updating the codes for new materials and finishes.
- Provide better/more clear requirements on fasteners types and a wider spread of applicable types for wind vs seismic, particularly adhesives.
- Better and more refined procedures / limitations on engineered and prescriptive proprietary systems.

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A haptic, high-performance house: The GRoW Home

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Abstract
This paper discusses the design, construction, and operation of a high-performance passive / active solar residential project which fundamentally engages ecology through daily and annual thermo-climatic patterns of sun and climate. Designed for the 2015 Solar Decathlon competition, the GRoW home endeavors to give solar energy tactile and haptic form, expanding upon the intangible electrical energy generated on the rooftop with photovoltaic panels. This house aims to bring residential occupants into an experiential and ritualized engagement with the biotic and abiotic elements of the solar-based ecology in which they participate. The house's architecture gives the user agency in the stewardship of these energetic flows to simultaneously create a dynamic and captivating set of spaces and a less fossil fuel-intense means of living. This paper reviews the core design concepts which influenced decisions of passive heating and natural ventilation, envelope construction, HVAC system selection and configuration, interior layout and detailing, and performative furniture design. It provides an overview of the analysis processes of lighting and energy simulation throughout design to provide quantitative feedback to the design in the development of performance. Last, it reviews the measured performance of the house during its competition period in Irvine, CA.

Introduction
Nearly every two years since 2002 the US Department of Energy (DOE) has issued a challenge for the design, construction and operation of exceptionally high-performance single-family housing. This call culminates in an exhibition of projects which show not only the latest in energy technology, but also a set of forward-thinking formal, spatial, and material ideas. The DOE's Solar Decathlon is on its surface an intercollegiate competition, but is with each subsequent iteration an increasingly sophisticated design exposition.

As a competition, the Solar Decathlon is exceptionally detailed and complex. As its name suggests, teams compete with one another in ten events. Of these, five (Comfort Zone, Appliances, Home Life, Commuting, and Energy Balance) are objective and evaluated with monitoring or through simple task completion (DOE, 2015). These contests ensure that the house is run as a typical occupied house would be, and energy loads from such things as space conditioning, dishwashing, laundry, cooking, refrigeration, home electronics use and electric car use are all applied to the house's energy systems. The other five (Architecture, Engineering, Market Appeal, Communications, and Affordability) are assessed with juries of professionals and academics who review the projects against specifically articulated criteria.

As an exhibition, the Solar Decathlon presents an opportunity to showcase architectural design innovation. The projects regularly take on formal, spatial or conceptual constructs which shape their eventual morphology as much as the need to capture solar energy or the need to operate at high efficiency. To cite a few examples, the DALE project in 2013, by Southern California Institute of Architecture and California Institute of Technology used two movable, prefabricated modules to differentially create an internal outdoor space living space, which tripled inhabitable square footage (Sci-Arc/Caltech, 2013). The DesertSol project, also exhibited in 2013, by the University of Nevada Las Vegas, is designed for the Nevada desert, addresses water concerns as well as solar needs, by capturing the occasional rainwater and using it for cooling through a cool tower (UNLV, 2013). The WaterShed project in 2011 by the University of Maryland, was inspired by the Chesapeake Bay ecosystem, and addresses not only energy but also water issues through onsite design strategies such as green roof and constructed wetland (U Md, 2011).

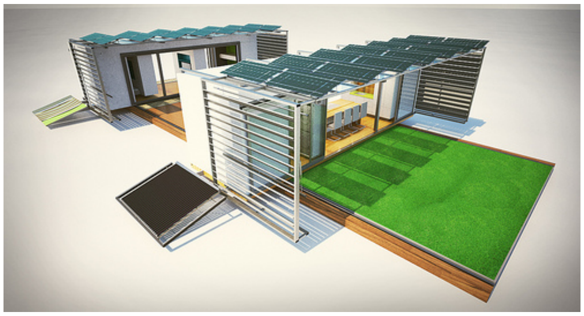


Figure 1: Sci-Arc/Caltech's Dale, competitor in the 2013 Solar Decathlon

Figure 2: UNLV's DesertSol, 2nd place finisher in the 2013 Solar Decathlon

Figure 3: U of MD's WaterShed house, 1st place finisher in the 2011 Solar Decathlon

The GRoW home, discussed in this paper, was positioned to address both the tight energy constraints of the competition as well as the broad design opportunities presented by this challenge. The project was undertaken with a hybrid structure of both curricular and co-curricular activities. The initial ideas were generated in a seminar course, and then developed through summer internships, and six subsequent semester-length design studios and three auxiliary seminar courses.

Theoretical design basis

The GRoW design team has drawn from the thinking of several architects and theoreticians. Reyner Banham recognized in *The Architecture of the Well-Tempered Environment* that advanced space conditioning systems led to a decoupling of architecture from the responsivity to climate (Banham, 1969). The GRoW Home reasserts the duty of the architect to inflect spatial design based on the climate resources available in a particular place. From Phillippe Rahm's conceptual work, such as

Figure 4: Lacaton & Vassal's Latapie House, which features an elegantly detailed polycarbonate enclosure outside the main conditioned volume.

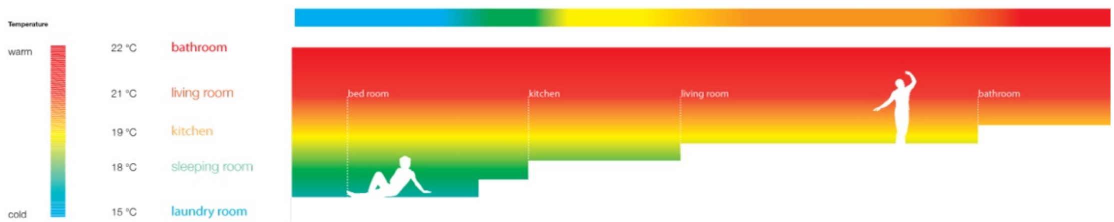


Figure 5: Section from Phillippe Rahm's "Convective Apartments" showing functions related to sepcific thermal conditions.

"Convective Apartments" and "School, Neuveville , Switzerland" we draw the ideas that spaces can be programmed based on their thermal characteristics, so that diversity, rather than homogeneity is to be celebrated (Rahm, 2010 and Rahm, 2007). From the current work of Lacaton & Vassal, such as the Latapie House, we observe that flexible, indeterminately

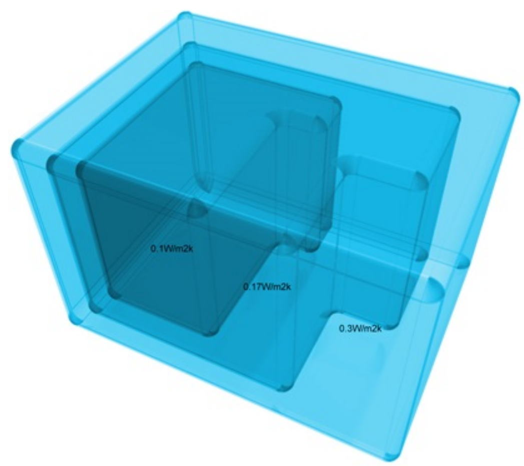


Figure 6: Diagram showing thermally nested spaces in Phillippe Rahm's "School, Neuveville, Switzerland"

Figure 7: Typical production greenhouse from the western NY / Southern Ontario region. Photo courtesy of Ontario Greenhouse Vegetable Growers.

programed spaces can be beautiful and inspiring, yet made from the most straightforward of materials (Lacaton & Vassal, 1993). Last, the shape of such vernacular forms as production greenhouses can yield interesting possibilities for residential work.

Core Design Concepts

Four key concepts have informed the GRoW Home design decisions from overall organization to system selection to material detailing. These four are the DNA of the project; the implementation of each will be discussed further in subsequent pages.

1. **Recognize energy hierarchy:** Consider passive design first, conserve energy next, and contribute power last.
2. **Live with nature:** Evoke the qualities of the outdoors with plants, light, air, material, color, and connections.
3. **Think functional flexibility:** Design for a longer life with a looser fit.
4. **Nurture active stewardship**: Empower the occupant to steward resources by engaging with energy and material use.

1. Recognize energy hierarchy: *Consider first, conserve next, and contribute last.*

Consider: To design a truly ultra-efficient home, it is critical first to reduce the energy loads the homeowner (or society) incurs. For the GRoW Home, this means a small conditioned area (770sf) enclosed with a superinsulated, tight envelope of structurally insulated panels (SIPs) with twice the code-required R-value. Windows are triple paned, argon-gas filled, and low-e coated, and located to distribute reflected sunlight off adjacent walls. Ample daylight is always provided from at least two sides in each room, and this design was verified with daylight simulation, as discussed later in this paper. Dedicated ventilators sized for the cooling load on a Buffalo summer day are located high on the lee-ward sides of the house to exhaust by cross and stack ventilation air brought in through the GRoWlarium. The separation of window and ventilator allows the wall to optimize light, view, and air flow. Passive solar gain through south-facing folding glass doors is retained in the dark tile floors, which are protected from summer sun by rolling shades on the GRoWlarium walls and roof. The house itself is sheltered with shades integrated into the overhead canopy, further reducing cooling loads.

The embodied energy of materials is reduced by using locally manufactured SIPs, regionally harvested wood finishes, and locally fabricated metals. Energy from fossil-fuel-intensive food systems is reduced by growing nearly all of the produce required for the two house occupants in the home and surrounding landscape.

Conserve: Some energy is required to run a home, but the GRoW Home has carefully selected equipment and appliances to minimize this use. LED lighting is used throughout, selected for a high color rendering index and low color temperature to be pleasant and complement incoming daylight. The exterior lights are generally dark sky compliant, so that energy is used to provide light only where desired. The appliances are best-in-class performers, including an induction stove and heat-pump clothes dryer. The mechanical system serves four zones independently, so heating and cooling is only delivered where needed, and is provided with a high performance heat pump and air handler. Fresh air is supplied with an energy recovery ventilator.

Contribute: The energy that the house does consume is more than offset through production of electricity and hot water from the sun.

2. **Live with nature:** *Evoke the qualities of the outdoors with plants, light, air, material, color, and connections.*

The GRoW Home uniquely puts the occupants into regular contact with nature and the outdoors in various ways. The interior spaces are directly connected to the outside through doors opening into the expansive all-glass GRoWlarium, which flows seamlessly onto the covered deck and out to the landscape beyond. The outside conditions are readily perceived within the home, whether through the play of light and shadow from the overhead structure or the sight of snow drifting overhead while sipping a hot beverage in winter. Nature is brought directly into the home through rolling GRoW tables, which nurture seedlings through winter, and larger plants when warmer. These share the flexible living space of the GRoWlarium. Plantings in the deck and landscape further biophilia. Wood interior finishes and cladding, and a nature-inspired color palette throughout recall the tones of the outdoors.

Figure 8: Photograph showing the play of shadow on the exterior deck. Image courtesy of Carl Burdick.

Figure 9: Photograph showing the indoor-outdoor living space dubbed the "GRoWlarium". Image courtesy of Carl Burdick.

3. **Think flexible functionality:** *Design for a longer life with a looser fit.*

While designed for a life enriched by rituals of tending home and garden, the GRoW Home is designed to be flexible beyond the extents of the current programming. The main spaces are designed to open up easily to one another, creating overlaps which can be appropriated to serve new or changing programs. The materials are designed for functionality, but with wide bounds on the function they serve. The dark tile on the floor of the "wet" module allows the floor to absorb winter sun, but also allows GRoW tables to readily roll in when plants are ready for processing, and can be easily mopped afterward. The tiled walls and glossy laminate cabinet fronts allow messes to be easily cleaned. The wood flooring and walls of the "dry" module are warm to the eye and touch, and suggest a more relaxed program.

The canopy provides a flexible infrastructure for a range of functions. It holds photovoltaic and solar thermal systems, shading devices, and lighting. It also readily supports various planters, outdoor movie screens, tool storage, hanging outdoor furniture and any number of uses the occupants might put to it.

Custom-designed furniture pieces each serve several purposes. The entertainment center can either divide or open the bedroom and living space, and holds a TV which swivels to face either room. The kitchen table easily rolls from inside to outside, and has a rotating top with a wood surface for eating, and a stainless steel top for food processing. The outdoor benches can be stood up and opened to reveal a glazed box for sun drying vegetables before putting them in storage.

Figure 10: Photograph showing entertainment center, which can rotate 180˚ to serve living room or bedroom beyond. Image courtesy of Carl Burdick.

The LED track lighting can be adjusted and controlled zonally to suit preferences and use, and can easily be updated over time with new or different fixture heads.

4. **Nurture active stewardship:** *Empower the occupant to steward resources by engaging with energy and material use.*

The GRoW Home owners engage with the architecture and environment by managing the house like a captain would a sailboat, riding the waves of solar, wind, and thermal forces. To use another metaphor, the house is tended like a garden, where the industry of the activity is the source of joy. This home suggests a new set of domestic tasks related to climate and environment, similar in some ways to the installing stormwindows each fall, or spring cleaning. In the GRoW home, the owners put up the canopy shades in spring, and takes them down each fall; on a daily cycle they rolls the shades in the GRoWlarium up or down to suit. The owner removes ventilator insulation plugs when the spring gets warm, and replaces them when the fall gets cold; to modulate temperature on a daily basis, they open or close ventilator doors. The GRoWlarium has two large double doors to open the south façade of the house to fresh breezes, and roof and clerestory vents can be opened to exhaust heat.

A web-enabled monitoring system tracks electrical consumption and production, as well as climate conditions. The occupant views this information from a handheld device or computer, giving her further agency over the house's resource usage. The GRoW occupant is a "smart user", making savvy, informed energy consumption decisions. In other homes these might be left to "smart systems", which generate high performance while insulating the user from knowledge about the impact of decisions.

Compositional design

The GRoW Home is composed of four elements:

Deck: The raised ground plane of the deck establishes the home's extents. The deck is subdivided on a 12'-8" grid, and zoned from south to north in program-organizing bands of circulation, vegetation, habitation, and utility.

Canopy**:** The elevated plane of the canopy further defines the extents of the project, while keeping view and access open on all sides. Columns are located on the 12'8" module.
Modules**:** The "wet" and "dry" modules are inserted within columns between the deck and canopy, yet pull back slightly from the grid to read as distinct elements.
GRoWlarium**:** The glassy GRoWlarium nestles between the modules, crystalizing the spatial overlaps between the two. The spatial sequence from outside, to under canopy, to within GRoWlarium, to inside modules makes a fluid transition from outdoors to indoors. When it is very warm or very cold, this sequence is heightened by a shift in thermal experience as one moves from distinctly outside to distinctly inside.

Figure 11: Floor plan showing major compositional elements of GRoW home

Figure 12: Photograph of GRoW home as exhibited at Solar Decathlon 2015. Photo courtesy of Carl Burdick.

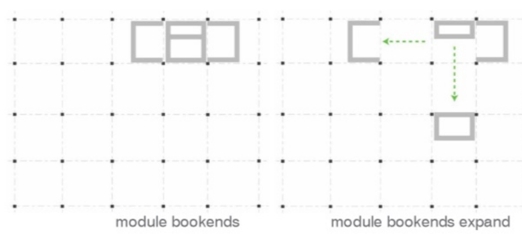


Figure 13: Diagram showing interior design "bookends" of GRoW Home.

The interior of the modules is composed of two pairs of programs bookending more indeterminate space. The "wet" module bookends of kitchen and bathroom are articulated with paired concave forms delineated with glossy white cabinetry and white tile. The "dry" module bookends of mechanical room and bedroom are articulated with paired masses of birch plywood. In between these bookends usage is less strictly defined ("work area" and "relaxation area"), where both space and program overlap between the modules and the GRoWlarium. These areas have great permeability to the outdoors: folding glass doors along one side, and ventilators along the other.

Integration of analysis into design

The GRoW home design incorporated analysis techniques at various points in the design process to inform and reinforce the decision-making. The first energy simulations were performed in the second of six terms of design studio, and therefore used a fairly preliminary three dimensional model of the house design. At this point, there were three primary questions: First, does the addition of an attached passive greenhouse space impose an energy penalty on the enclosed and conditioned portion of the home? This was broached by creating a paired set of models: a baseline house model without a greenhouse, and a design model with a greenhouse. Simulations were run in both the cloud-based Revit Energy Analysis and eQuest. These early simulations showed that, due to the added shading incorporated in the greenhouse and its role as a buffer zone, both winter and summer conditioning loads were reduced.

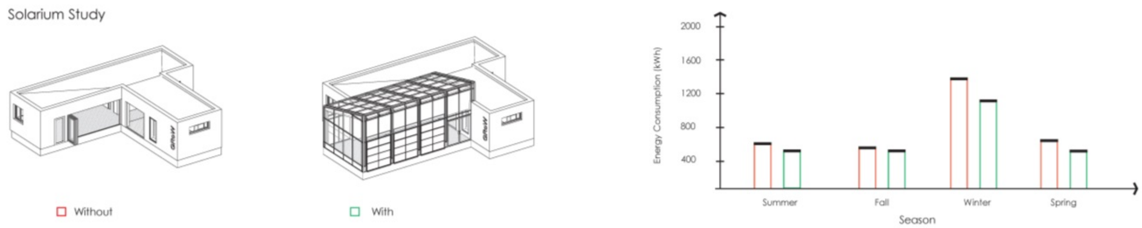


Figure 14: Results of early design-phase energy simulation runs to study attached greenhouse.

Second, where did increased thermal resistance in wall, roof, floors, and glazing begin to see diminishing returns? The design model was put to a series of sensitivity tests to determine the "sweet spot" for insulation R-value and window U-value. The results for the opaque portions of the assembly evidenced a discernable inflection point around R-40, whereas the glazing U-value assessment was inconclusive.

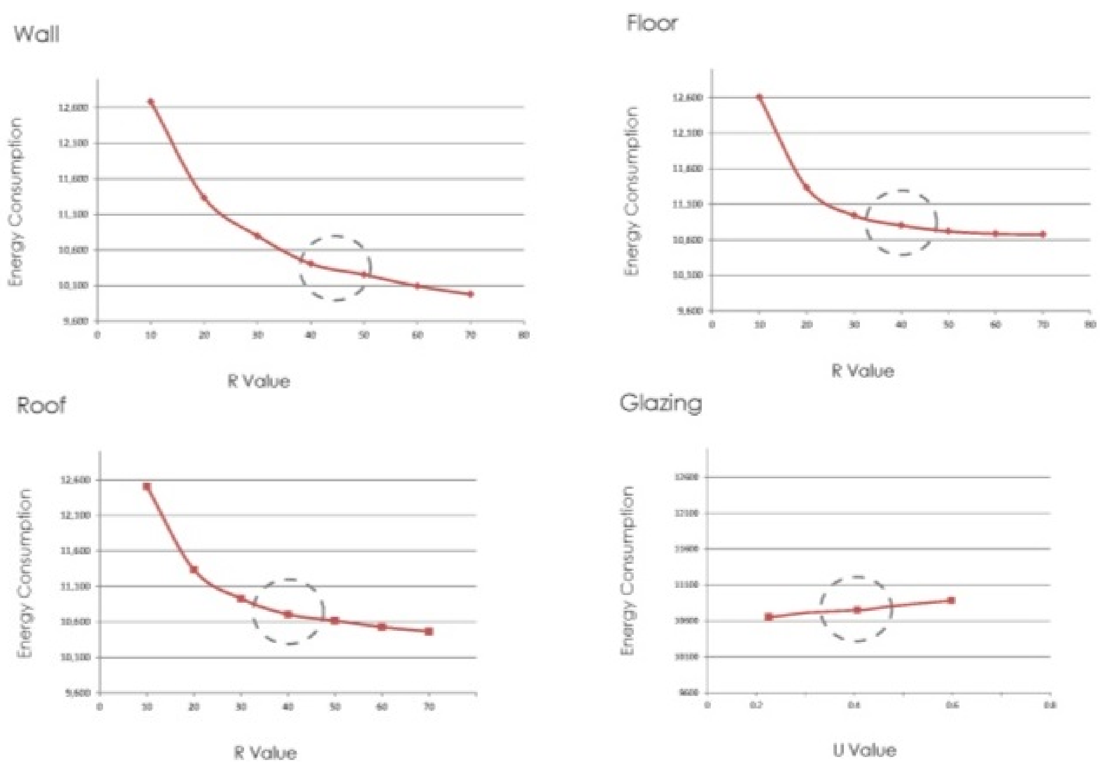


Figure 15: Results of early design-phase energy simulation runs to study optimal opaque and transparent wall resistances

Third, what was the overall annual energy production possible from the proposed size and configuration of photovoltaics in the design? A simulation using PV watts demonstrated the conditions that would provide sufficient electricity production for the predicted energy consumption during the competition period.

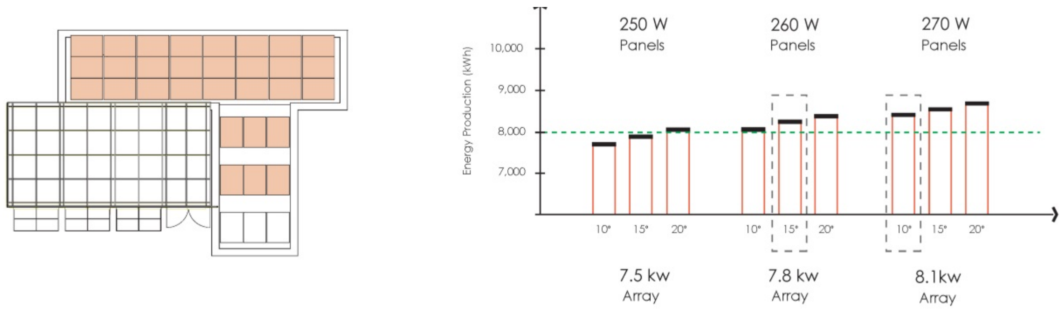
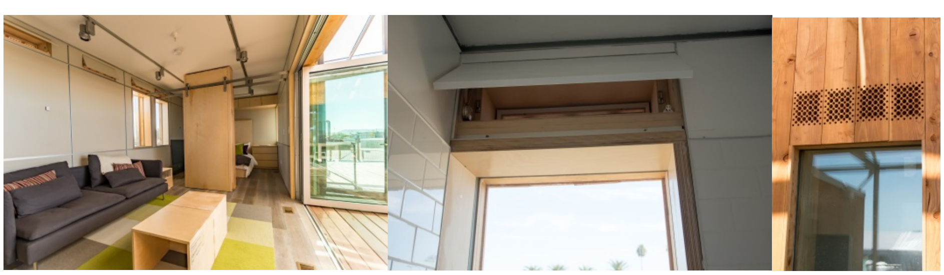


Figure 16: Results of early design-phase PVWatts studies of photovoltaic output.

In the next phase of the project, after dabbling in a somewhat time-consuming and inconclusive EnergyPlus model, a series of spreadsheet based calculations were performed to determine heating and cooling loads, using the Air Conditioning Contractors of America Association (ACCA) Manuals D and J, and the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 62.2. This allowed for the sizing of the air-to-air heat pump selected for heating and cooling.

Alongside the system selection and sizing for the mechanical system, analysis to size the passive systems of natural ventilation were also undertaken. Using the overall cooling load determined by the hand calculations described above and the average summer wind speed for Buffalo, NY, the overall size of ventilation apertures required was determined using the procedure articulated in the *Green Studio Handbook* (Kwok, Grondzik, 2007). The required area was provided on both windward and leeward sides of the building, and distributed through a series of discrete ventilators. This was a unique detail which, in contrast to a normative operable window, separated the ventilation requirements for the space from the daylighting and view requirements. The ventilators were either independent rough openings, or were constructed as part of the window rough opening in the SIP wall and subsequently framed individually. Perforations in the exterior rainscreen and an inboard insect screen, plus an interior operable aperture door provided a control mechanism for ventilation at the diurnal scale. A removable, gasketed plug of insulation allowed for ventilators to be closed on the annual scale, returning the opening in the wall to the same high-performance level as other areas of the opaque wall assembly.



Figures 17-19: Photographs showing the integration of ventilators with interior finishes, a close-up of one ventilator showing interior operable door, a close-up of one ventilator showing exterior perforations.

Given that the requirements for ventilation and lighting were disaggregated, the window placements could be driven purely by needs for daylighting and view. As an initial set of design constraints to achieve better distribution of daylighting, windows were ideally to be provided on at least two sides of each room, located immediately adjacent to a perpendicular wall. Through this strategy light would always be bounced off multiple surfaces, improving distribution and reducing high contrast. A series of studies using Radiance through Ecotect were performed to assess daylighting quality and quantity in the space, and aperture size and number were adjusted until suitable distribution was seen in the space.

Measured Performance

The GRoW Home was exhibited at the 2015 Solar Decathlon from October 8 to October 18. As part of the requirements of the competition, the house had to perform a wide range of tasks at designated times, each of which was designed to put an energy load on the house which was representative of the loads put on a “normally” occupied home. First, the house was required to be kept within a “comfort zone” of temperature and relative humidity. Second, certain appliances had to be operated within normal ranges (refrigerator, freezer, washer, dryer, dishwasher, cooktop). Third, lighting and home electronics were required to be on; the team had to draw a fixed amount and temperature of hot water (simulating a shower) and had to host dinner parties and a movie night. Last, the team had to drive an electric car 200 miles, and end the week with it fully charged. The teams were scored in each of five measured contests based on these four requirements, and a fifth which required them to do it while using a total of 175kWh or less while remaining energy positive (producing more energy than consuming).

In these five contests, the GRoW home performed admirably. The four zone heat pump system delivered adequate cooling when required (albeit with a 2+ hour throttling period on the hottest days), and the superinsulated walls and high-performance windows kept the house at temperature with minimal added energy. This earned the house the top prize in the “Comfort Zone” contest. Excepting the nightly temperature swings in the freezer due to an auto-defrost which could not be manually deactivated, the top-of-the-line appliances performed reliably throughout, earning the team second place in the “Appliances” contest. A botched first hot-water draw marred an otherwise nearly flawless performance in the “Home Life” contest, earning the team fourth place. As with most teams, the electric car performed as expected, earning the team an 11-way tie for first place.

Most notably, however, among this performance, is that the GRoW home performed all required tasks in the 10-day period while only consuming 161 kWh. This was the lowest consumption of any team which performed all of the required tasks, and the only team to stay within the 175kWh threshold performing the tasks. (Mass/Central America did not perform many of the driving tasks, and did not always have functioning appliances and HVAC system. Texas/Germany also had problems with their HVAC system operations.)

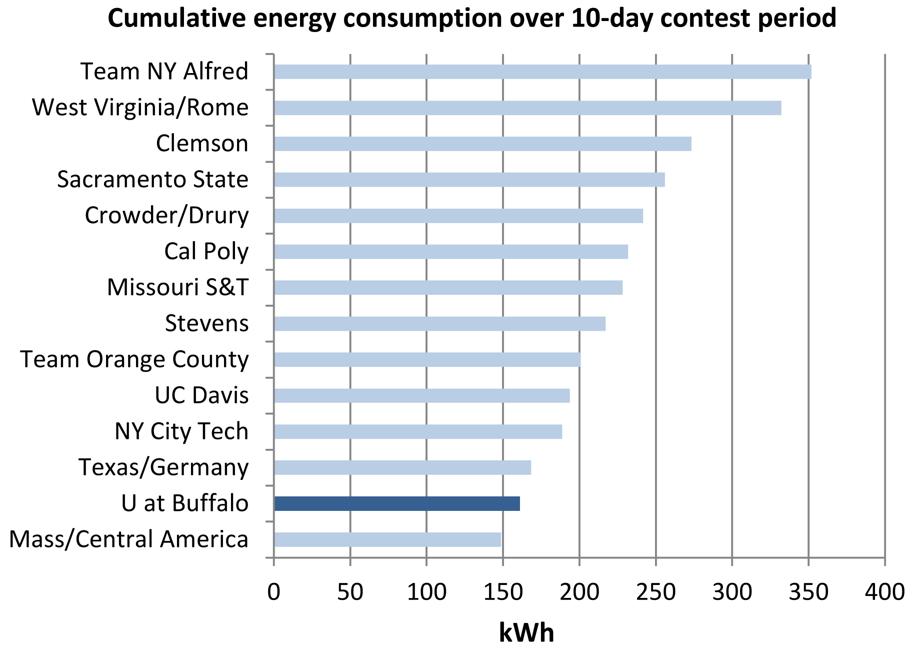


Figure 20: Chart showing each competing project's cumulative energy consumption, in kWh, over the contest period.

Along with eight of the thirteen other competitors, the GRoW home finished the contest period with a net positive energy balance. The GRoW home had the third highest energy balance, at 79kWh net positive. Arguably the PV system was designed with a larger than necessary safety factor.

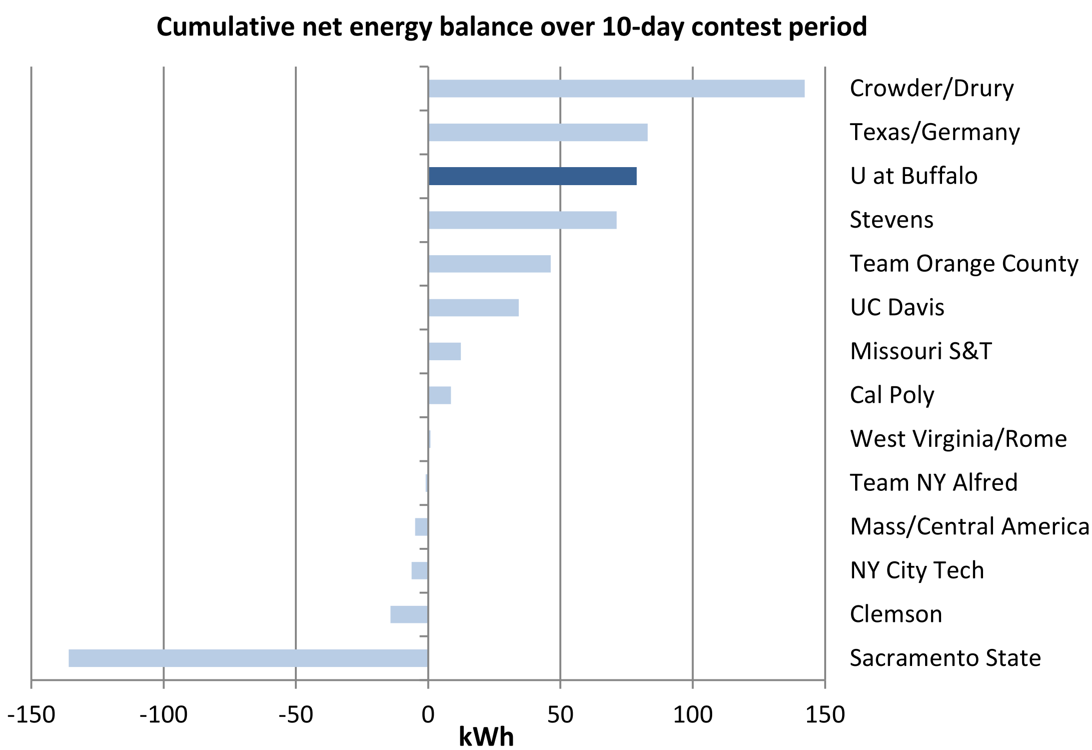


Figure 21: Chart showing each competing project's cumulative energy balance, in kWh, over the contest period.

Conclusions

The GRoW home project set out rather ambitiously to provide a unique occupant experience of solar design. Based upon feedback from and engagement with roughly 12,000 visitors during the 10-day exhibition period, it can be said that the public responded well to the sequence of spaces leading into the home, and were drawn to the core GRoWlarium space.

The public also responded well to the suggestion of new energy-based rituals of the home, from the annual installation / removal of the ventilator plugs, to the daily adjustment of shading devices, to the seasonal moving of the GRoW tables, visitors were intrigued by these elements which allowed them to take unique actions in the operation of the home. The GRoW tables were particularly popular, and many visitors remarked that they would make food cultivation so easy that they might take on gardening; several others observed how the tables accommodate gardening for children or those with limited physical ability to bend and kneel.

While we anticipate that this increased agency will engender greater stewardship of resources, this is ultimately a hypothesis, which will need to be tested over a longer period of time with a consistent occupant. The competition setting does provide a vehicle for rigorous testing of house performance, but it cannot truly test the kinds of longer-term behaviors which would emerge from interaction with an innovative residential design.

The home will be set up semi-permanently on the campus of the University at Buffalo; after an initial exhibition as a home, the building will be converted into a multipurpose space for seminars, professional education classes, and faculty research. Beyond the obvious questions about long-term performance and energy-related user behavioral choices, there has also been faculty interest in studying occupant behavior relative to food production, obesity, and food choices.

The GRoW home was proven through the Solar Decathlon contests to achieve high energy performance as a house, resulting in its second place overall finish. Also, through its conception and implementation within many constraints, it also presents an innovative and unique piece of architectural design.

Acknowledgements

The work of the GRoW home was carried out through nearly 3 years of effort by over 200 students from 14 departments across the University at Buffalo. While too many to name here, their many contributions are noted and honored.

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The Performance of a Net Zero Home in the Solar Decathlon 2011 and Beyond

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ABSTRACT

The Solar Decathlon is a biennial Department of Energy (DOE) collegiate contest wherein twenty universities are selected to design, build, and showcase residential structures that would ultimately be relocated to a competition campus to be viewed by the general public and judged by representatives of the DOE. The project structures are homes that are designed and built to conform to the parameters set forth by the DOE in an effort to showcase the use of solar power as a practical means of residential line voltage power supply. The projects are then judged according to how well they performed within those parameters.

The challenges involved in the design, construction, and operation of a "net-zero" house, that is a house that produces at least as much electricity as it consumes, were formidable. Equally formidable were the technical/logistical issues inherent in designing and constructing a building that could be disassembled and transported. Multidiscipline work groups analyzed the architectural, structural, mechanical, electrical, plumbing, building controls, and photovoltaic performance requirements. These systems not only had to be integrated within each other, but they also had to work within a tight construction budget and build schedule. Those requirements are challenging enough on a normal construction project. Added to the complexity is that the home was be built on the university campus and then shipped to the competition site, and then shipped back to its permanent location.

This paper highlights the process and strategies that a team utilized to design, build, operate, move, and successfully compete in the Solar Decathlon with a net zero home. It also presents the energy usage data that has been collected since it was rebuilt on a permanent location for January 2014 to July 2015.

INTRODUCTION

Architectural, engineering and construction projects typically have a very linear process. The design phase of a project starts with the proposal, and then moves to the preliminary design phase. After prelims are complete and the owner signs off, the engineering and construction drawings are completed. These drawings are sent out for bid, where contractors estimate cost and develop a construction schedule. The owner negotiates with the contractor over the cost and a budget is agreed upon.

Contracts are signed, permits are applied for, and construction is started. The construction process starts with the foundation, then the walls, then the roof. The steps through to building completion follow a step by step linear process. In the typical construction education curriculum, students learn a piece of the construction process while working on a set of construction plans. They take an estimating class and work on a set of donated project plans. They also take a scheduling class where they work on a different set of plans. The students experience a piece of the AEC process while working on these small parts of a whole project, but they never experience the process in the normal project path. In fact, they rarely get to experience the full construction process on a single project in their college career. However, those students who choose to be involved in extracurricular team projects often find themselves gaining greater experience. The Solar Decathlon project allows students to experience the entire AEC project path from start to finish.

The Solar Decathlon is a biennial Department of Energy (DOE) sponsored collegiate contest to “promote and speed to market” solar powered, residential homes (Grose, 2009). It is a student competition wherein twenty universities are selected to design, build, and showcase residential structures that would ultimately be relocated to a competition campus in West Potomac Park in Washington D.C. During the competition, homes are viewed by the general public and judged by representatives of industry professionals from the fields of Architecture, Engineering, Real Estate and Development. The challenge is to “design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive” (DOE). Each team’s home is designed and built to conform to the parameters set forth by the DOE in an effort to showcase the use of solar power as a practical means of residential line voltage power supply. The projects are then judged according to how well they performed within those parameters.

The challenges involved in the design and construction of a “net- zero” house, that is a house that produces at least as much electricity as it consumes over the course of a year, were formidable. Equally formidable were the technical and logistical issues inherent in designing and constructing a building that could be disassembled and transported. Finally, reconstructing a residential dwelling, complete in all respects in the allotted time period of seven days created educational opportunities that mirror conditions a construction manager will face in his or her professional life.

Purdue University was one of twenty teams selected to compete in the 2011 Solar Decathlon. The INhome, short for Indiana home, was not only Purdue University’s first entry in the decathlon, but also the first home to represent the State of Indiana in the competition’s history. The project fielded by Team Purdue ultimately placed second in the competition.

The resolution was however only a small part of what was accomplished. All who were involved in the project came away with a new depth and a new found level of maturity within their specific fields of endeavor. While the classroom provides an educational framework for the process of construction management, student competitions like the Solar Decathlon, gives context to what is learned in the more traditional venue of the classroom. This study investigates those educational opportunities and explores how those opportunities form an essential component of the process of construction management education.

Over the two years working on the Solar Decathlon project, the students have the opportunity to work on a residential project with commercial caliber design submission requirements. To manage the workload, track the process, and keep students working, a class was created each semester for this project. The earned credits were tied to meeting the DOE deliverable due that coincided with that semester. There were over 200 students from multiple disciplines that worked on this project including: Mechanical Engineering Technology, Building Construction Management, Interior Design, Computer Graphics Technology, Civil Engineering, Mechanical Engineering, Visual Arts and Design, Hotel Tourism Management, Industrial Engineering, and Health & Safety.

The project started with a group of students visiting the Solar Decathlon 2009 to catch the vision. The next step was the proposal writing and submission process. Once the team was notified that the proposal was accepted, work groups were created to start the preliminary design process. Each group created multiple preliminary designs and then they were reviewed by the entire team. Through this process, the team was able to use the collaborative design-review approach to refine down to a single floor plan design. The class then worked in different work groups broken up by area of focus; interior & exterior finishes, structural engineering, MEP design, estimating and costing. The preliminary design was then refined, reviewed, and construction drawings were created. The groups created shop drawings, material lists, estimates, and construction schedules. This construction packet was submitted to the "owners", the Department of Energy, for review and comment. At the end of the design process, the students had created a 100 page construction document set, a Building Information Model (BIM), a 500 page project and specifications manual, and a 400 page safety manual.

Once the project was approved by the DOE, permits were pulled and the house was constructed by the students on a site located on Purdue University's campus. The students self-performed much of the home construction and worked alongside industry professionals to build and commission the home in preparation for the competition in DC. While the student construction team was working on the home, other student teams were creating the website, brochures, speaking points, tour presentations, dinner party menus and logistical plans. Once the home was completed on campus, the teams tested every system, practiced every competition, and hosted multiple open houses for the public before packing the home up for the competition. The team also spent two weeks practicing taking the house apart and putting it back together, a monumental feat unto itself. The house was taken apart for a second time and the entire project was shipped to Washington D.C. Student managers worked with teams of students to rebuild the home in seven days. Then they competed in five juried and five measured contests while hosting open houses and dinner parties for 10 days. After the commencement of the competition, the home was disassembled and cleared off the site in a mere five days. With this intense two year timeline, many of the students spent the majority of their college careers working on this project.

RESIDENTIAL ENERGY USAGE

Residential energy consumption remains the largest untapped opportunity to reduce the dependence on fossil fuels. While the public and private community continue to invest in new energy sources, today wind costs are still ranging from $0.08/kWh - $0.20/kWh and solar projects upwards of $0.24/kWh for large scale productions (US DOE, 2014). By simply retrofitting residential properties, an energy company can produce savings through conservation and individualized energy production at a cost of $0.03/kWh (Friedrich, 2009). Research in the area of specific residential applications is scarce, but with the opportunities recognized by the DOE, NREL, Berkeley labs, and research universities across the globe, new advancements are being published every day. Current related research is found in the commercial sector but has often been misused in a residential application (Yudelson, 2008). Commercial properties and occupancy habits remain fairly consistent with building practices having been standardized for years. This makes calculating energy usage and savings in the commercial sector much easier and more accurate. When dealing with a residential application, many homes built in the same period and style are often done using various framing and design techniques. Couple these building differences with the specific unique homeowner habits, and it becomes difficult to accurately use commercial science on a residential retrofit (Augenbroe, 1998; McGraw-Hill, 2008; Bowen, 2005). Seeking an opportunity to understand and reduce consumption, the scientific community has developed a number of tools and technologies in an attempt to accurately analyze energy usage. The solar-decathlon projects, specifically the Inhome allowed for the opportunity to not only predict energy consumption, but monitor the data monthly in a traditional home-owner setting.

In 2014, 41% of total U.S. energy consumption was consumed in residential and commercial buildings (Figure 1) (EIA, 2014). While the commercial sector seemed to effortlessly convert to using “green” building practices, the residential sector has been stagnant with specific pockets or communities gaining momentum only to lose it due to economic slowdown or lack of government funding (McGraw-Hill 2009; EIA, 2008). With government funded residential properties accounting for less than 1% of the entire building portfolio (NAHB, 2010), it has had little to no influence on the building practices. When trying to influence and change century old building practices, accessing and educating the commercial sector becomes a much more obtainable and effective task. Educating and training a residential sector in which 95% of the firms employ less than 10 people has often been linked to the lack of green momentum in the home building industry (McGraw-Hill, 2006). Finally, the budget allocation for energy use has not been taken into account until recent years. A commercial building can incur yearly utility bills in the tens of thousands of dollars. When commercial investors are looking at a useful life expectancy in the building for over 50 years, the investment to save 15-20% of those utility costs makes energy efficient practices such as solar financially viable. These budget opportunities quickly become constraints in the residential sector. With the average stay in a home being less than seven years (NAHB, 2010) and utility costs reaching only a few thousand dollars per year, the budget and salability of advanced energy efficient practices become difficult.

Imagine the impact if all American residences were to transition into net-zero environments. The country would drastically reduce consumption, thus resulting in major reductions of greenhouse gas emissions. Nevertheless, this scenario is utopic. "In the United States, cheap and readily available energy obtained from the burning of fossil fuels has driven economic prosperity since the end of the 19th century." (NAS, NAE, & NRC, 2010) With fossil fuel based energy being accessible and affordable, marketing of the solar energy alternative must also show accessibility, affordability and increased environmental benefits in order to compete. The U.S. Department of Energy Solar Decathlon is one avenue striving to prove to the American public that solar energy in the residential sector is a viable and necessary option.

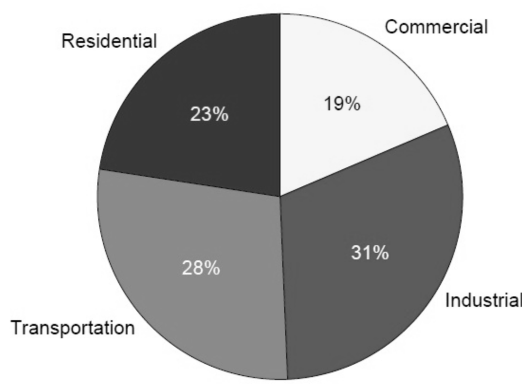

Figure 1: End-Use Sector Shares of Total Consumption *(U.S. Energy Information Administration Annual Energy Review, 2010)*

Solar Photovoltaic in Residential Applications

Understanding that the residential building community has constraints differing from those in the commercial sector does not allow researchers to ignore the rising energy consumption problem. In fact, it is the duty of the applied sciences to investigate the current limitations and identify potential solutions to the residential energy crisis. While wind and solar technologies are advancing, today kWh production from these sources range from $0.8 to $0.24 (US DOE, 2014). This does not include the infrastructure costs and grid updates needed to accept this energy source on large scale programs. With utility companies reaching infrastructure capacity during peak demand season, many are aggressively looking for ways to reduce demand. This opportunity for conservation has been seen as the solution with utility companies investing in conservation programs and incentives packages. Programs have allowed residents to invest in loans for HVAC upgrades, perform energy audits, and become more educated on habitual changes that can lower their energy consumption and ultimately their monthly costs. While these have been able to show an impact on a small scale, there has yet to be a model developed that shows a sustainable and large scale impact on the residential sector. The Solar Decathlon was an opportunity to highlight the influence of individual solar applications on residential properties.

Private investors, non-profits, utility, and government based programs have all attempted to infuse energy production models into the residential sector, some with more success than others. Private companies often struggle with payback projections and workforce training that makes their business unsustainable when any sort of government rebate or tax incentive runs out (McGraw-Hill, 2009). The non-profit based groups tend to focus on senior citizens or low-income families by making improvements to homes. These groups are most often mission based and narrow in focus. The utility based programs often attempt to work with the homeowners and financial loan programs. While some of these programs are effective, they are state specific, exclude solar, and still require a large financial commitment from the consumer. The long-standing government retrofit programs have exclusively targeted low-income housing, leaving 80% of the population unable to access these programs (Stern, 1986; U.S. Census, 2008). This “middle” class is the majority of homeowners that are considered too wealthy to qualify for government assistance but too poor to afford any substantial out-of-pocket upgrades.

Understanding that today’s housing stock stands at over 132 million homes (U.S. Census, 2014) and is currently replacing older homes at a pace of 700,000/year (NAHB, 2010), the development of a truly market-driven residential solar application model is not only possible, but necessary. The National Renewable Energy Laboratory has implemented a project called the “Open PV Project” that catalogues all solar photovoltaic installations in the United States. Updated on a daily basis the project has catalogued over 175,000 installations in the United States, showing a combined total installed capacity of over 2500 Mega-watts (MW). (NREL, 2012) Among these installations is Purdue University’s INhome. On an international stage in the Solar Decathlon, Purdue strove to show Americans the accessibility, affordability and practicality of solar electric installations in the residential sector in an attempt to inspire residential consumers to think of solar photovoltaic installations as a realistic option. By monitoring the energy usage after the competition, the researchers are able to add to the science of prediction monitoring and increased accuracy of residential energy consumption.

THE DESIGN OF THE INHOME

During the INhome’s conceptualization phase, Team Purdue analyzed challenges associated with solar home design for the Midwestern market and climate conditions. They looked at design strategies to maximize efficiency while minimizing costs, and prioritized the importance of creating an attractive and marketable home.

The philosophy behind the INhome’s design was to create an efficient, practical and affordable home that would appeal to the broad market of residential homebuyers. Often times consumers relate solar powered houses to modern architectural styles and high price tags. It was the team's viewpoint that in order to inspire a major shift in the way homeowners view solar installations, the team needed to create a marketable solar home that would fit into neighborhoods across the country. By utilizing rich natural resources local to the Midwest, all commercially available off-the-shelf components, user friendly controls, and open living spaces, the INhome shows consumers that they do not have to sacrifice modern comforts and amenities to live in a solar powered home. Solar homes can be comfortable, spacious, luxurious and look "normal".

Figure 2: Picture of the INhome in Washington D.C. (*The Purdue INhome Team, 2011*)

The variable Indiana climate posed a real challenge in designing a solar home for Midwest solar living. The Indiana State Climate Office describes the maximum and minimum temperature range in the State of Indiana between above 100 degrees Fahrenheit in the summer to below -30 degrees Fahrenheit in the winter. Also, average first and last freeze dates occur on October 16 and April 22. The systems and construction of the home has to be able to handle all climate extremes for the entire year. (Indiana State Climate Office)

According to the DOE, heating and cooling of the space uses the most energy, followed by heating of water, lighting, and appliance and refrigeration (see figure #3). Focusing on these areas to reduce energy consumption is the most effective strategy to use when designing a net zero home. These are the main areas that the Purdue team focused on when designing the INhome.

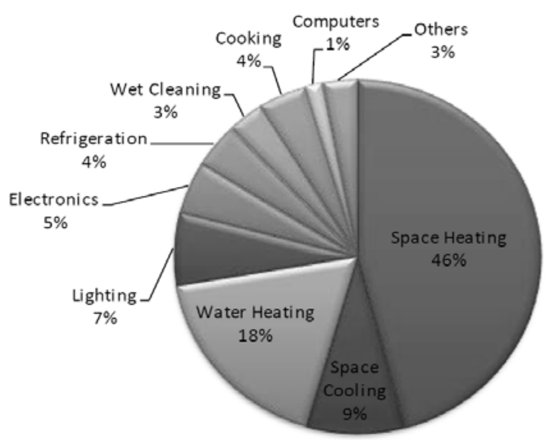

Figure 3: 2008 Residential Energy End-Use Splits. EERE Building Energy Data Book, (*U.S. D.O.E., 2011*)

Reducing the energy needs of the home is one of the crucial first steps in the design of a net zero home. (NAHB_Reserch_Center). This can be achieved through decreasing the physical space that needs to be heated or cooled. Smaller homes use less energy. Larger and or poorly designed homes use more energy or use it ineffectively. The INhome was only 984 square feet and its efficient use of space planning and multiple function travel planning within rooms allows for a very efficient floor plan. As you can see in Figure 4, there was only 20 square feet of actual hallway space.

The INhome was designed in three modules including the Public Core, Mechanical Core, and Private Core. The Public Core consisted of living and dining rooms, while the Private core included two bedrooms. The Mechanical Core housed all of the plumbing and mechanical equipment as well as the majority of electrical wiring including the bathroom with dual sinks, kitchen with bar and mechanical closet/laundry. Refer to Figure 4 for a rendered floor plan of the INhome.

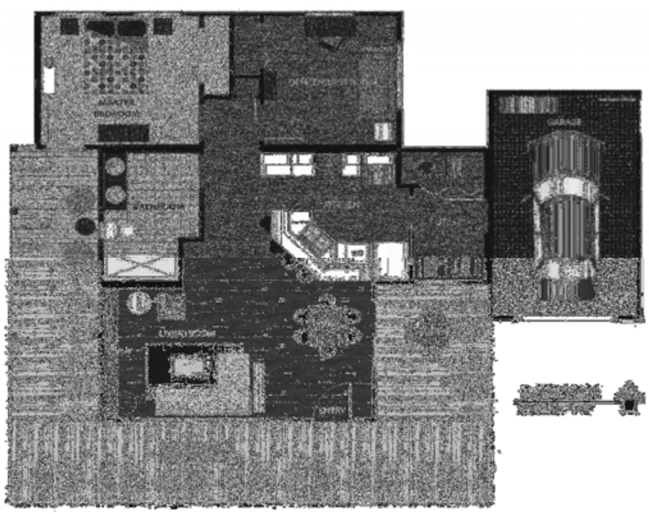

Figure 4: INhome Floor Pan – Not to Scale (*The INhome Team, 2011*)

Orientation on the lot is very important for a solar home. The INhome was located facing south. It utilized passive solar design principles with solar shading built into the east and west sides of the home. As the sun rose in the morning, the west side garage shaded the solar heat gain until the sun rose high enough in the sky to hit the solar panels of the roof. As the sun set at the end of the day, the west covered porch shaded the home from the evening solar heat gain.

Maximizing the energy efficiency of the thermal envelope through increasing insulation in the foundation, walls, and ceilings greatly reduce the energy needs of the home. (NAHB_Reserch_Center). For the competition in DC, the INhome sat on a raised open foundation system of pier pads. To create an insulated floor system, the underside of the floor joist were sheathed with 7/16 OSB and six inches of closed cell polyurethane insulation blown into the floor joist cavities. This not only provided an insulation value of R-36 in the floor, it also insulated the band joist of the entire home and sealed the entire floor system from air leakage.

The walls and roof of the INhome were constructed with a Structural Insulated Panel System (SIPS). "SIPs are engineered composite load-carrying panel products consisting of a ridged insulated foam core sandwiched between two structural facings" (Kermani, 2006). This removed typical structural stud framing in the construction of the walls. Studs not only reduce the insulation capacity of a wall, they also provide a thermal bridge and transfer energy outside the thermal envelope. The INhome's SIPs were constructed from two layers of 7/16 OSB sandwiched together with blown in closed cell polyurethane insulation. The four inch wall panel had R-24 insulation and the eight inch roof panel had R-50 insulation. The electrical boxes on exterior walls were molded into the panel and sealed completely around with blown in foam. Every panel joint, corner joint, floor to wall, and wall to roof panel joint had a double flexile foam gasket to seal the joints. This gave the INhome a very tight thermal envelope with very little air leakage. It had a 0.147 Air Exchanges per Hour (ACH) of infiltration at ambient pressure, and 0.217 ACH with the Energy Recovery Ventilator (ERV) in operation.

Using low U-Value, low-E windows and doors was also a very important part of an energy efficient thermal envelope (NAHB_Reserch_Center). The INhome's windows were triple paned low-E Argon gas filled windows with a 0.2 u-value (R-5). To take advantage of passive solar design, 73% of the INhome glazing was south facing, with only one window and door on the east side and none on the west side. The front overhangs of the home were designed to allow the sun to shine into the windows during the winter months, contributing to solar heat gain, but block the sun during the summer months. All the windows were operable, including the clerestory awning windows. This allowed the home to be passively cooled through the stack affect. As hot air existing in the home exited through the upper clerestory windows cooler air was drawn though the lower awning windows.

Among the equipment in the home were a high efficiency dual stage heat pump with an efficiency rating of SEER 19, and an air handler with variable frequency drives. Also, an energy recovery ventilator served to regulate the fresh air entering the home on an as needed basis. Need is determined by levels of carbon dioxide and volatile-organic-compounds (VOCs) in the air. A ducted dehumidifier was also placed in the home to pull moisture out of the air in an attempt to separate latent and sensible loads.

An innovative feature of the home was the Biowall. The biowall was a vertical living plant wall that housed heart-leafed philodendron. The biowall was unique because unlike a simple living wall, it was connected to the HVAC system in the home serving as a natural air purifier. As return air passed through the biowall and into a duct located on the opposite side, the philodendron removed carbon dioxide and other contaminants and used them as a food source. In a closed loop hydroponic system, the biowall was self-sufficient with light-emitting diode (LED) grow lights set on a schedule to compensate for days with minimal interior reflected daylight.

In addition to the biowall, smart home controls enabled the residents to be energy conscious about their consumption within the home, and production coming from the solar panels. This was made possible with the use of an energy monitoring system and a smart home control system. All circuits in the home were monitored via the internet as well as door locks, security cameras, light switches, and the thermostat, all the while recording usage and production trends for the user. The smart home control system was chosen for its simple user interface, wireless components, and internet access. Another aspect of the controls system was the fact that it was composed completely of off the shelf components.

To reduce the energy used to heat water, a 50 gallon heat pump water heater was installed in the INhome. The water heater absorbs the heat in the ambient air and transfers it to the water. As long as the ambient air was above 40 degrees, the water heater operated at 550 watts in heat pump mode. Below 40 degrees, it ran as a standard electric water heater at 4,500 watts. This unit was installed inside the conditioned thermal envelope of the INhome, located in the mechanical closet, where the ambient temperature should always be above 40 degrees. During the competition, it always ran in the heat pump mode and was able to produce 15 gallons of hot water (110°F/43.3°C) in 15minutes for the hot water draws.

Another way the INhome reduces energy consumption is through the lighting design. By allocating LED and compact fluorescent (CFL) lighting types in different spaces, the total interior and exterior lighting package in the home totaled no more than 600 Watts.

All appliances within the home were Energy Star rated. To coincide with the team's philosophy about solar living, the appliances were all full size including refrigerator, dishwasher, microwave/convection oven combination, induction cooktop and oven. Also a full scale washer and dryer were housed adjacent to the kitchen. These appliances minimized the INhome's power consumption needs, without sacrificing modern comfort or amenities.

The INhome's photovoltaic array was designed to achieve net zero energy consumption. Net zero is a term used to describe buildings which produce as much or more energy than the users consume over the course of a year. In order to adequately size the array, Team Purdue used energy modeling software to determine average annual energy consumption with an occupancy of three residents. Using current ASHRAE standards to set performance assumptions, the models showed estimated yearly energy consumption of the INhome at approximately 7,000 kilowatt-hours (kWh). Average daily sun exposure for the state of Indiana is four sunshine hours per day, thus calculations determined the INhome's array size at 8.64 kilowatts. This system consists of 36 240 Watt monochrystallic photovoltaic panels. The INhome's array was a grid-tied system with the local electric utility. A grid-tied system enables a withdrawal/deposit process similar to a bank account for electricity produced by the home. In summer months, or on days with extended sun exposure, the panels produce more energy than the occupants will consume; thus additional electricity produced is supplied back to the electricity grid. However, on days with minimal sunlight, the INhome is able to pull from the grid to compensate for electricity needs. This process works well for the INhome located in Indiana by ensuring homeowners of the security of access to electricity year round.

THE CONSTRUCTION OF THE INHOME

The INhome was designed as a real home to be built and lived in by a homeowner. Though it was built by students, the construction team was required to meet the same building code standards, inspections, and process that a professional builder deals with every business day. The drawings were reviewed and signed off on by the DOE. All homes had to be built to the 2009 International Residential Code (IRC) and also the regulation of the National Parks Service. All structural drawings had to be stamped by a local engineer. A local building permit was applied for and received. During the construction period, all the standard construction inspections required by the local Building Official were performed.

The students started construction by laying out the foundation systems. Since homes involved in the decathlon are designed to be moved and temporarily placed on the competition site, the INhome was built on temporary foundation systems. The foundation and floor systems were engineered to accommodate large public tours. Each of the core unit's floor systems was set in place. Plumbing supply and drain lines were run through the mechanical core floor system, and then the entire floor systems was insulated and sealed to form the bottom of the thermal envelope.

The wall and roof systems were built out of Structural Insulated Panel systems (SIPs). The panels were designed per the construction drawings of the home, with shop drawings and electrical details reviewed and signed off by the construction team. The walls were then manufactured in a factory under controlled conditions and shipped to the jobsite. Students worked alongside a professional set crew to set the wall panels over the course of a day, followed by the setting of the roof panels over the course of two days. At the end of day three, the structural walls and roof were in place, along with insulation, air and moisture barriers, exterior wall electrical boxes and conduit.

Once the structure was in place, interior partition walls were built, and the HVAC ductwork was installed. The next item completed was the plumbing rough in above the floor system, along with the sprinkler system. Finally the electrical and control systems were installed. All mechanical, electrical and plumbing (MEP) systems were built inside the thermal envelope of the home.

As mentioned above, the INhome was designed to be taken apart and moved. To get the home to the competition site, it was designed to be divided into six modules. The six modules comprised of each of the three core pieces, Public, Mechanical, and Private, as well as their corresponding roof sections, totaling six pieces. A double stud wall was constructed between each core called a marriage wall. This marriage wall enabled each core to be a standalone unit when separated. With a roof peak at almost 18 feet tall, the cores were also separated along the horizontal at the eight foot ceiling plate line to allow travel below bridges. The modules were held together by 1400 screws and bolts. Drywall was cut and exterior trim was removed at the line allowing for the easy removal of screws and bolts when the home was disassembled.

In addition to roof and base wall joints, every MEP system that passed through the marriage wall or base/roof connections were well planned out. The plumbing system was the simplest, with only one vent stack to disconnect and reconnect. The HVAC ductwork had four compression fittings that needed to be resealed after every move. The sprinkler systems had to be drained along with three compression joints that had to be disconnected. The electrical wiring was the most complicated system. The home was wired with commercial conduit and stranded wire to make the job of disconnecting and pulling new wires as simple as possible.

As the interior mechanical systems were being roughed in, the exterior shell was being made water proof. House wrap was installed over the exterior SIPs which protected the oriented strand board (OSB) from premature weathering, and it also gave another level of air penetration protection. The exterior windows and doors were installed per manufacturer recommendation and sealed with window and door flashing tape. The exterior module joints were covered over with exterior trim boards so they could be easily removed for the disassembly and reassembly of the home. Finally, the exterior fiber cement siding was installed.

The roof was covered with ice and water shield instead of roofing felt paper, as an added layer of protection due to the necessity for multiple shingle replacements during reassembly. Energy Star rated cool roof asphalt shingles were installed as the roof's finish material. The asphalt shingles were chosen because they were affordable and could easily be replaced when needed between moves. Also, an asphalt shingled roof is common in the Midwestern market, thus incorporating these shingles into the design further promotes the marketability of the INhome.

Once all the systems were roughed-in, a blower door and a duct blaster test were performed on the INhome. This gave the team a baseline of how much air was infiltrating the home. There was also a pre-drywall inspection performed by the local building official, to certify that the systems were indeed installed per the 2009 IRC. With much planning and anticipation, the INhome passed its rough-in inspection on the first round.

Once the dry wall finish was complete, then the interior was painted with low VOC paints. Engineered hardwood flooring was installed throughout, excluding for the bathroom and laundry/mechanical closet, where ceramic tile was laid. Cabinets, interior doors, baseboards and casing were installed followed by appliances and electrical fixtures. After all aspects of finishing were complete, final inspection was performed by the local building official and a conditional Certificate of Occupancy was issued. The reason the certificate was conditional was due to the home's temporary foundation.

From the issuance of the building permit to completion, it took the student team 4-1/2 months to construct the INhome. At this time, the team began practicing for the competition in Washington D.C. A final blower door test was performed. Every measured and juried contest was simulated by team members testing energy use. And once satisfied with the home's performance, the team took the home apart for a practice reassembly. During the construction phase of the competition, every team was given seven days to complete construction on the competition site. The INhome team wanted to make sure that the design and engineering of all the systems could be reassembled in seven days, and adequately perform as intended. It was an extremely stressful week of practice, but the team pulled it off. This practice run gave the student's knowledge of potential precautions and problems that would occur on the decathlon site. They went to the completion knowing that there would be problems, but that they had done this before.

Once the home was rebuilt, it was taken apart again two weeks later. This time the entire home, furnishings, tools, and accompanying student team shipped out to Washington D.C. The team successfully reconstructed the home on the competition site within the seven allotted days and began the competition.

THE PERFOMANCE OF THE INHOME AT SOLAR DECATHLON 2011

The INhome had been modeled and built to be a net zero home. During the 10 day competition in Washington DC, it performed as a net zero home. Every system of the house was utilized and tested during the competition days. There were 18,549 visitors through INhome, including Secretary of Energy, Sr. Steven Chu.

Each night, after the house had been open all day for public tours, the HVAC system was required to heat or cool the home to maintain a comfort zone within a temperature range of 71°F (22.2°C) and 76°F (24.4°C) and a relative humidity level less than 60%. The team hosted two dinner parties and a movie night simulating a lived in environment by consuming energy through the utilization of appliances and electronics Multiple times during the week, hot water draws were performed. Teams were required to deliver 15 gallons of hot water (110°F/43.3°C) in 15minutes. The purpose of these contests was to use the home as if it was occupied by homeowners.

The final contest was the energy balance. Each team's house was equipped with a bidirectional utility meter that enabled competition organizers to measure the net energy a house produced or consumed over the course of the competition. In the Energy Balance Contest, a team received full points for producing at least as much energy as its house needed, thus achieving a net energy consumption of zero during contest week. This was accomplished by balancing production and consumption. The INhome was one of just seven teams to achieve net zero energy consumption at the decathlon, proving that is was a net zero home under contest conditions. Overall, the

INhome placed 2nd in the Solar Decathlon 2011. A major contribution to this accomplishment was the performance of the home in the measured contests with placements including: 1st place tie in energy balance, 2nd place in comfort zone, and 3rd place in hot water production.

PERMANTLY LOCATING THE INHOME

At the completion of the solar decathlon, the INhome was once again disassembled by the team, packed up, and shipped by to Lafayette, IN. Upon arrival, it was placed on a permanent crawl space foundation, on a south facing lot, in a revitalized multi and single family community redeveloped neighborhood. Due to the covenants of the subdivision, the single car garage was removed, and an insulated storage/energy monitoring utility room was built in its place. A detached 2 car garage was added to the home site. The public, mechanical, and sleeping cores were rebuilt just as it was in the competition in DC, with all the energy monitoring systems in place and installed in the new utility room.

After the home was reinstalled on the permeant foundation and given a permanent address, third party rating and certifications were applied for and achieved. Without the PV array, it has a 58 Home Energy Rating System (HERS) and a -13 with the PV array. It was also certified Energy Star v2.5, certified Gold to the National Green Building Standard (Certificate # 4113), and LEED Platinum registered. It was also nationally recognized as the 2012 Project of the Year – Single Family Concept/Research (Academic) award winner as part of the National Green Building Awards competition, through the National Association of Home Builders (NAHB).

The INhome was sold to a real homeowner and there is a five year research covenant attached to the sale, where researchers can monitor via the internet monitoring system. The new owners moved into the home near the end of 2013. They are a professional couple, age 50 to 70 years old, with one working and one retired.

UTILITY DATA ANALYSIS

At the forefront of residential efficiency analysis is the ability to accurately calculate current energy consumption and thus potential energy savings. Unfortunately baseline characteristic-driven software is inaccurate on an individual level, especially with concerns to pre-1979 single family residences (Stein, 2000). The issue then becomes the ability to access actual consumption data from either the resident directly or, more conveniently, the utility provider. This “smart” grid approach has been implemented in various regions across the country, with continuous resistance from customers who are concerned with individual privacy laws (Cummings, 2010).

The U.S. Department of Energy has acknowledged that although the current electrical grid could be viewed as one of the greatest engineering achievements of the 20th century, it is increasingly out of date and overburdened (DOE, 2008). As technologies have advanced, the opportunity to utilize the current infrastructure by implementing "smart" systems has been seen as the most viable, economic solution. As a complete package, a Smart Grid would possess the following capabilities (DOE, 2008).

- **Intelligence** – capable of sensing system overloads and rerouting power to prevent or minimize a potential outage; of working autonomously when conditions require resolution faster than humans can respond and cooperatively in aligning the goals of utilities, consumers, and regulators
- **Efficiency** – capable of meeting increased consumer demand without adding infrastructure
- **Accommodating** – accepting energy from virtually any fuel source, including solar and wind, as easily and transparently as coal and natural gas; capable of integrating any and all better ideas and technologies – energy storage technologies, for example – as they are market-proven and ready to come online
- **Motivating** – enabling real-time communication between the consumer and utility so consumers can tailor their energy consumption based on individual preferences, like price and/or environmental concerns
- **Opportunistic** – creating new opportunities and markets by means of its ability to capitalize on plug-and-play innovation wherever and whenever appropriate
- **Quality-focused** – capable of delivering the power quality necessary – free of sags, spikes, disturbances and interruptions – to power our increasingly digital economy and the data centers, computers, and electronics necessary to make it run
- **Resilient** – increasingly resistant to attack and natural disasters as it becomes more decentralized and reinforced with Smart Grid security protocols
- **"Green"** – slowing the advance of global climate change and offering a genuine path toward significant environmental improvement.

With this new smart grid movement, utility regulators play an important role in insuring the information privacy rights of individual consumers. In 2000, the National Association of Regulatory Utility Commissioners' passed a resolution urging all state commissions to adopt general privacy principles. However, these adoptions of principles do not insure the consumer of the ever more prevalent information hackers across the globe (NARUC, 2011).

The INhome, as well as the other Solar Decathlon participants, highlights another opportunity to involve residents in utility data collection and analysis. By incorporating individual solar panels and educating the owner on a "zero-net" home, the analysis and complimentary positive results fall on that of the resident. They have a financial interest in monitoring their usage patterns and can now take a concerted effort to curtail habits that historically have been found to be poor energy habits. The results of the Solar Decathlon show an opportunity to avoid any prescriptive measure that must be adopted by the masses and simplifies energy use at the single home level or exact point of energy production.

To monitor the energy usage of the INhome, an e-monitoring circuit systems (by Nexia Home Intelligence) was installed, both for the competition and the permanent location. This allows the researcher to collect real time energy usage data from each individual circuit and the power systems of the INhome, without disrupting the homeowner's life and privacy. The homeowner can also monitor their personal usage on a daily, weekly, monthly, and yearly basis with an intelligent and efficient dashboard screen on any internet enabled device. The system dashboard reports the power being used and power production in real time, along with the top energy circuits and the 30 day Carbon Footprint of the home in comparison to the IN average (see figure 5 below).

Figure 5: INhome Energy Monitoring Dashboard

The system also reports out the energy usage for all the circuits, organized by the individual appliances, HVAC equipment, laundry and hot water usage, room lighting, and outlets. It give the homeowner recommendations to save even more electricity based on their typical usage. The system also shows them their saving history, total net metering usage, and lbs of CO2 saved. Figure 6 shows the total kWh produced by the INhome the past year (October 2014 to October 2015) was 10005, with 6,734 kWh exported to the grid. This produced a savings of $999 and 15,387 lbs of CO2.

kWh Produced	10005
Dollars Saved	$999
lbs CO2 Saved	15387
kWh Exported To Grid	6734
Dollars Exported To Grid	$673

Figure 6: INhome kWh Produced and CO2 Saved, October 2014 to October 2015

Over an 18 month period (1/26/2014 to 7/26/15), the INhome has operated as a net zero home, producing and saving more power than the owners need to live comfortably. Figure 7 shows the usage of the owners relative to the outdoor temperature and time of year for the stated time period. The largest power requirements occur in the winter months due to the air to air heat pump switching into electric heat backup mode when the outdoor sir temperature drops below 30 degrees. Figure 8 shows the INhome production relative to the outdoor air temp and time of year for the same time period. Production drops in the winter months due to the shorter daylight time and lower sun angle in the sky, but production peaks in the spring and summer due to the longer daylight per day and higher sun angle. Figure 9 shows the usage overlaid with production for the same time period. Though the INhome uses more power during the winter months, it over compensates in the spring and summer to have an overall less than net zero power usage every year.

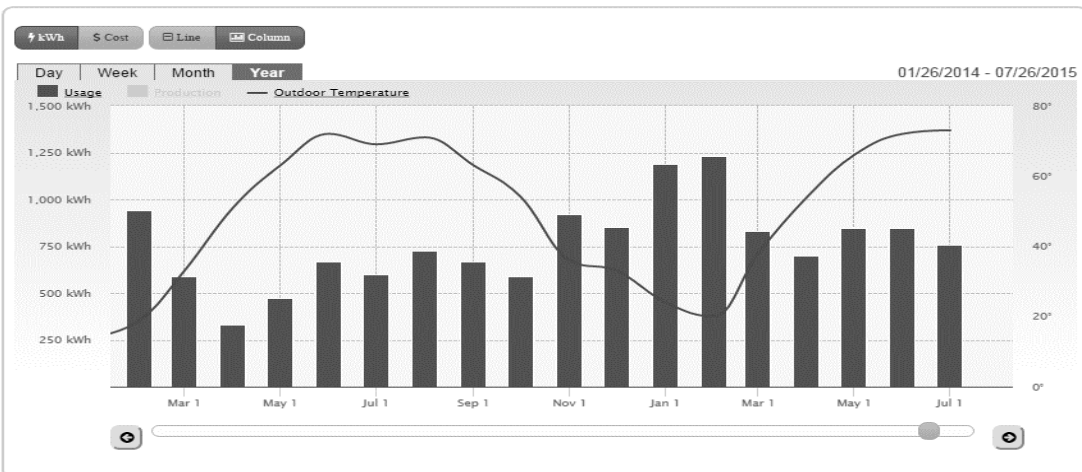

Figure 7: INhome Power Usage, January 26th, 2014 to July 26th, 2015

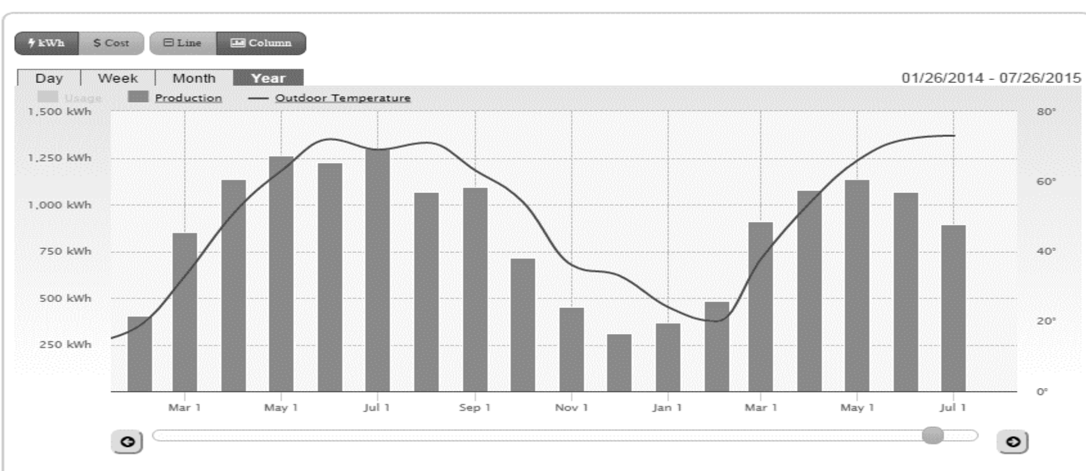

Figure 8: INhome Power Production, January 26th, 2014 to July 26th, 2015

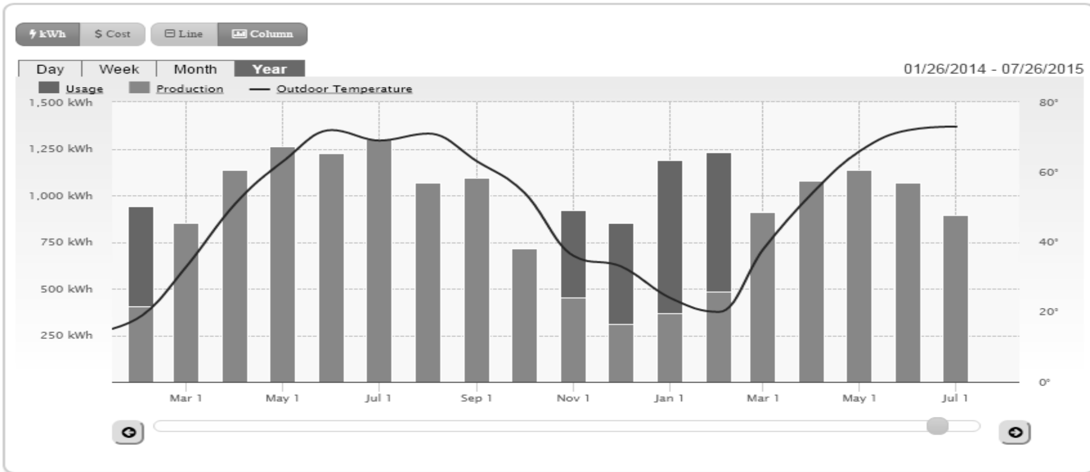

Figure 9: INhome Power Usage and Production, January 26th, 2014 to July 26th, 2015

CONCLUSIONS OF THE INHOME

The U.S. Department of Energy Solar Decathlon program creates a real-world learning environment for students that cannot be replicated in the classroom (Grose, 2009). The students and faculty involved were challenged beyond what they would have experienced in the classroom setting and what they learned could not be replicated in the traditional university learning environment. Although this learning experience was contained within the solar decathlon program, it is not limited to this program only. The process that the students went through and lessons learned can be generalized to other student teams and other experiential projects (Grose, 2009). It provides a practical application in a real world context. And collaborative and engaging learning opportunities are what students of the 21st century are wanting to be involved with (Rodgers, Runyon, Starrett, & Von Holzen, 2006).

The INhome was not only a successful learning experience, it was a successful competition home in the Solar Decathlon 2011, placing 2nd overall. This was due to the teams guiding principles of minimizing the energy loads of the home without sacrificing modern comforts, while maximizing the energy efficiency of those modern comforts, while keeping the cost within budget. It has also been a successful green certified home, through the third party certifications of Energy Start v2.5, National Green Building Standard Gold, (Certificate # 4113), and LEED Platinum registered. It was also nationally recognized as the 2012 Project of the Year – Single Family Concept/Research (Academic) award winner as part of the National Green Building Awards competition, through the National Association of Home Builders (NAHB).

The INhomes greatest success is its ongoing operation as a net zero home under normal living conditions. Every year it produces more energy than the owners need to live comfortable, giving back \$600 to \$700 worth of electricity to the grid, and saving 15,000+ lbs of CO_2 from the environment every year. This will continue year after year for the life of the home, long after the competition, awards, and research is over.

ACKNOWLEDGEMENT

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Opportunities and Constraints for Townhouse Developments Meeting DOE's Zero Energy Ready Home Standard

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ABSTRACT

This paper discusses opportunities and various constraints that arise when attempting to meet the Department of Energy's (DOE) Zero Energy Ready Home (ZERH) Standard for townhouse developments. Besides a broader analysis of economical limits of performance for different consumption categories, the paper discusses the specific constraints that arise for production homebuilders when trying to meet this design goal. This study builds on findings that emerged from a submission to DOE's Race to Zero Student Competition and expands the application to constraints and opportunities for other climate zones. The submitted design proposal and analysis yielded interesting findings that can be of high relevance for other production builders looking into ZERH, as it identified focus areas of performance that are different to single family detached homes. The paper also discusses the modeling challenges and limitations of the software tools that are currently utilized to demonstrate that ZERH requirements are met.

BACKGROUND

High-Performance Buildings and the Production Home Builder

The trend towards energy efficient, high-performance homes has attracted various businesses across the housing market in hopes to benefit from the economic and marketing power of energy savings. Thus, it is no surprise that production builders are also trying to enter the high-performance building market and try to improve the typical standard homes they offer by featuring more energy efficient technologies. However, production builders, who typically construct homes in large quantities of similarly sized and designed houses within a community in a short time frame, face considerable challenges when making this transition. High-performance buildings require additional planning and processes, which includes building science analyses (e.g. for thermal and hygrothermal performance), customized framing, enhanced air sealing techniques, and advanced HVAC installation methods, all of which can disrupt critical schedules and budget constraints for production builders. Such changes and associated challenges are in general less strenuous for a custom homebuilder, where their project timelines are not necessarily governed by automated systems of procurement, production, and installation.

With such a vast amount of processes to ensure remain efficient, production builders have communicated the need for extra guidance and support towards designing and constructing high-performance homes. In an effort to help production builders with the transition into the high-performance building market, Pacific Northwest National Laboratory (PNNL) worked with several production home builders to identify the challenges typically faced by them when constructing to high-performance standards (Widder et al. 2013). Some of the common challenges encountered include difficulties faced during planning, implementation, and certification. In regards to planning, the scheduling and communication requirements with subcontractors were the biggest obstacle. Confusion over the need for schedule adjustments to accommodate new training for advanced construction techniques and critical installation activities was often missing or overlooked. Implementation was discussed as requiring the need for more building science support to optimize the construction process. Additionally, certification was an issue the builders discussed as another obstacle, specifically in regards to deciphering the HERS "black box", which refers to the score and energy consumption assessment and modeling tool REM/Rate, which is used to obtain design specific performance metrics. The builders believe that having more information and understanding for the weight/impact of various design characteristics that are written into and hidden in the energy consumption algorithms within the software, could assist with reaching certification goals more easily.

The lack of accuracy of HERS scores as compared to actually obtained performance numbers was also an issue. Many homes constructed and certified by the builders performed better than the predicted score when compared to actual utility bills, which has led to a loss of reliability in using HERS as a marketing tool. This result is consistent with a recent investigation, where the energy consumption of a large sample of high-performance multi-family building units were evaluated using observed utility use data compared against HERS estimated utility consumption data for the same units (McCoy et al. 2015). The results of the investigation revealed a significant overestimation of the HERS scores compared to actual usage data, with additional insight presented in regards to the variables and building technologies that may be driving the HERS score predictions.

In a similar attempt, specifically to identify common challenges production builders encounter when designing and constructing to high-performance building standards, and the Department of Energy's Zero Energy Ready Home (ZERH) standard in particular, a roundtable discussion of production builder executives organized a forum to gather relevant input and observations (Rashkin 2014). Key obstacles identified included a lack of software that can effectively capture the influences of high-performance technology contributions, and similar dissatisfaction with the inaccuracies of modeling tools predicting energy consumption data as discussed previously.

It is clear that there is still a learning curve and various barriers that exist for production builders transitioning into high-performance building design and manufacturing processes. Research and support that can remove these obstacles could help production builders with a faster and smoother transition into the high-performance building market, and assist them in achieving their high-performance building design goals with more ease.

U.S. Department of Energy Race to Zero Student Design Competition

The Race to Zero (RTZ) competition is an annual event, in which students and faculty teams from universities and other institutions of higher education across the country, including several international participants, compete to design a zero energy ready home (ZERH). The competition requires teams to abide by the DOE ZERH standard in their designs while also incorporating additional innovations and strategies the team deems fit to create a high-performance home. Designs are either original ideas developed by the team, or are based upon real-world scenarios by redesigning existing house plans that are typically provided by an actual homebuilder.

The Virginia Tech student team "Invent the Future" participated in this event in 2015 and submitted redesigned construction documents and building science analyses for a townhome development currently under development by a production homebuilder. Many of the rather small proposed changes, which could relatively easily have been implemented by a local custom home builder, had much larger impacts on the whole production and supply chain that is an integral part of the company structure for a production home builder. This collaboration between enthusiastic students and a large-scale, conservative production builder created a challenging yet interesting experience for the design team, and brought attention to key details that may be of value for other inquisitive production builders, who are planning to extend their product lines into the high-performance building market.

Zero Energy Ready Homes. To achieve the DOE ZERH standard it requires a home to attain a HERS score of approximately 55 or lower, which represents an energy performance improvement of 40%-50% beyond typical code requirements (DOE 2015). There are mandatory requirements prescribed to meet the ZERH standard through prescriptive or performance paths, which are specific to the climate and size of the home being designed and constructed. The requirements established by the DOE (2014) include the following:

- Compliance with the ENERGY STAR Qualified Homes Version 3 checklist
- Compliance with EPA Indoor airPLUS
- Compliance with the Renewable Energy Ready Home checklist
- Enclosure fenestration meets or exceeds ENERGY STAR requirements
- Enclosure insulation meets or exceeds 2012 IECC levels
- Ducts are located within the enclosure thermal and air barrier boundaries
- HVAC systems meets or exceeds 2012 IECC levels
- Minimized infiltration rates

- Hot water system meets EPA WaterSense conservation and energy efficiency requirements
- Lighting and appliances are ENERGY STAR qualified

To ensure that the home can become net zero if a photovoltaic (PV) system is installed, designing the size and selecting the characteristics (e.g. tilt and efficiency) of the PV system to determine the potential energy output and monetary value must also be accomplished. In this case, the annual kWh output of the proposed PV system should equal or exceed the projected annual energy consumption of the occupied home, and subsequently achieve an adjusted HERS score of “0”, or below zero if surplus energy is being generated.

The Virginia Tech student design proposal was able to accomplish all of these goals to meet the ZERH requirements, all while successfully managing to address some important challenges faced with when collaborating with a production builder. The final design proposal submitted for the competition was named the TownHauZ.

The following sections provide a summary of the major project constraints that influenced the design, followed by the building science modeling challenges and analysis solutions conducted for the project, and discusses recommendations and opportunities towards designing net zero energy ready homes for production builders.

THE TOWNHAUZ PROJECT

A Net Zero Energy Ready Production Built Townhouse Development

For the RTZ Competition, the Virginia Tech student design team submitted a development proposal consisting of zero energy ready townhouses in Baltimore, Maryland. The partnership with a production builder allowed for the opportunity to engage with an actual townhouse development project in preparation, which provided typical initial design plans, and thus also provided the real-world context to apply advanced design objectives.

The project features a row of adjacent three-story units, each with approximately 1690 square feet of conditioned living area and 9 feet ceilings. Each unit has three bedrooms and two bathrooms on the third level, and an open living area and half bath on the second level. The first level is used for a one-car garage and a laundry room. This floor also provides ample space to convert the remaining unconditioned floor space into a recreational room at the homeowner’s discretion, with additional rear space for potential additions to the home. The design of the TownHauZ project focused on an ultra-efficient enclosure system, high-performance HVAC systems, energy efficient lighting and appliances, and high quality comfort and control that can rival many high-performance homes available today. A summary of technical specifications for the townhomes as compared to the original standard design is listed in Table 1.

Table 1. Data & Technical Specifications: Proposed vs. Standard Design

Specifications	TOWNHAUZ	Standard Design
Project Location	Dundalk, Baltimore, MD	
IECC Climate Zone	IECC Climate Zone 4 (Mixed-Humid)	
Conditioned Area (sq.ft.)	1690	1690
HERS Score	39	106
HERS Score with PV	- 4	N/A
Monthly Energy Cost	$84.33	$192.75*
Wall Insulation	R-40	R-15
Foundation Insulation	R-10	R-10
Roof Insulation	R-60	R-49
Window Performance	R-7.6	R-3.5
Heating/Cooling	1.5 ton 16 SEER Heat Pump w/ Electric Backup	90% AFUE gas 13 SEER AC
Ventilation	Ductless Heat Recovery Ventilation	-
Dehumidification	ENERGY STAR 70H Dehumidifier	-
Water Heater	2.9 EF Hybrid Water Heater and PEX Distribution	Electric Storage Tank

**Based on Energy Information Administration (EIA) data for a standard home in Maryland*

Project Constraints

The overall project goals of making the townhouse development net zero energy ready with high-performance enclosure and building systems, and high levels of thermal comfort, faced two dominating challenges that became paramount for a successful design integration. These challenges were 1) to ensure that these homes with their high-performance enclosure system were designed appropriately for the moisture-laden climate, and 2), to design homes that are suitable for a production builder process, specifically in regards to construction limitations and marketability.

Production Builder Challenges. Discussions held with the production builder provided additional design constraints that had to be considered. In summary, it was found that

- the design needed to align with the manufacturing process and its limitations in the plant, e.g., the maximum height that fits under the production line bridge;
- the design needed to withstand the transportation process and thus limit the materials selection;
- changes of required labor on site can have significant impact on other processes, e.g. a change in duration of one process can disrupt other objects built on the same site. Additionally, for the particular production builder associated with this project, 7-9 of the townhomes are typically constructed at the same time, each house with a total schedule of 87 days, which includes quality inspections and customer walkthroughs. A design that compromises this would not be practical for the proposed type of builder;

- material selection can have a significant impact on worker health, which is one of the most valuable assets of a larger company, and thus can have long lasting impacts on a worker's productivity;
- there is a specific buyer's market, which can be challenging if you offer high-performance features only for a subset of units in a larger development, a path we suggested to implement as a demonstration project.

Due to these constraints, drastic changes and ambitious solutions proposed by the design team to alter the building enclosure and mechanical systems in an effort to achieve more energy efficient standards underwent significant scrutiny.

Climate Appropriate Design. The townhouse development was located in Baltimore, Maryland, which is classified as Climate Zone 4 according to the International Energy Conservation Code (IECC). This climate zone is predominantly a mixed-humid climate, with fairly mild temperatures that are experienced year round. The average annual temperature in Baltimore Country is 60.2 degrees Fahrenheit, with the highest temperatures observed in July (low 80s), and the coldest temperatures in January (mid to low 20s). An average of 41" of rainfall hits the Greater Baltimore area annually. Snow also adds to the mix of wet, but cold weather with an average of 22.7" of snow during the snowfall season.

Controlling moisture was an important goal for this design in particular in order to maintain quality and comfort, but also efficiency in energy and durability for the various building elements exposed to the challenges of a humid climate. More specifically, the highly insulated enclosure system with a resulting reduction of the HVAC loads created a scenario where dehumidification needs become the dominating variable that needs to be monitored and controlled. Market availability of such solutions has shown to be the biggest challenge to identify practical solutions.

ANALYSIS FINDINGS

Modeling Methods

When analyzing the thermal and hygrothermal performance of the building enclosure, as well as the energy performance of the proposed townhomes, several modeling tools and evaluation methods were used to design an appropriate solution that abided by the proposed concept and goals. These tools and methods included THERM, WUFI, REM/Rate, and additional specific heat loss calculations. ASHRAE design temperatures were considered when sizing and designing the space conditioning and dehumidification systems, as well as an analysis of local heating and cooling needs using degree-days data.

THERM. Thermal bridges are caused by higher thermally conductive materials that "bridge" across the envelope. For example, studs are a simple form of a thermal bridge, spanning from gypsum on the inside to sheathing on the outside, and thus provide less resistance than the highly insulated cavities. Thermal bridging should be minimized as much as possible not only to reduce energy consumption but also to improve other thermal performance characteristics of enclosure assemblies, such as surface temperatures. To obtain more accurate input parameters for our energy analysis, the simulation tool THERM was used. THERM is a finite element method based heat transfer modeling tool developed by the Lawrence Berkeley National Laboratory (LBNL), and is used by many researchers and practitioners in the architecture, engineering, and construction domains to conduct heat-transfer analyses (LBNL 2015). THERM was used by the student design team to calculate more accurate U-Values of the enclosure assemblies, including additional assessment of losses through thermal bridges throughout various building component intersections.

WUFI. To investigate the hygrothermal performance of different wall assembly design alternatives under transient conditions, the software tool WUFI was used. WUFI can conduct dynamic heat and moisture transfer simulations for various wall material components exposed to different interior and exterior climate conditions (Fraunhofer IBP 2015). While the educational version only allows access to the standard ASHRAE material database, and limits simulation run-time scenarios to a maximum of two years, it provided enough insight into condensation risk tendencies for the local Baltimore climate.

REM/Rate. The energy modeling software tool REM/Rate is the standard tool defined by the DOE ZERH standard to obtain energy performance values, such as the HERS score, and it was thus used to calculate the score for the townhouse units with and without a photovoltaic system. The software additionally provided energy consumption estimates for the domains of heating, cooling, water heating, lighting and appliances. Developed by NORESCO LLC, REM/Rate was created specifically to meet the needs of HERS raters, and uses internal proprietary calculations to estimate the energy consumption of a building based upon the input of various housing characteristic variables such as R-values, climate, and domestic hot water and HVAC systems (NORESCO LLC 2015).

Additional Heat Loss Calculations. To further analyze the thermal performance of the enclosure system, different enclosure detail solutions in terms of their linear loss coefficients due to thermal bridging effects were assessed with detailed heat loss calculations. These analyses were again performed within THERM for validation. The results were also compared with REM/Rate energy performance results produced for the final design proposal in order to determine if thermal bridges are considered within the model, and if, to what degree.

Design Challenges and Modeling Limitations

Enclosure Thermal Performance. Various design alternatives of enclosure systems were evaluated in terms their thermal performance prior to selection of the final enclosure system design. Figure 1 depicts an example of a THERM simulation showing isotherms and flux vectors and the thermal bridging effect around studs of the original, cavity filled 2x4 stud wall prior to any design adjustments.

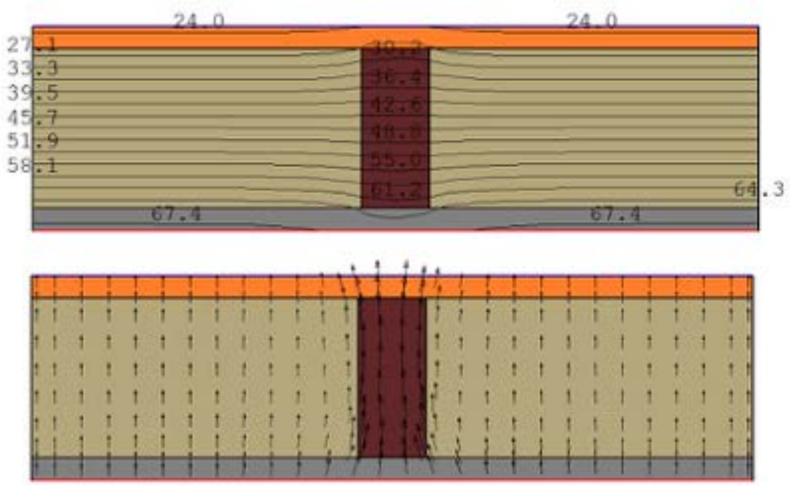


Figure 1. Isotherms and Flux Vectors of the original wall system

Initially, the design team began with the idea to improve the thermal performance of the original stud wall without the need to significantly change the construction process as currently carried out by the builder. The first step in this process was to increase the cavity by 2” and move to a 2x6 stud system, as it can be found in residential construction projects that are implementing advanced framing techniques. This concept of an increased thickness for the insulation cavity was then developed further to achieve even higher thermal performance. Eventually, a solution to break the thermal bridge of the studs was devised that not only improves the overall performance of the wall, but also achieves higher surface temperatures for thermal comfort.

Limited by a production height for wall panels in a manufacturing process, the preassembled panels could not be increased any further. However, since the builder already utilized blown in cellulose insulation in the roof assembly, the design team recommended using the same system for filling wall cavities. Utilizing this technology, the solution could be further improved by adding a 2” XPS insulation strip, e.g. ripped from larger boards, and attaching them directly to the studs.

The challenge of this solution was that XPS would not provide a good mounting material for the interior finishing system, which is typically a drywall installation. In lieu of any existing product, it was proposed to utilize the ZIP system panels that can be ripped into 1.5” or 2” wide strips and can be easily mounted to the studs, while at the same time providing a mounting base for the gypsum boards. Obviously, the additional layers on the exterior of the ZIP system, which is typically used for other control functions, are overkill for this application, and a simpler/cheaper product would be desirable. In any case, adding additional cellulose is relatively cheap as compared to adding exterior insulation, and thus this wall assembly could serve as a viable alternative for a builder, achieving a total average R-Value of 25. This solution is shown in Figure 2.

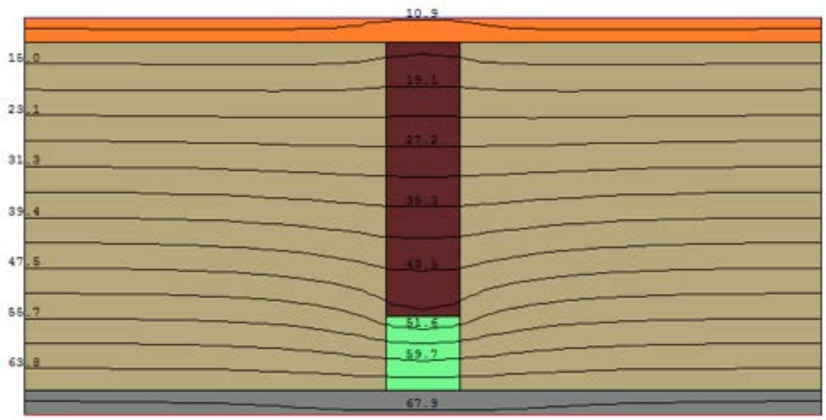


Figure 2. Alternative wall assembly achieving R-25

Considering the potential constraints that were voiced by the production builder, specifically those related to labor and construction processes with an unfamiliar product solution, the student design team looked into exterior insulation options. When adding exterior insulation, the previously proposed solution to increase the insulation cavity by adding XPS strips was determined to become less competitive for the builder since the added labor would not offset the same performance gain than just increasing the exterior insulation by the same thickness.

A cost versus performance gain analysis conducted by the team showed that exterior insulation levels beyond 3” bring no significant energy consumption savings for townhouse projects, which have on average a smaller enclosure/floor-area ratio than comparable single-family detached homes. However, for this project the team decided to use 4” of exterior XPS foam insulation to increase thermal comfort and to come closer to the typical performance of walls following the PassivHaus Standard.

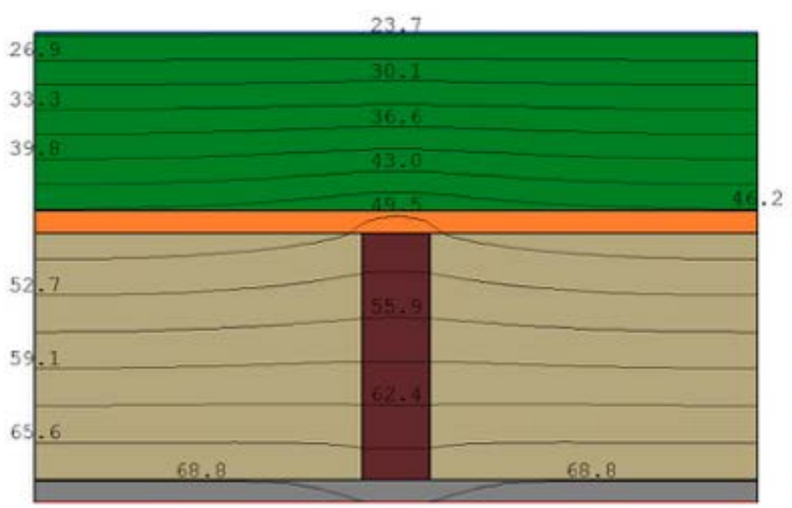


Figure 3. High performance wall system achieving R-40

The final proposed assembly is shown in Figure 3, and is composed of 1⁄2” gypsum board, a 2x6 stud system with 5 1/2” of blown-in cellulose in its cavities, 1⁄2” OSB as structural sheathing, 4” XPS exterior insulation, 3/8” strapping for a capillary break, and vinyl siding. This proposed wall system achieves R-40 and can thus significantly increase the interior surface temperatures during colder days.

Hygrothermal Performance of the Enclosure System. The wall assembly shown in Figure 3 comes close to the “perfect wall” as it is often referred to and published by the Building Science Corporation (Lstiburek 2008). For comparative reasons the project team analyzed different approaches of modelling and compliance as they can be found in different international hygrothermal standards and codes.

When checking the condensation risk of this assembly under steady-state conditions during winter months as required by German standards, interstitial condensation can be anticipated when the exterior temperature is below 20°F and interior relative humidity is above 35% as shown in Figure 4. This is significantly lower than the 50% required by German standards, and would trigger interstitial condensation at the OSB board. Now, it is still debatable if 35% interior humidity under cold weather conditions with more or less continuous heating is a reasonable long-term interior condition. However, if it is assumed that the proposed enclosure follows airtight building standards, and the home has a rather high occupancy rate (e.g. 4 BRs) compared to the total square area (actually volume), these relative humidity rates become more likely, which in turn increases the condensation risk.

Admittedly, the German DIN Standard applied in the analysis shown in Figure 4 is based on a very low-risk modeling approach that is applied as a blanket solution for the German climate. This method is applicable in moderate climates with no significant humidity levels in summer, which in turn allow for longer periods of evaporation of eventual accumulated condensation amounts during colder periods.

The correct assessment and remedy of any condensation risk is essential to achieving a viable and durable high-performance enclosure system for climate appropriate designs. Knowledge on how to assess this risk is a building science fundamental that can prove invaluable to a builder. Enhanced thermal performance and airtight construction is only half the battle in designing an ultra-efficient enclosure. Failing to acknowledge the potential for moisture to impede on the durability of the system could lead to costly and hazardous undesired results.

The proposed wall assembly was then investigated more closely under transient conditions with the software tool WUFI. Figures 5 – 6 first show the hygrothermal performance of the original regular 2x4 stud wall for the Baltimore climate to demonstrate the performance variability that can be captured through this tool.

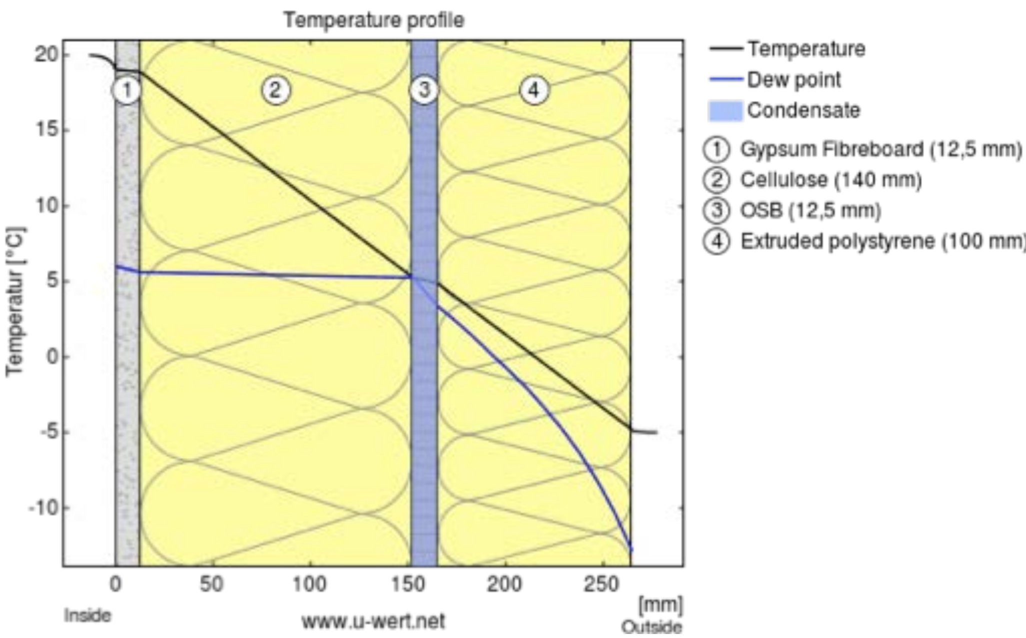
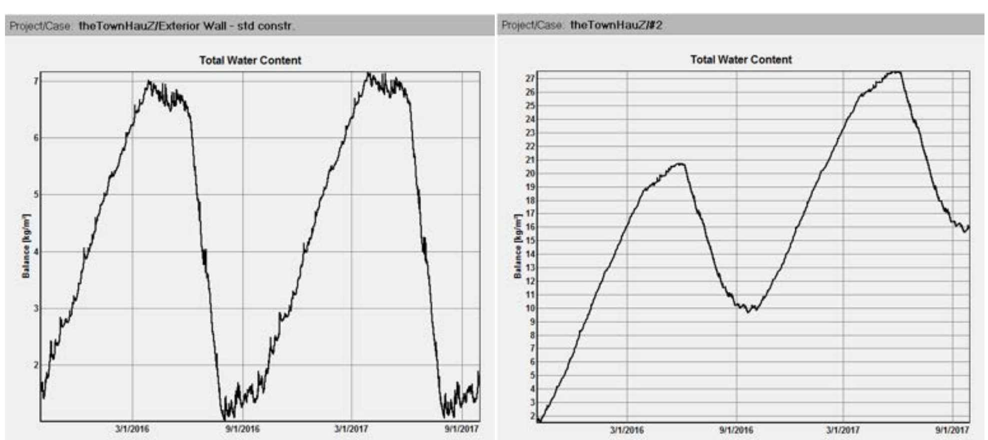
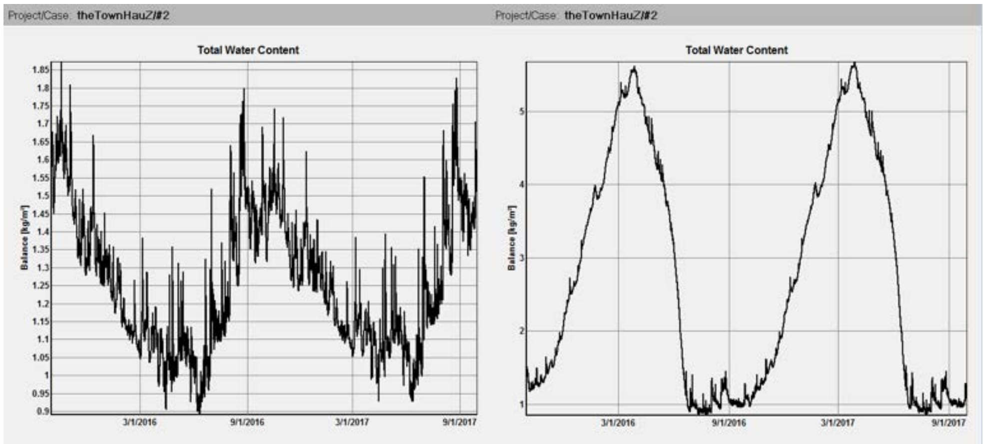


Figure 4. Hygrothermal performance under steady state conditions of 35% interior relative humidity in winter climate.

Figure 5 shows on the left that as long as the enclosure is built to regular standards (ACH~2.0), there will be enough drying potential during the summer, which theoretically would allow for any condensate accumulated during winter to evaporate through diffusion. However, relatively high total amounts of water content accumulate and are stored in the assembly, which can be a concern to some building materials. Once more airtight construction is implemented (ACH<1), this drying potential is gone (Figure 5 right). This issue can be resolved in two ways: a) through introduction a vapor retarder on the interior side to reduce the overall diffusion rate as shown in Figure 6 on the left, or b) control for humidity levels on the interiors side (i.e. actively dehumidify) to increase the evaporation potential again (Figure 6 right).

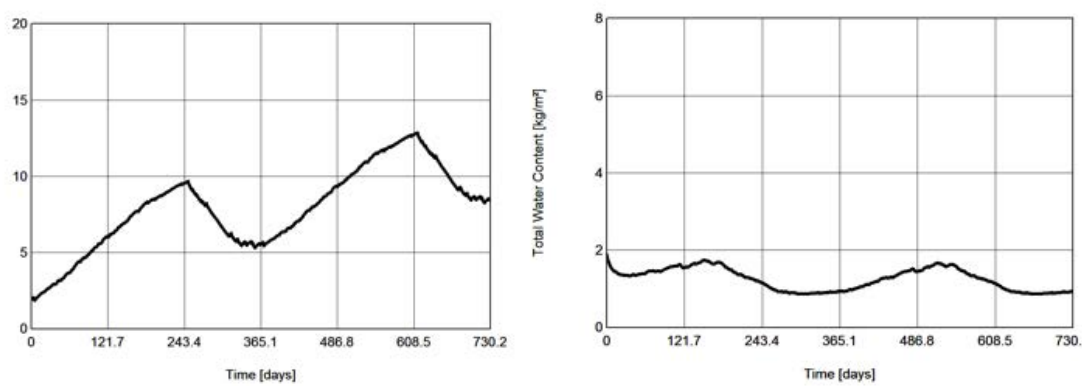


Figures 5. Left: Standard 2x4 wall assembly. Right: 2x4 wall assembly - airtight



**Figures 6. Left: 2x4 wall assembly, airtight, with additional vapor barrier on the interior
Right: 2x4 wall assembly, airtight, with controlled interior dehumidification**

A WUFI analysis assessing the condensation risk of the proposed R-40 wall would also face some condensation issues if airtight construction is assumed and interior humidity levels are not actively controlled and maintained (Figure 7 left). This scenario was then compared with a proposed active dehumidification system that could hold the interior humidity levels below 50% during the summer months. Figure 7 shows the simulated total water content in this wall assembly over two years on the right, and it appears to have enough drying potential under these conditions.



**Figures 7. Left: Exterior wall without vapor barrier and without interior humidity control
Right: Exterior wall without vapor barrier but with active interior humidity control**

The introduction of a vapor-retarding layer on the interior side of the wall assembly was subsequently investigated as an additional measure to evaluate its impact on the water content. Figure 8, shows on the left how the vapor control layer can successfully achieve the same as a system controlling for interior humidity, which still is an energy intensive process. One challenge with two vapor-retarding layers, such as the retarder on the interior side and the OSB board in the center, is to prevent larger amounts of moisture (e.g. rain during construction) being trapped between these layers. The biggest challenge for this solution is the correct installation of this layer and translating the importance of this function to construction practice without errors. This process may require additional training and coordination, which is often not necessarily feasible for established schedules and budgets set by a builder. With this in mind, an evaluation of the wall assembly including a vapor retarder while also actively controlling for interior humidity was performed. This strategy results in better hygrothermal performance and built-in redundancy, which reduces the risk of errors on either side, be it construction process or system failures (compare Figure 8 right).

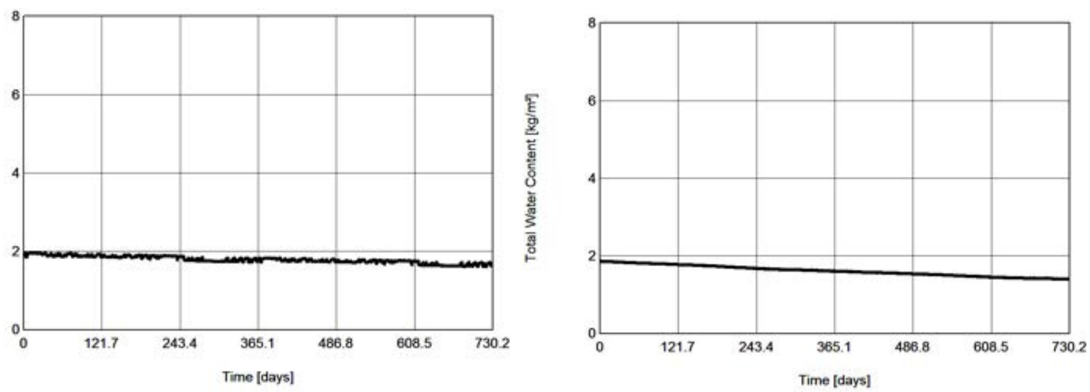


Figure 8. Left: Exterior wall with added vapor barrier but without interior humidity control
Right: Exterior wall with added vapor barrier and active interior humidity control

As shown in Figure 9, the ultimately proposed solution for the exterior wall system even meets the stringent German standards, which requires reduction of the condensation risk based on a constant interior relative humidity of 50% over 90 winter days.

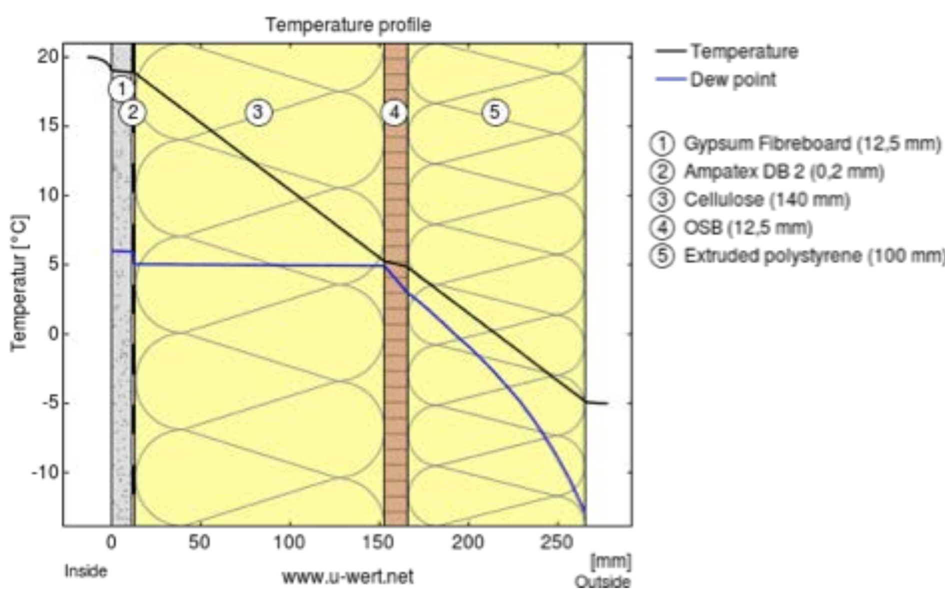


Figure 9. The TOWNHAUZ R-40 exterior wall system

Thermal Bridges and Window Integration. To analyze the thermal performance of the enclosure system further, different detail solutions were investigated in terms of their linear loss coefficients due to their thermal bridging effects. This analysis was carried out with spreadsheet based heat loss models and calculations. It was found that REM/Rate, which was used for our energy analysis, does not account for thermal bridges, even though thermal bridges can have a significant impact on energy performance in high performance enclosure systems.

After conducting an individual energy analysis of the original wall assembly with simulations for a single façade of one level, the difference between the analysis a) without considering thermal bridges (1,731 BTUh) and b) an alternative solution that considered the effects of double and triple studs below windows, in corners, and the window frame installation (1,818 BTUh) were compared. The difference between the two approaches came to 12.6% of the total losses for a typical façade segment. These analyses were again performed using THERM for verification.

Thermal bridges are specifically critical around window installation details. The project team thus evaluated different installation methods and processes to improve these thermal bridges. The original window is shown in in Figure 10, while the proposed window installation design shown in Figure 11 moved the window installation pane from the exterior close to the center axis of the enclosure system. The OSB provides a sufficient mounting basis, and allows for reaching 2” over the edge of the raw opening formed by the surrounding studs and headers. This additional space can now be filled with solid insulation while the remaining gap will be filled with spray foam. This option allows for a thermal bridge free construction, bringing the linear thermal loss coefficient around the perimeter of the window close to zero.

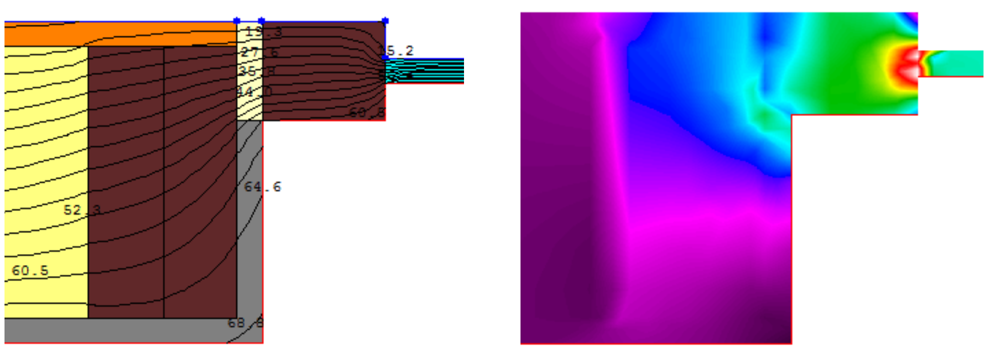


Figure 10. Original window detail

The analysis of the final wall assembly carried out in the spreadsheet model, which also includes windows that have a 40% better performance, showed that the total heat losses could be considerably reduced, namely from 1,818 BTUh down to 711.8 BTUh, which represents a 60% reduction.

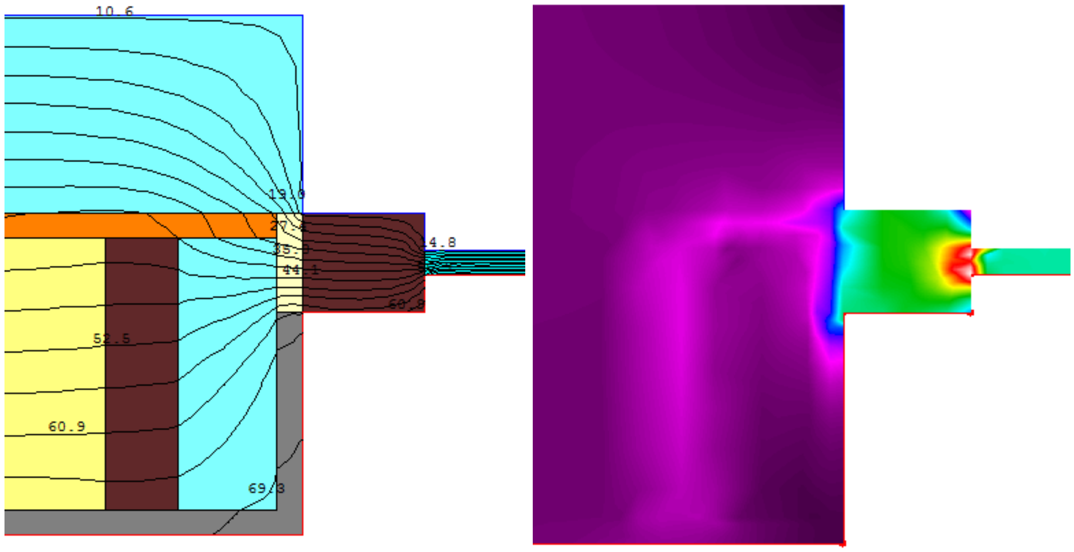


Figure 11. Thermal-bridge free window detail

Energy Analysis: To achieve the ultimate energy consumption reduction goals required to meet the ZERH standard, the design team first tried to cut down on energy loads in a way that was still feasible to the construction process of a production builder and cost efficient in material selection and systems operations. Initial strides were made through the enclosure design as discussed in the previous analysis section. This was done through a combined effort of reducing thermal transmission and infiltration, thermal bridge free details, enhancing insulation levels, and ensuring airtight construction.

However, specifically for townhouse developments, where enclosure to floor area ratios are rather low for mid units, the enclosure alone is not enough to meet the ZERH energy goals. Additional attention must be paid to the HVAC system, hot water heating system, lighting loads and appliance selections specified for the home in order to identify high-performance systems that meet the new load reduction requirements. Ultimately, the HERS score for this development could be drastically reduced and came in below the initial target score of 50.

For a project like this, a renewable source of energy is needed to achieve real net zero energy consumption. To supply the total remaining annual energy consumption balance here, 27,500 kBTU of energy must be produced annually on site. The site orientation and location in regard to the potential for harnessing adequate solar radiation play a significant role when determining the size of a photovoltaic (PV) system. Using the NREL PVWatts Calculator, the team could show that an array of 20 PV panels, each with an output of 320 Watts, resulting in a total array size of slightly larger than 6 kW can make the project net zero. Using this data in the energy models for the project generated a final HERS rating of -4.

Applicability in Across Different Climate Zones

The analysis and findings discussed in this paper are relevant for developments in the hot-humid climate zone found along the eastern coastal states of the U.S. While these are rather densely populated regions, where townhouse developments are quite common, the same results for developments in other climate zones are not immediately applicable. To elaborate, humidity levels during summer months (if not directly controlled through the HVAC system) and average exterior temperatures during winter months can have a significant impact on the hygrothermal performance solution shown in this paper.

At the same time, the rather mild mid-Atlantic climate seen in Baltimore made the enclosure system play a less significant role than it would receive in mid central climates, where many more days are below freezing temperatures. It can be anticipated that additional insulation levels beyond the utilized thicknesses presented here can be economically feasible.

CONCLUSION

The design and eventual construction of production builder friendly and climate appropriate high-performance townhouses can be a complex task, where many variables must be considered in order to create viable, efficient, durable, and ultimately profitable solutions for all involved stakeholders. As presented in this paper, meticulous planning and analysis is essential when selecting appropriate materials and constructions methods to achieve a successful product. Failure to do so could result in costly scheduling and installation mistakes, as well as long-term durability issues, which are not only detrimental to a builders bottom-line and reputation, but can become an additional hazard to the health and financial well-being of their homebuyers.

This paper provided specific building science analysis insights and recommendations for production builders planning to or already transitioning into the high-performance building market. Some of the main obstacles mentioned by production builders as discussed herein, such as challenges with planning, implementation, certification, and marketing can be summarized in the following takeaways that are key elements for a successful implementation of high-performance building standards and processes.

Key Takeaways. Builders and designers must not overlook the potential impacts technology solution decisions can have on labor, specifically in regards to the importance of necessary training investments to properly install unfamiliar high-performance construction systems and details. Implementing fail-safes (e.g. controlled dehumidification and correct vapor diffusion design) is an additional strategy that can help mitigate the risk of failures due to possible implementation issues.

Building science fundamentals such as thermal and hygrothermal performance understanding are essential knowledge elements that should become mandatory across all stakeholders. This means horizontal knowledge integration across the different design and management domains, and vertical dissemination across supply chains and the building construction industry, starting from CEOs recognizing the risks, project managers understanding the issue, and construction trades executing details.

As demonstrated in this paper, modeling and simulation analyses can be conducted to ensure decisions are appropriate for short-term and long-term goals of cost efficiency and durability. Once the underlying principals are understood, the actual procedures are comparatively simple for individuals in the architecture and building construction industries, and they can quickly become proficient with minimal time investment. Furthermore, optimizing for comfort is another benefit to performing building science analyses that can be used as a marketing tool for customers interested in the additional benefits of their investments.

It is important to note that when applying these strategies in other climates, appropriate adjustments must be made to ensure a solution is still effective. While it may be tempting to apply the same design to multiple project locations in order to maintain established schedules and training competencies, high-performance buildings are not a one size fits all model. An understanding for the processes and design strategies that will need to change for successful implementation in various locations is fundamental to a successful application across different climate zones. .

Finally, the "blind" use of energy modeling and scoring tools, such as the HERS rating tool can lead to a lack of attention to critical construction details. Thermal bridges are often not captured well in available energy modeling tools, which can skew energy consumption estimates and/or result in local condensation issues. Identifying thermal performance problem areas in the design phase can allow for more accurate estimation of thermal losses, and can additionally help with the optimization of the thermal boundary layer. Presenting this information to customers in a way that can explain possible discrepancies between HERS scores and actual energy consumption could potentially be a powerful design and marketing tool, which exemplifies the builders rigor beyond simply abiding by the construction standard.

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EVALUATION OF SHADING THE SOLID PARTS OF BUILDING ENVELOPES UNDER CLIMATE CHANGE SCENARIOS IN EGYPT

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Abstract:

As a vital method for mitigating the solar radiation effect on buildings, shading is considered of paramount importance, especially in Egypt as a hot arid climate country, with very high solar radiation intensity most of the year. Hence, the importance of studying shading strategies against future climate change emerged. Therefore, current practice of construction industry in Egypt needs to consider passive architectural design for residential buildings, which consume about 20% of the energy consumed in the built environment, and emit about 4% of CO2. Wherefore, this paper focuses on the determination of the optimum ratios for shading the solid parts of the building envelope in three main climatic zones in Egypt, under different climate change scenarios, to support both policy and decision makers taking steps forward towards energy efficiency obligations in Egypt. To achieve this objective, multiple dynamic thermal simulations have been conducted in order to evaluate the effect of the solid parts shading while maintaining the optimum thermal comfort conditions, reducing energy consumption and gaining long-term financial benefits. All the possible combinations (for a certain set of assumptions) of shading the solid parts of the envelope were tested for the different orientations (South, East, and West). The findings confirm the secondary role of shading the solid part of the building envelope once appropriate thermal insulation and fenestration have been selected to achieve thermal comfort and long term cost effectiveness, while minimising the energy consumption.

Keywords: *Bioclimatic Architecture, Shading techniques, Fenestration, Energy Consumption, climate change.*

1. Introduction

Buildings provide many of the necessary requirements to humans, such as shelter, security and comfort. For thermal comfort it's essential to control the heat flow between outdoor and indoor spaces, through the thermal characteristics of the building envelope (Bradley and Johnston 2011, USDoE 2004, Okba 2005). In addition to the high temperatures, another environmental contributor to a building's heat gain is solar radiation (radiant energy), the primary source of heat gains (Al-Temeemi 1995) in the hot arid zones with little cloud cover and high solar radiation most of the year, such as Egypt. When the sun's energy impacts a building envelope, heat will enter either directly through transparent areas, or it will be absorbed through the building fabric and heat will enter the building through conduction. Protection against strong solar radiation in the hot arid zones is essential to reduce cooling loads required to achieve thermal comfort within the indoor spaces, especially in the summer, as facade configurations responsible for up to 45% of the building's cooling loads (Hamza 2008). Appropriate envelope design can be optimized for natural lighting and efficient thermal performance through passive solar techniques (Makram 2008, Kassim and Bathis 2003). Vernacular architecture demonstrate such examples (El-Wakeel and Serag 1989). Shading the external envelope was achieved in different ways, E.g. by surrounding the building by a group of trees that hinder the exposure to the solar radiation, by cultivation of green areas to reduce the reflection of the solar radiation on the walls, or by clustering the buildings to reduce the exposure of the external surfaces to direct sunlight. The different heights of the buildings and the small width of the pedestrian streets, lead these buildings to shade each other, resulting into less thermal energy penetrating indoors. However, modern development and vehicular traffic, it was difficult to keep the narrow roads with human scale and the previous climatic advantages (El-Wakeel and Serag 1989).

Not all the design features of the traditional houses might be appropriate today, although the traditional house considered the climate as a main determinant. Solar screens were widely used in the Middle-Eastern countries for centuries to reduce the required cooling energy. However, there is a lack in understanding of their performance quantitatively, in addition to the unavailability of scientific means to develop new efficient designs to suit the harsh desert conditions nowadays (Sherifa et al. 2012). A considerable number of publications have addressed the effect of shading wall openings (such as windows) on energy consumption in different regions, some with the same climatic conditions as Egypt, all stressing the importance of the shading technique (Ali and Ahmed 2012, Ahmed 2012, Al-Tamimi et al. 2011, Yang and Hwang 1995). However, these studies considered the effect of shading devices over fenestration or on a combination of walls including windows. In sharp contrast, a limited number of publications addressed the effect of shading the solid parts of the building envelope (opaque solid walls) specially in such a hot arid climatic zone like Egypt (Sherif et al. 2011, Sherifa et al. 2012). Of these very rare manuscripts, El-Wakeel (El-Wakeel and Serag 1989), who only mentioned the technique of using another wall to shield the main wall, Kravchuk and Boland (Kravchuk and J. W. Boland 2000), who concluded that the wall shading will improve the indoor thermal comfort in Adelaide city in South Australia. Ahmed al-Sharif, et al. (Sherif et al. 2011), paid attention to the effect of shading the external opaque walls on the potential savings in energy consumption, in order to conclude the best utilization of external wall shading methods.

In this work the solid parts of the external walls is addressed for exposure to different proportions of direct or reflected solar radiation, subject to the direction of the sun during the daylight hours and to the changing in the ray's incidence angles in the different seasons of the year. One of the solutions for solid walls treatment is shading it using the sun breakers, such as those used for fenestration (the non opaque parts) or by using double walls (Gomez-Munoz and Porta-Gandara 2003a, El-Wakeel and Serag 1989, Gomez-Munoz and Porta-Gandara 2003b). The latter will be used (with some adjustment) to determine the optimum ratios for shading the solid parts of the building envelope using solid screens to increase the energy conservation for cooling. This is additional to the integration of thermal insulation of the external wall types commonly used in Egypt as examined in (Mahdy and Nikolopoulou 2012, Mahdy and

Nikolopoulou 2013), and dealing with different fenestration and shading parameters (Mahdy et al. 2013, Mahdy and Nikolopoulou 2014) mentioned in the Egyptian Code for Improving the Efficiency of Energy Use in Buildings – Part 1: Residential Buildings (HBRC 2008), (for simplicity it will be referred to as EREC for Egyptian Residential Energy Code), in terms of a long term financial study of these parameters, to achieve thermal comfort with minimum energy consumption and consequently minimum CO_2 emissions, along with optimum initial investment and running costs. The effect of the solid envelope will be examined in three different climatic regions in Egypt, under the different scenarios of climate change, essential to evaluate the building's thermal performance over the long term. The hours of sunshine and the proportion of direct radiation to diffused radiation are projected to increase in the future, while the modelling studies demonstrate a steady increase in building's cooling capacity and associated energy consumption (Levermore et al. 2012). Hence, the importance of studying shading strategies against future climate change emerged to minimize the expected overheating.

The focus of the current study aims beyond the energy consumption at the present time to address climate change scenarios in the future, as well as the long-term consumption, based on financial analysis for the economic returns in the long-term, taking into consideration the project's initial cost (capital cost) as well as the running cost. Our results are likely to be of interest to a wide range of designers, architects and to support both policy and decision makers taking steps forward towards energy efficiency obligations, particularly in Egypt

2. Methodology

Dynamic thermal simulations were employed for this research using Energy plus, and its architectural friendly interface DesignBuilder (DB) in its third version (V.3.0.0.105) (DB 2012). For the simulations, a model of a typical residential building (one of the commonly used prototypes for the governmental housing in Egypt) in Cairo with mechanical air conditioning installed was employed, which was then tested in three of the Egyptian climatic zones defined in EREC (HBRC 2008, OEP 1998), Cairo and Delta, the North coast and the Southern climatic zone, while keeping the same orientation. Overall:

1) 768 dynamic thermal simulations have been carried out, to evaluate the effect of various parameters on monthly energy consumption (kWh), indoor air temperature (°C) and associated consumed energy cost on the long term. These have been tested under the current climate conditions (2002), and the different climate change scenarios for three periods: 2020, 2050 and 2080.
2) A new code (EPP) (discussed in section 2.2) has been developed and used to facilitate the huge number of simulation processes and to ensure the accuracy of the results.
3) Modelling of long-term financial analysis was carried out (section 4.2) to identify the most cost-effective technique to be used in each climatic zone in Egypt. This takes into account the initial cost as well as the running cost of each case.

For the purpose of this work, the following assumptions have been made:

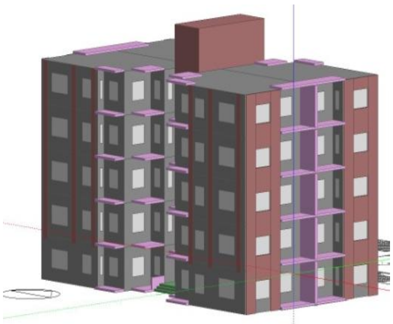
1) As shown in EREC and previous work (Mahdy and Nikolopoulou 2014), the maximum Window to Wall Ratio (WWR) allowable for the entire climatic zones in Egypt is 20%, which will be used in the work.
2) To represent the effect of the external shading provided by the surrounding buildings, vegetation and other obstacles. A ratio of 30% has been assumed for each façade.
3) The building self shading produced by the balconies and the other prominence elements in the building, assumed to cover another 10% of the building's envelope.

This set of assumptions does not represent all the possible eventualities in real life, but it's a start for more investigations in the same field to prove whether it is efficient to use this kind of shading techniques.

2.1. Solid shading screens

According to the aforementioned assumptions, there will be about 60% of the building's envelope covered, and about 40% of each façade left without protection against the direct and indirect solar radiation. The cost effective protection for these remaining parts will be evaluated, by taking into account all the possible probabilities in shading these remaining 40% of each façade using solid screens mounted on the external walls. The screens are assumed to be 10 cm away from the main walls, made of light steel frames with iron mesh covered with cement, then painted in light colours, with a total thickness of 5 cm.

All the shading probabilities for the South, East and West façades have been addressed by altering the different percentages from 10% to 40% of unprotected parts of each façade (see Fig.1 for examples, 10-40-20% refers to the shading screen's area: 10% of the total façade area for the Southern façade, 40% for the Eastern façade and 20% for the Western façade). All the percentages alternatives are shown in Table 1 (64 probabilities). This process is repeated for the three climatic zones (Alexandria, Cairo and Aswan) resulting in 192 simulations, while repeating the process for the four current and future Weather Data Files (WDF) (2002, 2020, 2050 and 2080) gives a total of 768 simulation, providing the results for this work.



10-40-20%

20-30-20%

Figure 1: Examples for the different probabilities of shading the solid parts.

Table 1: Building's shading probabilities for one climatic zone for one WDF.

South Façade		East Façade			
10%		10%	20%	30%	40%
West Façade	10%				
	20%				
	30%				
	40%				

South Façade		East Façade			
20%		10%	20%	30%	40%
West Façade	10%				
	20%				
	30%				
	40%				

South Façade		East Façade			
30%		10%	20%	30%	40%
West Façade	10%				
	20%				
	30%				
	40%				

South Façade		East Façade			
40%		10%	20%	30%	40%
West Façade	10%				
	20%				
	30%				
	40%				

2.2. Automation of the simulation processes

The initial simulation execution strategy (Fig.2) was to use DesignBuilder (DB) and its Energy Plus integration. Three parts are included, a model, a location setting on the model and a WDF per location and year settings. The simulation is then run and the results are observed by exporting the simulation results as a CSV file through DB for the visual representation. The approach was sufficient as a proof of concept and for initial tweaking of the model and other parameters. However, the plan was to run 768 simulations, which led to the need of a faster less human dependent solution. Thus, Energy-Plus-Plus (EPP) was born.

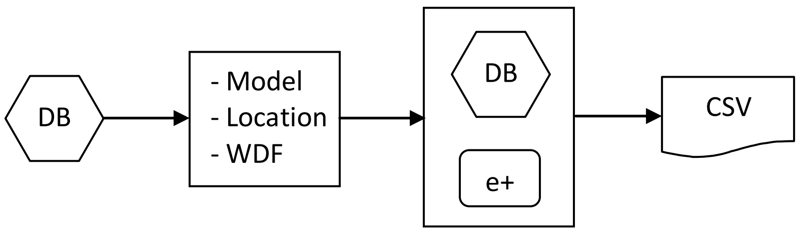


Figure 2: The ordinary method used to conduct simulations.

A Java automated runner for Energy Plus simulations (e+), the first version (see Fig.3) of which was used to produce the results in this work. This version provides automation for the simulation step, the most time consuming step of the process. The simulation scripts (IDF files) are produced using DB after configuring the location and are independent of the yearly weather files. I.e. A single simulation script can run against all four weather data files the study is concerned with (2002, 2020, 2050 and 2080). So all scripts of a specific model and location is then gathered in batches and then passed as inputs to EPP along with all the weather files of the specific location. It is then run to generate Energy Plus output (ESO files), that is parsed using DB later on and then exported into CSVs. EPP is modular in design and built with the intention of streamlining the entire process including script generation, output parsing and parallel simulation execution. EPP yet is under development aiming to reduce the human intervention in the multiple simulations execution as much as possible, granting the ability to execute more simulations and cover a broader spectrum of possibilities with more supporting evidence.

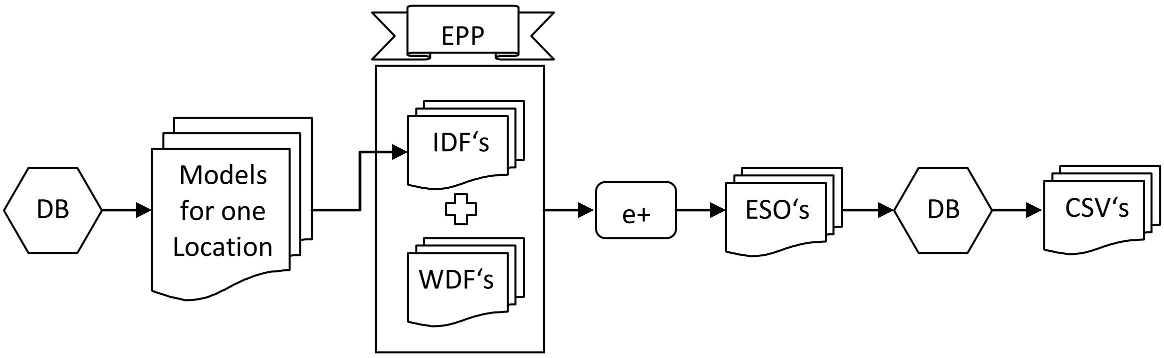


Figure 3: New technique used to handle the simulations.

3. Parameterization

Egypt is a large country with an area of approximately 1,000,000 km^2, located between 22º N - 31º 37′ N latitude and 24º 57′ E - 35º 45′ E longitude. Egypt possesses a diversity of climate conditions ranging from extremely hot conditions in the desert regions such as the Western Desert, to cold conditions in Mountain St. Catherine in Sinai Peninsula (Mahmoud 2011). However the overall climate of Egypt is characterized by the hot arid climate (Köppen classification: BWh) with very high solar radiation intensity most of the year (Solar-GIS 2013, SODA 2013). Egypt is divided into eight climatic zones. The current experiments will take place in three climatic regions in Egypt: (1) Cairo and Delta zone (Cairo governorate), (2) North coast zone (Alexandria governorate) and (3) the Southern Egypt zone (Aswan governorate). About 50% of the construction projects carried out in Egypt are located in Cairo and Alexandria governorates (Huang and Berkeley 2003), while Aswan governorate is considered a very different zone in terms of the climatic aspects compared to the other zones (El-Wakeel and Serag 1989, HBRC 2008, Gira 2002).

Depending on the theory of Adaptive Comfort (Humphreys et al. 2013, Humphreys 1996), and according to Givoni (Givoni 1998), the thermal comfort zone 20°C-29°C, has been used in the experiments. This is an modification of the original comfort zone (22.2°C-25.6°C) mentioned in EREC (HBRC 2008).

Four different WDFs ranging from the current weather conditions (2002), to the predicted WDFs (2020, 2050 and 2080) have been used to provides a maximum test period of 88 years, as 2012 was assumed to be the starting construction year (the WDFs were divided as shown in Table 2. The current weather data file (2002) was obtained from the official site of the U.S Department of Energy (USDoE 2012). Then by using the Climate Change World Weather File Generator (CCWorldWeatherGen) (SERG 2012), the future WDFs for 2020, 2050 and 2080 were generated. The new weather data files have been used accordingly for the simulations, after using the DB weather data converter tool to convert them into an hourly weather data files that can be used with DB. Figure 4 demonstrates the future climate change scenarios for the different climatic regions involved in the study (Alexandria, Cairo and Aswan respectively), starting with the present climate conditions until the 2080 projections. The left graphs presents the outside dry-bulb temperatures for the current and the three future scenarios, while the graphs on the right shows the direct solar radiations for the same climatic periods. Out of the diagrams, the apparent increase in the temperatures from a climatic period to the period following can easily observable. On the contrary the solar radiation rates were very close to the existing conditions.

A fixed schedules for energy consumption were used in all the different simulations (in conjunction with the cooling and heating setpoints) to control the timing in DesignBuilder and to define certain activities in the simulations, such as occupancy times, equipment, lighting and HVAC operation (DB 2011). The schedules were defined through a fixed activity template, based on the common lifestyle for the residents of Egypt (holidays, work hours, etc.) (Attia et al. 2012). A mixed mode of HVAC systems and natural ventilation were used to benefit from passive cooling when available and make efficient use of mechanical cooling systems during extreme periods. Simple HVAC systems setup were used in the simulations, where the heating and cooling systems are modelled using basic loads calculation algorithm (Energy Plus zone HVAC ideal loads) (DB 2011). The HVAC specifications include the use of split air-conditioning units (with cooling COP=1.83) for the whole day in the summer when the temperature exceeds 29ºC until it drops below 25ºC; otherwise, natural ventilation was used. It should be noted that, the aforementioned parts of the methodology has been discussed extensively in the previous work (Mahdy and Nikolopoulou 2014, Mahdy and Nikolopoulou 2013).

The simulation techniques including modelling, building materials assignment, lighting and HVAC systems configurations have been examined in order to validate the simulated results. To attain this objective, the monthly energy consumption data for two different flats (in Cairo) were obtained out of the energy bills, then the exact energy consumption was compared with the simulated results for each model. The accuracy reached almost 90% for one of the cases and about 87% for the other. This reflects that the predictions are in good agreement with the on-site measured data, thus this simulation processes can be used to validate the research objectives in the current weather conditions, and under future climate change scenarios.

Table 2: Different time periods covered by the WDFs.

WDF	Covered period (years)	From - to
2002	14	2012 - 2025
2020	14	2026 - 2039
2050	30	2040 - 2069
2080	30	2070 - 2099

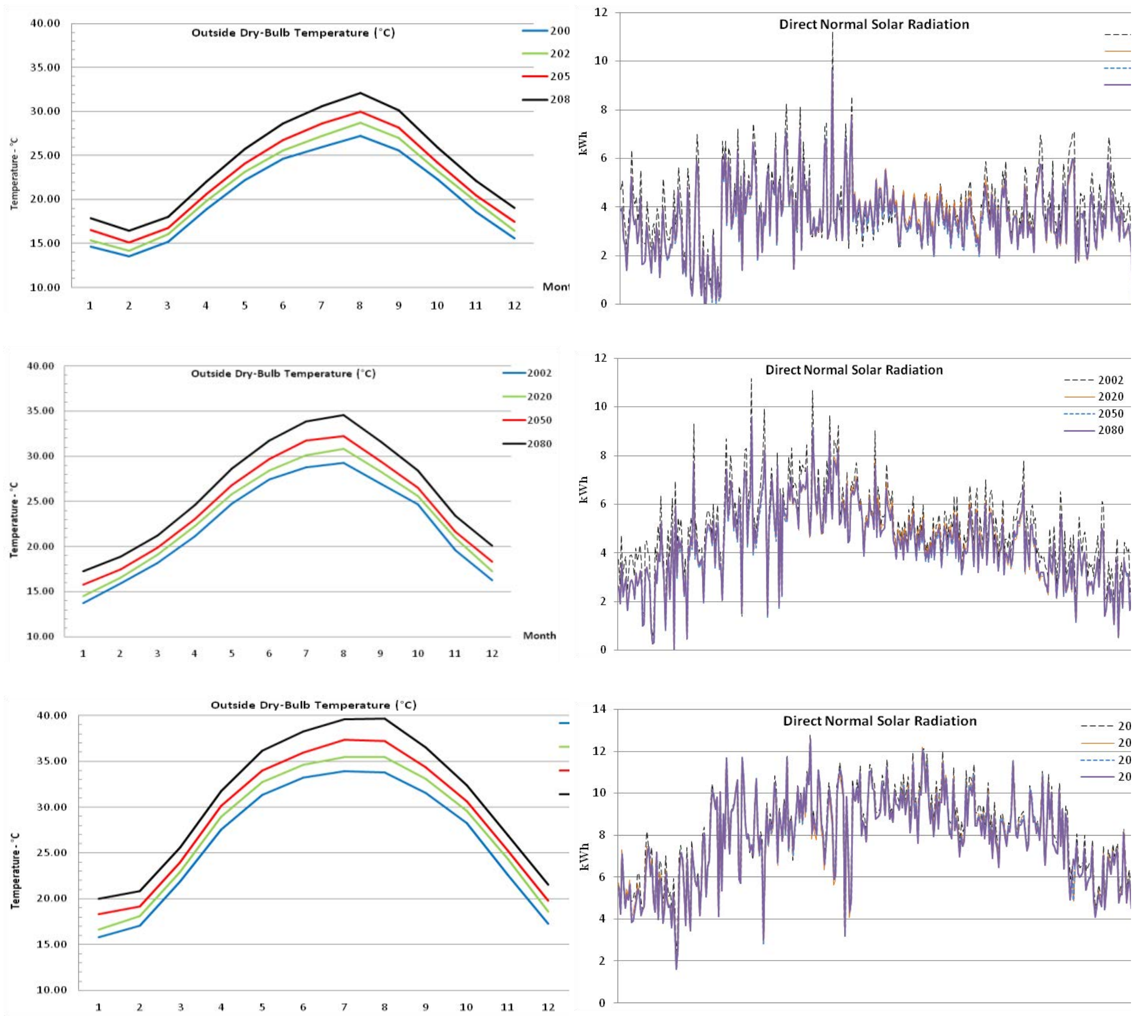


Figure 4: Future weather projections for Alexandria, Cairo and Aswan.

3.1. Model definition

The building which underwent treatment processes and simulations is a governmental housing building consists of six floors, where each has four residential flats with an approximate area of 86 m^2. The average number of occupants per flat is four. The building floor plan is shown in Fig 5.

Figure 5: Typical plan for the Modelled flat.

3.2. *Building materials specifications*

A set of materials were used for the model's construction in the different three climatic zones, evaluated in previous work (Mahdy and Nikolopoulou 2014, Mahdy and Nikolopoulou 2013), which recommended the use of:

(1) External walls: the double wall of half red-brick with 5cm of internal expanded polystyrene thermal insulation layer (Dins) wall as the optimum external wall in Aswan, and the use of the double wall of half red-brick with 5 cm air gap in between (Dair) wall for Alexandria and Cairo (see Fig. 6 and Table 3 for the thermal specifications).

(2) Fenestration: the Single Clear Reflective 6.4mm, with 8% Stainless-Steel Cover, along with 20% WWR, as the most cost-effective glass type and WWR to be used for the long run in the three climatic zones (see Table 4 for characteristics).

These are the optimum specifications shown to achieve indoor thermal comfort, minimize the energy consumption, while attaining the maximum financial benefits. The models which used these materials only without any shading for the solid parts will be known as the "Base case" model. The thermal properties for the building materials were obtained from EREC (HBRC 2008), and the Egyptian Specifications for Thermal Insulation Work Items (HBRC 2007).

Table 3: External Walls main characteristics.

External Walls	ABBRV.	Thick. (mm)	U-Value (W/m^2K)
Double wall of half red-brick with 5 cm air gap in between.	*Dair*	290	1.463
Double wall of half red-brick with additional internal 5cm of expanded polystyrene thermal insulation layer.	*Dins*	290	0.503

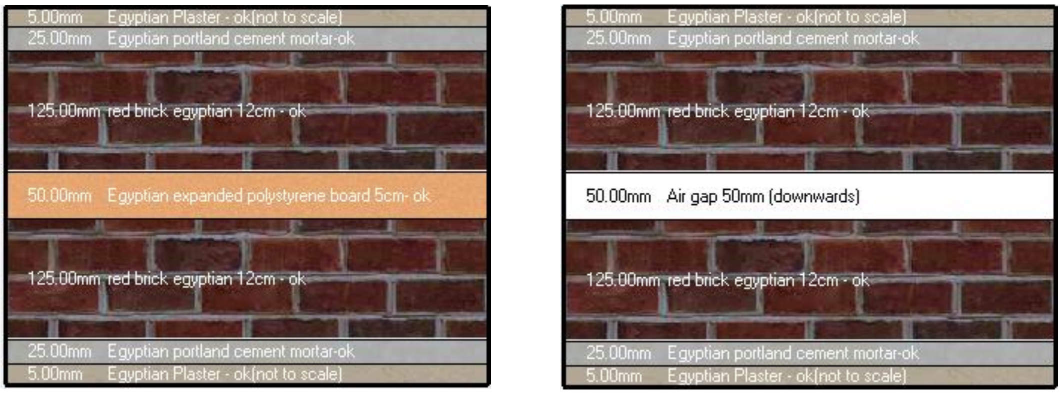


Figure 6: Wall sections used.

Table 4: Used glass specifications.

Name	Category	SHGC*	LT**	U-Value (W/m^2K)
Clear Reflective 6.4mm – (Stainless steel Cover 8%)	Single Reflective	0.18	0.06	5.36

*SHGC: Solar Heat Gain Coefficient. **LT: Light Transmission.

3.3. Financial information

3.3.1. Construction materials costs

The price-list of Construction materials, obtained from The Engineering Authority Indicative Guide (EAAF 2012) was used to calculate the initial cost of project. These numbers were used later for the financial analysis (section 4.2).

3.3.2. Electric energy prices

For the financial analysis, the cost of the energy consumption per flat per year was calculated using the electricity tariff derived by the Egyptian Ministry of Electricity and Energy for the residential sector (MOEE 2012), which is referred to as operation cost or running cost. The different categories and prices are shown in Table 5.

Table 5: The electricity tariff.

no.	Category (kW)	Price (EGP)	no.	Category (kW)	Price (EGP)
1	50	0.05	4	351-650	0.24
2	51-200	0.11	5	651-1000	0.39
3	201-350	0.16	6	Over 1000	0.48

4. Results and discussion

A huge reduction in energy consumption was expected. However, a very small reduction resulted due to the appropriate construction materials that have been used, which obtained from the previous work (see section 3.2). The analysis process will address three phases: (1) Thermal comfort results, (2) Financial analysis and (3) Assessment of different alternatives.

The results obtained from the different simulations are divided in three separate graphs: Monthly Energy Consumption (kWh), Annual Energy Cost in Egyptian Pound (EGP) and Indoor/outdoor temperature (°C). These measures were plotted for the three climatic zones, different shading alternatives and different climate change scenarios in 48 graphs. However, as the results for the three different climatic zones were consistent, almost with the same indications, therefore, the results for Cairo climatic zone (16 graphs) were discussed and some of its graphs were displayed (Figs.7-14) as a representative for the other obtained results, which generally followed the same patterns, but with some decrease in energy consumption, subsequently the annual energy cost in Alexandria (to the North), and some increase in energy consumption in Aswan (to the South), due to the general weather conditions in each climatic zone. The graphs were listed according to the climatic periods (2002, 2020, 2050 or 2080) and to the solid parts shading ratio which named after the Southern façade (10, 20, 30 or 40%). For each weather period, the upper left graph represents the monthly energy consumption for the different shading ratio's alternatives of the solid parts of the building envelope. As expected for the same climatic region, the energy consumption increases from a climatic period to the following period due to the temperature increase under climate change (Crawley 2007), this applies to all climatic zones. The upper right graph in each weather period represents the annual energy cost according to the household electricity tariffs used in Egypt (MOEE 2012). As predictable, the results show that the cost is directly proportional to the increase in energy consumption. Finally, the lower graph presents the indoor and outdoor mean temperature variations for the whole year, with each number corresponding to the respective month, along with the thermal comfort zone. As expected, these vary for the different climate zones, climatic periods, types of construction for the external walls and its different shading ratios.

4.1. Thermal comfort results

The thermal comfort is one of the main and the most influential concerns in the design process. The thermal comfort (in cost effective way) was already achieved for all the tested models with different shading probabilities in all the different climatic zones and periods, due to using of the proper building envelope insulation and fenestration treatment (the base case itself already achieved thermal comfort from the beginning). Nevertheless, the goal was to decrease the energy consumption and enhance the financial aspects using the solid parts shading technique while maintaining the thermal comfort conditions.

As it turns out, the simulations did not show any remarkable development in the thermal comfort curves (see Figs.7-14), just a very small improvement (reduction in the indoor air temperature) of 2-3% achieved as the best result in Cairo, and from 1-2% in Alexandria and Aswan according to the Indoor Air Temperatures resulted from the simulations, but as mentioned before within the acceptable range of the thermal comfort zone. At the same time this slight improvements have not shown any noticeable effects on the financial aspects.

4.2. Financial analysis

As all the cases achieved the thermal comfort, a long term financial analysis has been conducted to find out which case is more effective than the base case on the long term. The different solid shading alternatives used in our simulations were compared with respect to a long term financial aspect of 88 years period. The aim was to point out the best cost effective solid shading ratio for the whole building to be used in each climatic zone, and in all the future climate change scenarios taking into account the initial cost and the running cost of each alternative when applied. As a non professional financial study, some financial equations have been developed and derived based on the Net Present Value (NPV) financial model. The subsidized electricity tariff as well as the interest rate are assumed to be fixed over the study period. Putting into consideration that, the increase in the electricity tariffs (the removal of subsidies) or the decrease in the interest rate will not affect the general conclusion, to verify this several attempts were conducted on the economic model. The interest rate was reduced to 2% and the price of energy was increased up to six-fold, despite of this the general indicators of the results remained stationary, although the figures have been changed.

The financial implications for the results of the simulations in Cairo (representative for the rest of the climatic zones Alexandria and Aswan) are summarized in Table 6. The table shows the running costs for the energy consumed in Cairo for each climatic period (sub-total), as well as the average annual running cost obtained by dividing the running cost of the four periods added together (Overall annual running cost) by 88 years. The financial study has been performed for each climatic zone separately. For each tested probability, the initial cost has been calculated according to the area that has been shaded in each case. The difference in the initial cost of any case and the base case (with zero solid shading) is invested by saving the money in a bank with the regular 9% interest rate in Egypt (NBE 2012), following the formula:

$$V \qquad \text{(Eq.1)}$$

Where:
M : The difference in the initial cost in Egyptian pound (EGP).
N : The investment period in years.
: The amount of money rose after N years.

In addition, the bills paid for the consumed energy in each different case is referred to as the running cost. The difference in the running cost between any case and the base case will reflect in saving M_2 in EGP in the annual energy bill. After N years the amount of money V_2 raised from the running costs savings which calculated using the following formula:

(Eq.2)

However, none of the different alternatives has out paten the base case in any of the different three climatic zones. As indicated in table 6, only the negative numbers in the column "saving in initial cost vs. saving in running cost" according to the mathematical equations, indicates financial gains on the long term for any of the various alternatives of the study versus the base case, which proves that a proper thermal insulation and fenestration treatment are sufficient to achieve thermal comfort in cost effective way on the long term and under the climate change scenarios.

4.3. Assessment of different alternatives

In spite of the ineffectiveness of the different tested ratios and the sufficiency of using the insulation and fenestration treatments, the energy consumption (running cost) and initial cost analysis has been conducted to point out the optimum solid shading ratio in case of the desire of improving the thermal comfort and energy consumption even by a small amount. The ratio 10-10-10 was found to be the most cost effective case among the other ratios in all the climatic zones, when the running cost compared to the initial cost on the long term, due to the very small differences in the running cost between the different shading ratios, while the differences in the initial costs was higher (see Table 6).

5. <u>Conclusions</u>

In this paper, we have evaluated the effect of different ratios for shading the solid parts of the building envelope, on thermal comfort, energy consumption and cost effectiveness, in three main climatic zones in Egypt (Alexandria, Cairo and Aswan) under different climate change scenarios. In the simulations, many probabilities for shading the building envelope's solid parts combinations have been tested for the different façades of the model (Southern, Eastern and Western facades) all in the same time. The experiments are based on building performance simulations that take into account the external walls construction, WWR, glazing type, shading devices recommended by EREC and previous work findings for each climatic zone, and four weather data files representing the current and future climate change scenarios (2002, 2020, 2050 and 2080), to evaluate the energy consumption and the thermal comfort of the building model. In addition, a long term financial analysis was carried out based on the results of the simulations to reveal the effectiveness of using the solid part's shading strategy, with respect to the initial investment and the running costs. Simulation results as well as the associated financial analysis showed that, there is no need to use the solid parts shading technique in the presence of the proper external walls insulation and fenestration treatments for each different climatic zone, as it is not achieving significant improvements to the indoor thermal comfort, and moreover it is not cost effective for any tested ratio as well.

The initial investment and running costs were the main focus in this paper, as they are of primary importance for people developing and living in the buildings; so the focus has been on energy costs for keeping the building comfortable along with the associated financial costs (from construction to operation), as these are the costs that the user would have to bear. Although we agree that the life cycle cost is important, it is beyond the focus of this paper.

6. Further research

Fenestration's solar screens proved to provide high energy savings in severe desert environments, unlike the solid parts shading technique which this study advise not to use it in the presence of external wall's appropriate construction materials and suitable fenestration treatments. However, the preference of the use of heat treatments for walls with the fenestration treatments or solid parts shading techniques separately are under investigation by the authors, to find out which is better to achieve thermal comfort and financial profits on the long term, and the applicability of using the best techniques in the other Egyptian climatic zones is under investigation as well. Future work may include extending the set of assumptions that have been tested in this paper and simulating more models, to represent as much as possible the probabilities in real life and in order to assure generalizing the results.

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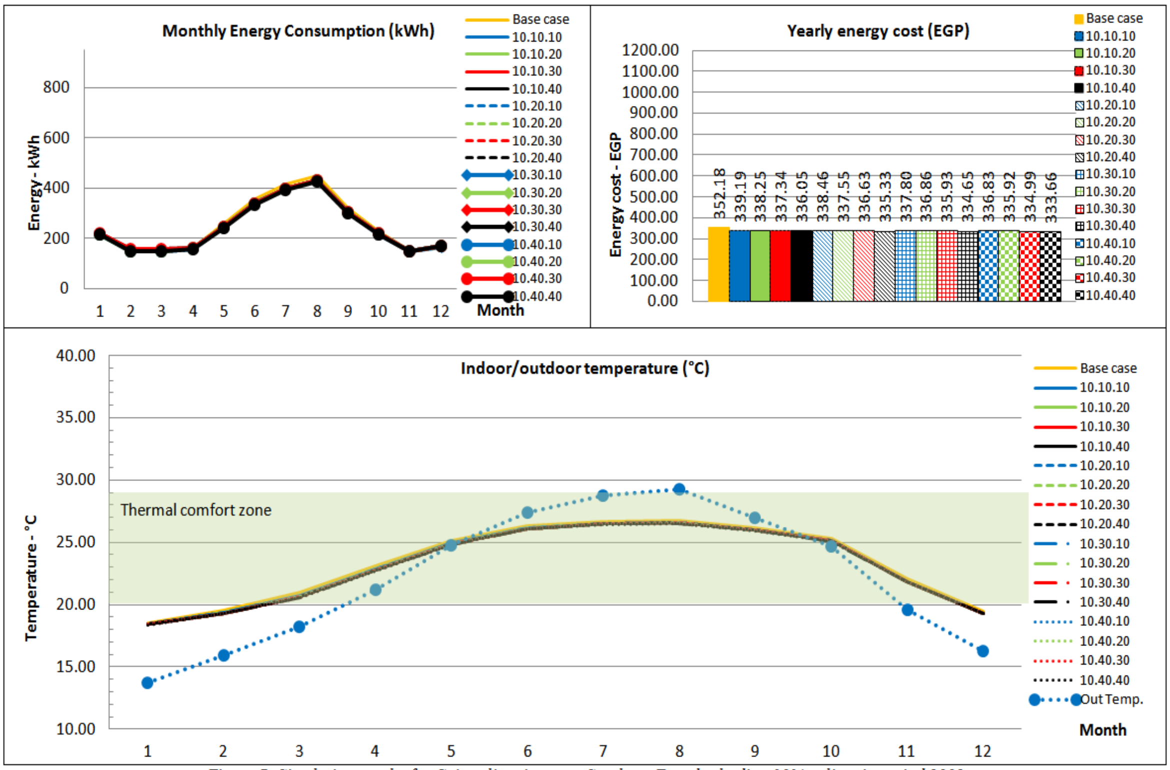

Figure 7: Simulation results for Cairo climatic zone - Southern Façade shading 10% - climatic period 2002

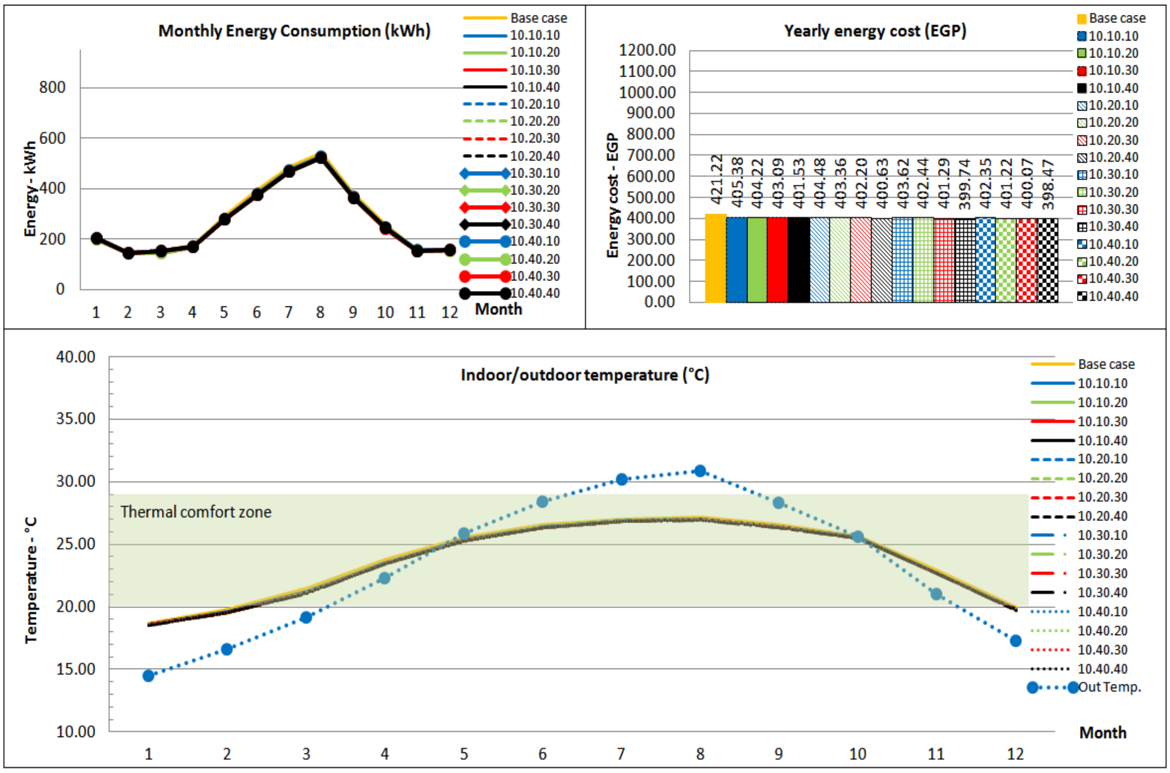

Figure 8: Simulation results for Cairo climatic zone - Southern Façade shading 10% - climatic period 2020

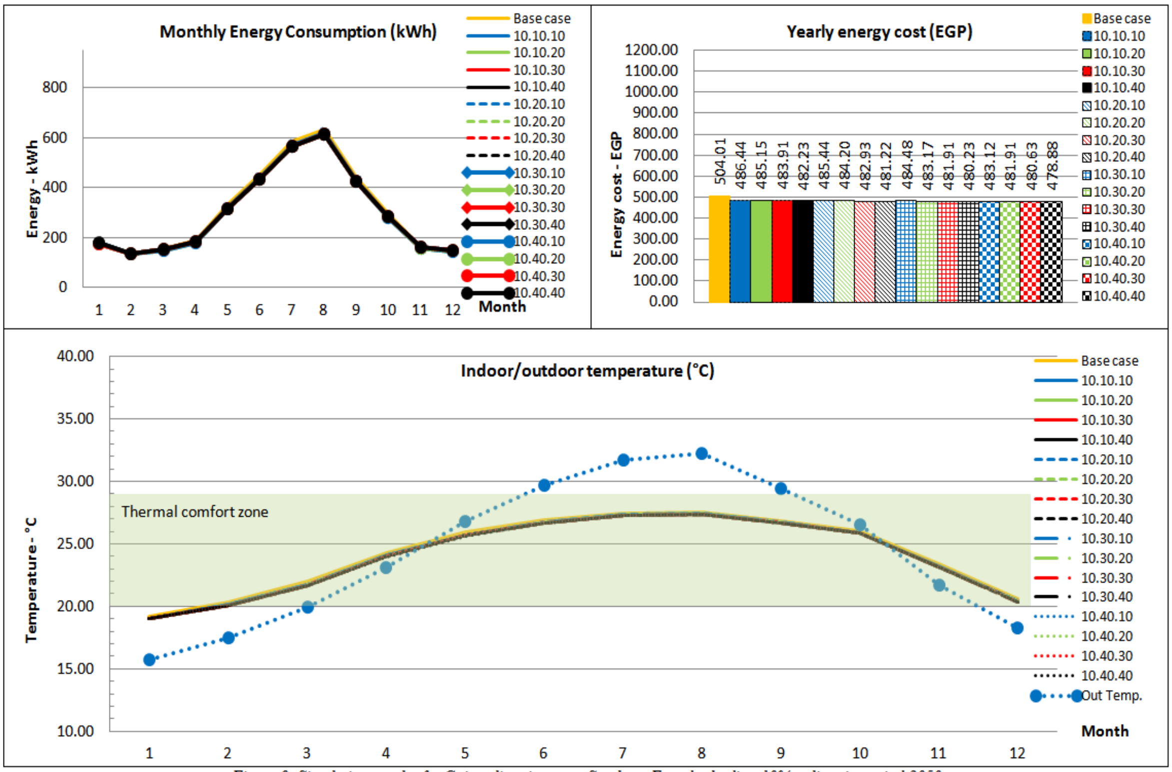

Figure 9: Simulation results for Cairo climatic zone - Southern Façade shading 10% - climatic period 2050

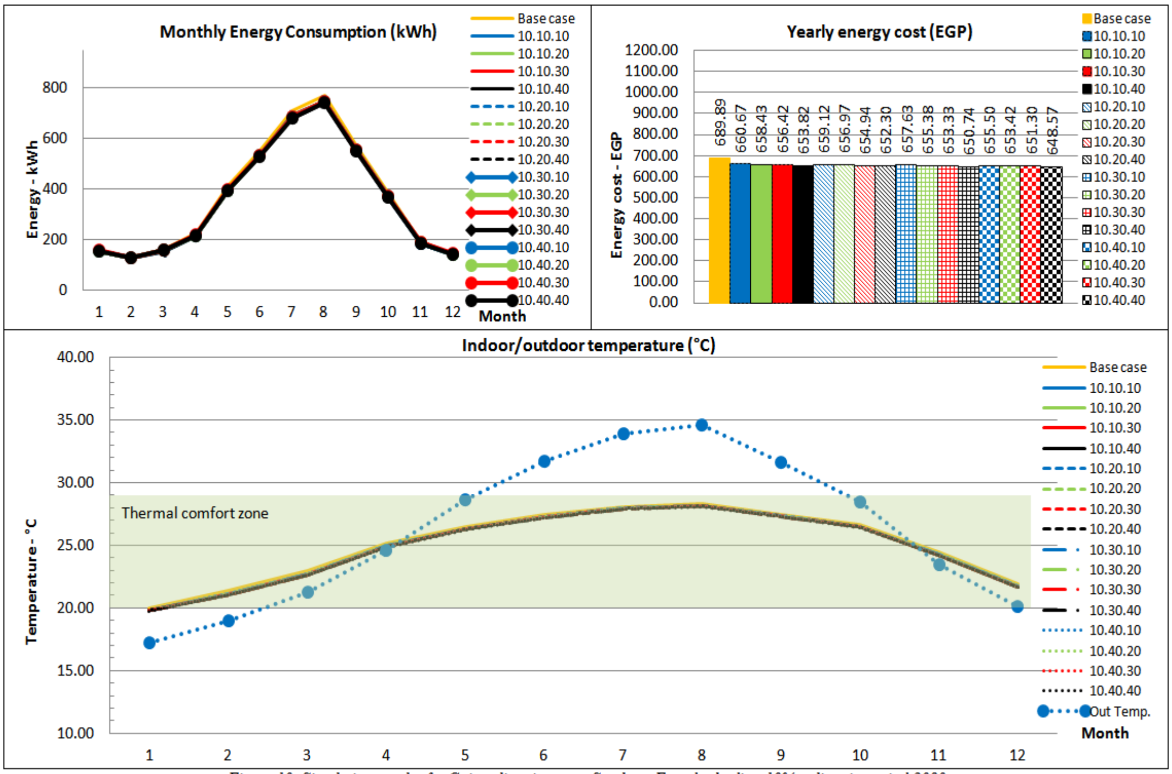

Figure 10: Simulation results for Cairo climatic zone - Southern Façade shading 10% - climatic period 2080

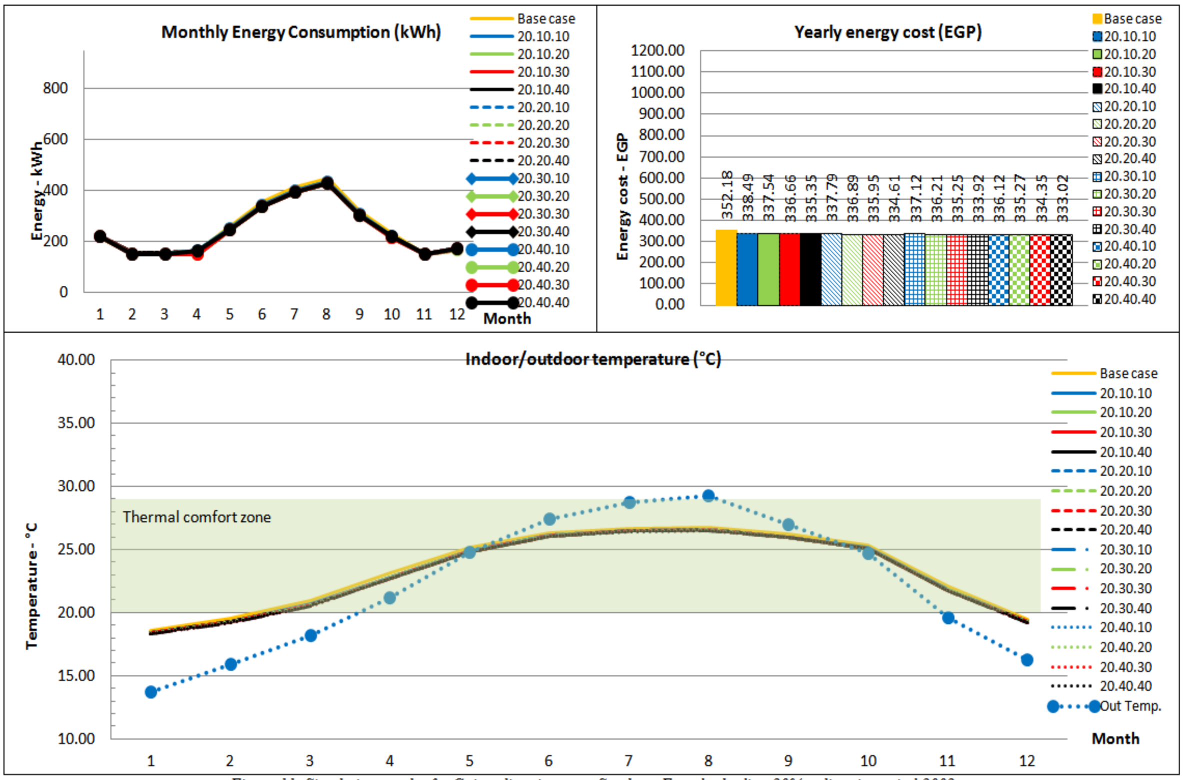

Figure 11: Simulation results for Cairo climatic zone - Southern Façade shading 20% - climatic period 2002

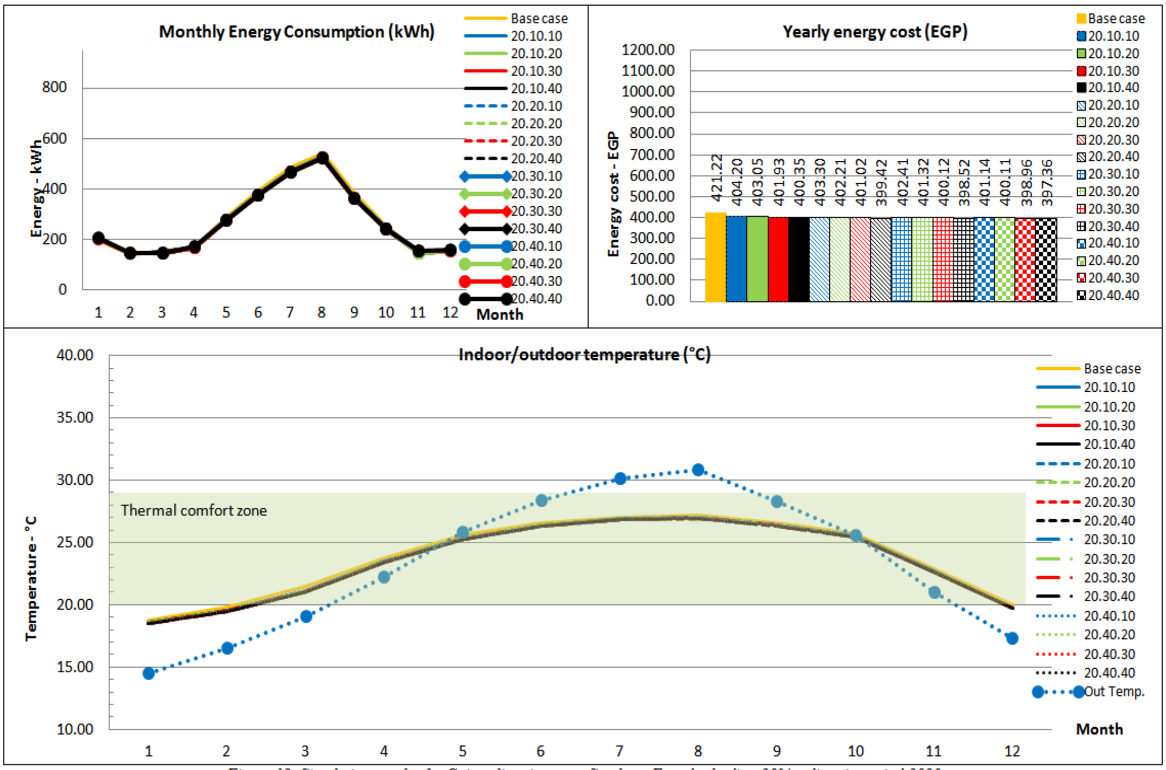

Figure 12: Simulation results for Cairo climatic zone - Southern Façade shading 20% - climatic period 2020

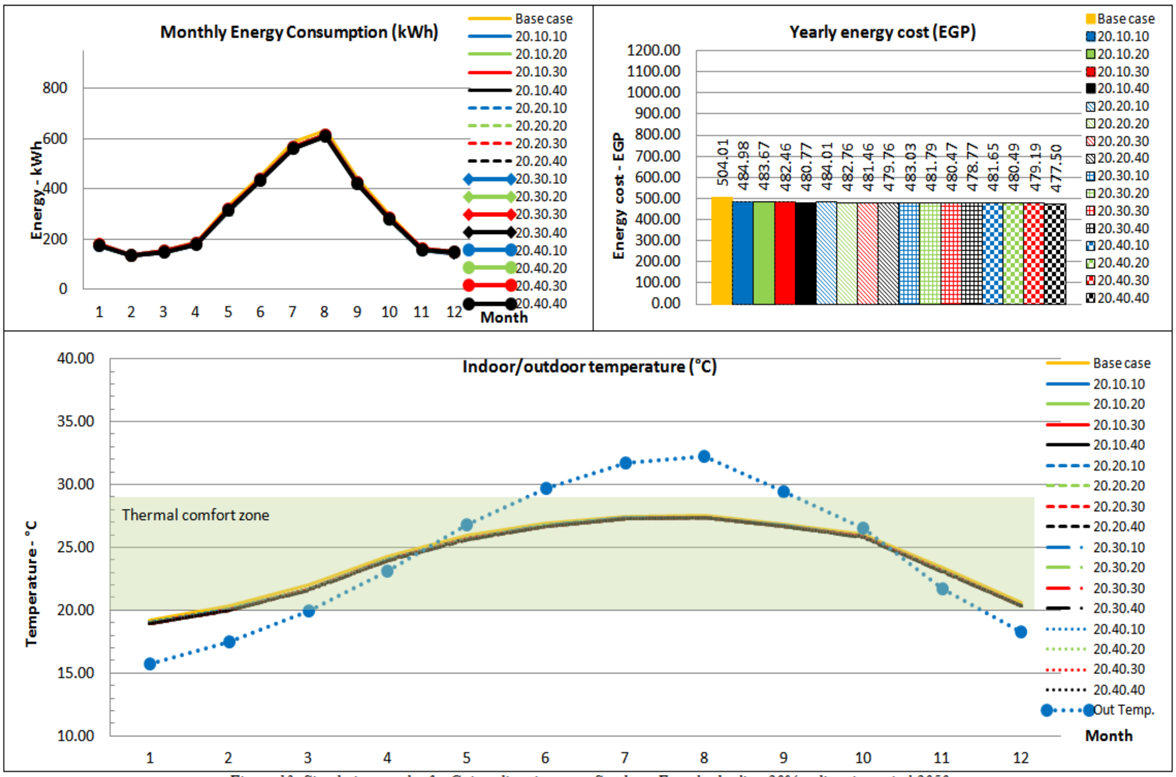

Figure 13: Simulation results for Cairo climatic zone - Southern Façade shading 20% - climatic period 2050

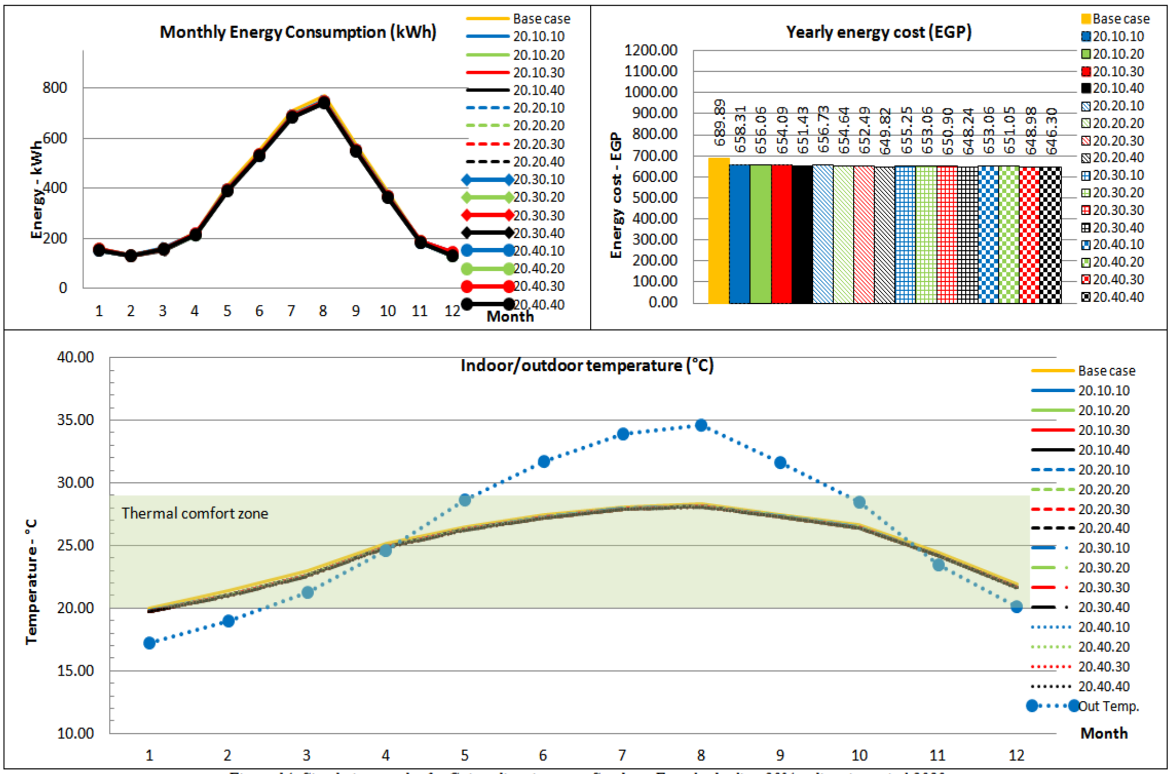

Figure 14: Simulation results for Cairo climatic zone - Southern Façade shading 20% - climatic period 2080

Table 6: Financial analysis for the simulation results of Cairo climatic zone.

	SS	Initial cost	2002: 2012-2025 (14 years)		2020: 2026-2039 (14 years)		2050: 2040-2069 (30 years)		2080: 2070-2099 (30 years)		Overall annual running cost	Average annual running cost (Overall/88)	diff in initial cost	accumulation after 88 yrs	diff in running costs	accumulation after 88 yrs	saving in initial cost vs. saving in running cost
			Running cost	Sub total	Running cost	Sub total	Running cost	Sub total	Running cost	Sub total							
	Base B	EGP	352.18	4930.4943	421.22	5897.0748	504.01	15120.221	689.89	20696.5694	46644.36	530.05	0	0.00	0.00	0.00	
	10-10	6465.6	339.19	4748.6767	405.38	5675.375	486.44	14593.138	689.89	20696.5694	45713.76	519.47	6,465.60	11,660,418.93	- 10.58	- 230,860.32	11,429,558.62
	10-20	8236.8	338.25	4735.4831	404.22	5659.0949	485.15	14554.649	658.43	19752.9929	44702.22	507.98	8,236.80	14,854,698.51	- 22.07	- 481,799.38	14,372,899.13
	10-30	10008	337.34	4722.7081	403.09	5643.2086	483.91	14517.383	656.42	19692.5984	44575.90	506.54	10,008.00	18,048,978.08	- 23.51	- 513,136.86	17,535,841.22
	10-40	11779.2	336.05	4704.6516	401.53	5621.4381	482.23	14466.918	653.82	19614.6143	44407.62	504.63	11,779.20	21,243,257.65	- 25.42	- 554,882.24	20,688,375.42
	20-10	8236.8	338.46	4738.4411	404.48	5662.6949	485.44	14563.1	659.12	19773.5674	44737.80	508.38	8,236.80	14,854,698.51	- 21.67	- 472,971.92	14,381,726.59
	20-20	10008	337.55	4725.7581	403.36	5646.9871	484.20	14526.137	656.97	19709.0079	44607.89	506.91	10,008.00	18,048,978.08	- 23.14	- 505,200.40	17,543,777.68
	20-30	11779.2	336.63	4712.8417	402.20	5630.8554	482.93	14488.027	654.94	19648.0828	44479.81	505.45	11,779.20	21,243,257.65	- 24.60	- 536,974.83	20,706,282.82
10%	20-40	13550.4	335.33	4694.5651	400.63	5608.7662	481.22	14436.581	652.30	19569.0018	44308.91	503.51	13,550.40	24,437,537.23	- 26.54	- 579,369.26	23,858,167.97
	30-10	10008	337.80	4729.2617	403.62	5650.7321	484.48	14534.424	657.63	19728.9528	44643.37	507.31	10,008.00	18,048,978.08	- 22.74	- 496,398.55	17,552,579.53
	30-20	11779.2	336.86	4715.9973	402.44	5634.2035	483.17	14495.243	655.38	19661.4803	44506.92	505.76	11,779.20	21,243,257.65	- 24.29	- 530,247.55	20,713,010.11
	30-30	13550.4	335.93	4703.0344	401.29	5618.1081	481.91	14457.298	653.33	19599.7741	44378.22	504.30	13,550.40	24,437,537.23	- 25.75	- 562,177.30	23,875,359.93
	30-40	15321.6	334.65	4685.0323	399.74	5596.4114	480.23	14406.812	650.74	19522.2909	44210.55	502.39	15,321.60	27,631,816.80	- 27.66	- 603,771.79	27,028,045.01
	40-10	11779.2	336.83	4715.5935	402.35	5632.8343	483.12	14493.558	655.50	19665.0609	44507.05	505.76	11,779.20	21,243,257.65	- 24.29	- 530,217.13	20,713,040.52
	40-20	13550.4	335.92	4702.9087	401.22	5617.1446	481.91	14457.353	653.42	19602.4606	44379.87	504.32	13,550.40	24,437,537.23	- 25.73	- 561,767.49	23,875,769.73
	40-30	15321.6	334.99	4689.9199	400.07	5601.0484	480.63	14418.912	651.30	19539.0241	44248.90	502.83	15,321.60	27,631,816.80	- 27.22	- 594,256.13	27,037,560.67
	40-40	17092.8	333.66	4671.2998	398.47	5578.6029	478.88	14366.325	648.57	19457.1968	44073.42	500.83	17,092.80	30,826,096.38	- 29.22	- 637,788.65	30,188,307.73
	10-10	9388.8	338.49	4738.8303	404.20	5658.7435	484.98	14549.306	658.31	19749.262	44696.14	507.91	9,388.80	16,932,278.72	- 22.14	- 483,307.06	16,448,971.66
	10-20	11160	337.54	4725.617	403.05	5642.7459	483.67	14510.179	656.06	19681.754	44560.30	506.37	11,160.00	20,126,558.29	- 23.68	- 517,007.42	19,609,550.87
	10-30	12931.2	336.66	4713.1947	401.93	5626.9977	482.46	14473.749	654.09	19622.8228	44436.76	504.96	12,931.20	23,320,837.87	- 25.09	- 547,652.51	22,773,185.35
	10-40	14702.4	335.35	4694.8772	400.35	5604.9347	480.77	14423.223	651.43	19542.7924	44265.83	503.02	14,702.40	26,515,117.44	- 27.03	- 590,057.94	25,925,059.50
	20-10	11160	337.79	4729.0122	403.30	5646.2637	484.01	14520.408	656.73	19701.7957	44597.48	506.79	11,160.00	20,126,558.29	- 23.26	- 507,782.85	19,618,775.44
	20-20	12931.2	336.89	4716.4485	402.21	5630.9996	482.76	14482.73	654.64	19639.2653	44469.44	505.33	12,931.20	23,320,837.87	- 24.71	- 539,545.66	22,781,292.20
	20-30	14702.4	335.95	4703.3288	401.02	5614.342	481.46	14443.794	652.49	19574.7388	44336.20	503.82	14,702.40	26,515,117.44	- 26.23	- 572,599.47	25,942,517.97
20%	20-40	16473.6	334.61	4684.601	399.42	5591.9244	479.76	14392.801	649.82	19494.5592	44163.89	501.86	16,473.60	29,709,397.01	- 28.19	- 615,347.34	29,094,049.67
	30-10	12931.2	337.12	4719.6159	402.41	5633.7741	483.03	14490.949	655.25	19657.6373	44501.98	505.70	12,931.20	23,320,837.87	- 24.35	- 531,475.06	22,789,362.80
	30-20	14702.4	336.21	4706.8788	401.32	5618.4785	481.79	14453.844	653.06	19591.6511	44370.85	504.21	14,702.40	26,515,117.44	- 25.84	- 564,003.93	25,951,113.51
	30-30	16473.6	335.25	4693.4841	400.12	5601.6216	480.47	14414.228	650.90	19526.9828	44236.32	502.69	16,473.60	29,709,397.01	- 27.36	- 597,378.92	29,112,018.10
	30-40	18244.8	333.92	4674.9376	398.52	5579.3402	478.77	14363.042	648.24	19447.2663	44064.59	500.73	18,244.80	32,903,676.59	- 29.32	- 639,981.30	32,263,695.28
	40-10	14702.4	336.12	4705.7021	401.14	5615.9643	481.65	14449.462	653.06	19591.7511	44362.88	504.12	14,702.40	26,515,117.44	- 25.93	- 565,981.68	25,949,135.76
	40-20	16473.6	335.27	4693.7653	400.11	5601.5141	480.49	14414.645	651.05	19531.6098	44241.53	502.74	16,473.60	29,709,397.01	- 27.30	- 596,084.72	29,113,312.29
	40-30	18244.8	334.35	4680.9332	398.96	5585.4905	479.19	14375.759	648.98	19469.4217	44111.60	501.27	18,244.80	32,903,676.59	- 28.78	- 628,317.28	32,275,359.31
	40-40	20016	333.02	4662.3304	397.36	5563.0672	477.50	14324.976	646.30	19388.9276	43939.30	499.31	20,016.00	36,097,956.16	- 30.74	- 671,061.37	35,426,894.79
	10-10	12312	337.71	4727.9922	402.90	5640.5664	483.40	14501.968	655.68	19670.2753	44540.80	506.15	12,312.00	22,204,138.50	- 23.90	- 521,843.33	21,682,295.17
	10-20	14083.2	336.77	4714.8218	401.75	5624.5201	482.09	14462.842	653.44	19603.3319	44405.52	504.61	14,083.20	25,398,418.08	- 25.44	- 555,404.72	24,843,013.36
	10-30	15854.4	335.92	4702.8423	400.69	5609.6618	480.96	14428.724	651.60	19548.1189	44289.35	503.29	15,854.40	28,592,697.65	- 26.76	- 584,223.49	28,008,474.16
	10-40	17625.6	334.58	4684.1111	399.08	5587.0784	479.19	14375.847	648.83	19464.7668	44111.80	501.27	17,625.60	31,786,977.22	- 28.78	- 628,267.76	31,158,709.47
	20-10	14083.2	337.05	4718.6659	402.06	5628.8136	482.46	14473.769	654.17	19625.0959	44446.34	505.07	14,083.20	25,398,418.08	- 24.98	- 545,276.00	24,853,142.07
	20-20	15854.4	336.10	4705.4045	400.90	5612.5559	481.16	14434.91	651.94	19558.0901	44310.96	503.53	15,854.40	28,592,697.65	- 26.52	- 578,861.64	28,013,836.01
	20-30	17625.6	335.17	4692.4373	399.75	5596.4439	479.91	14397.413	649.88	19496.3643	44182.66	502.08	17,625.60	31,786,977.22	- 27.97	- 610,690.33	31,176,286.90
30%	20-40	19396.8	333.89	4674.4372	398.20	5574.7918	478.24	14347.255	647.29	19418.7295	44015.21	500.17	19,396.80	34,981,256.80	- 29.88	- 652,229.43	34,329,027.37
	30-10	15854.4	336.38	4709.3275	401.19	5616.6055	481.51	14445.26	652.69	19580.5631	44351.76	504.00	15,854.40	28,592,697.65	- 26.05	- 568,741.10	28,023,956.55
	30-20	17625.6	335.46	4696.4255	400.05	5600.7686	480.22	14406.622	650.53	19515.8381	44219.65	502.50	17,625.60	31,786,977.22	- 27.55	- 601,512.55	31,185,464.67
	30-30	19396.8	334.52	4683.2334	398.88	5584.2776	478.96	14368.906	648.45	19453.5454	44089.96	501.02	19,396.80	34,981,256.80	- 29.03	- 633,685.99	34,347,570.80
	30-40	21168	333.22	4665.0514	397.32	5562.4247	477.26	14317.67	645.81	19374.4151	43919.56	499.09	21,168.00	38,175,536.37	- 30.96	- 675,958.65	37,499,577.73
	40-10	17625.6	335.39	4695.4147	399.89	5598.3958	480.12	14403.478	650.49	19514.8454	44212.13	502.41	17,625.60	31,786,977.22	- 27.64	- 603,378.17	31,183,599.06
	40-20	19396.8	334.54	4683.5325	398.88	5584.2833	478.99	14369.733	648.50	19454.961	44092.51	501.05	19,396.80	34,981,256.80	- 29.00	- 633,053.98	34,348,202.82
	40-30	21168	333.61	4670.5119	397.71	5567.9391	477.70	14330.877	646.43	19392.9126	43962.24	499.57	21,168.00	38,175,536.37	- 30.48	- 665,370.90	37,510,165.48
	40-40	22939.2	332.31	4652.272	396.15	5546.0447	475.98	14279.356	643.76	19312.9182	43790.59	497.62	22,939.20	41,369,815.95	- 32.43	- 707,953.06	40,661,862.88
	10-10	15235.2	336.83	4715.5939	401.33	5618.6574	481.41	14442.408	652.34	19570.2363	44346.90	503.94	15,235.20	27,475,998.29	- 26.11	- 569,946.82	26,906,051.47
	10-20	17006.4	335.88	4702.3476	400.16	5602.2398	480.09	14402.74	650.01	19500.4425	44207.77	502.36	17,006.40	30,670,277.86	- 27.69	- 604,460.78	30,065,817.08
	10-30	18777.6	335.00	4690.0375	399.05	5586.6796	478.89	14366.73	648.06	19441.6638	44085.11	500.97	18,777.60	33,864,557.44	- 29.08	- 634,889.69	33,229,667.75
	10-40	20548.8	333.72	4672.1191	397.51	5565.0838	477.21	14316.45	645.47	19363.99	43917.64	499.06	20,548.80	37,058,837.01	- 30.99	- 676,434.45	36,382,402.56
	20-10	17006.4	336.12	4705.7144	400.44	5606.104	480.43	14412.933	650.81	19524.3797	44249.13	502.83	17,006.40	30,670,277.86	- 27.22	- 594,200.10	30,076,077.76
	20-20	18777.6	335.28	4693.8927	399.40	5591.6422	479.27	14377.999	648.81	19464.1536	44127.69	501.45	18,777.60	33,864,557.44	- 28.60	- 624,327.34	33,240,230.10
	20-30	20548.8	334.28	4679.9858	398.14	5573.9333	477.90	14336.88	646.56	19396.707	43987.51	499.86	20,548.80	37,058,837.01	- 30.19	- 659,103.12	36,399,733.89
40%	20-40	22320	332.99	4661.9211	396.58	5552.0962	476.20	14285.942	643.93	19318.0042	43817.96	497.93	22,320.00	40,253,116.58	- 32.12	- 701,162.57	39,551,954.01
	30-10	18777.6	335.48	4696.7518	399.58	5594.0933	479.49	14384.673	649.31	19479.3891	44154.91	501.76	18,777.60	33,864,557.44	- 28.29	- 617,574.83	33,246,982.61
	30-20	20548.8	334.55	4683.7152	398.43	5578.0184	478.19	14345.752	647.07	19412.0348	44019.52	500.22	20,548.80	37,058,837.01	- 29.83	- 651,160.90	36,407,676.11
	30-30	22320	333.65	4671.0456	397.29	5562.0743	476.98	14309.305	645.06	19351.94	43894.36	498.80	22,320.00	40,253,116.58	- 31.25	- 682,209.19	39,570,907.40
	30-40	24091.2	332.49	4654.8027	396.08	5545.1877	475.75	14272.475	643.25	19297.4146	43769.88	497.38	24,091.20	43,447,396.16	- 32.66	- 713,090.96	42,734,305.20
	40-10	20548.8	334.61	4684.5381	398.64	5580.8958	478.55	14356.561	647.90	19436.8881	44058.88	500.67	20,548.80	37,058,837.01	- 29.38	- 641,396.18	36,417,440.83
	40-20	22320	333.61	4670.5074	397.22	5561.1163	476.89	14306.81	644.99	19349.6397	43888.07	498.73	22,320.00	40,253,116.58	- 31.32	- 683,769.86	39,569,346.72
	40-30	24091.2	332.71	4657.9368	396.08	5545.1028	475.61	14268.356	642.92	19287.5498	43758.95	497.26	24,091.20	43,447,396.16	- 32.79	- 715,803.60	42,731,592.56
	40-40	25862.4	331.41	4639.749	394.52	5523.2165	473.91	14217.178	640.27	19208.0998	43588.24	495.32	25,862.40	46,641,675.73	- 34.73	- 758,150.74	45,883,524.99

* Only negative numbers in the last column "saving in initial cost vs. saving in running cost" indicates financial gains against the base case.

Sustainability: What's That, and So What?

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ABSTRACT

In this paper I try to do two things. One is to describe what is really important to understand about sustainability. Two is to relate that understanding to homes. I've been working on understanding and applying sustainability to engineering education and buildings for over 25 years. In my book in progress on sustainability, three key ideas are identified: growth, happiness, and nature. An overarching concept is that of connectedness – to each other, to our communities, and to nature. The paper will explore these ideas, including how our current beliefs and expectations changed with time. You could say that sustainability is a projection of those changing beliefs into the future.

We already see sustainability beginning to be expressed in housing. New home size is leveling off. I expect a gradual decline in size, reflecting both a decline in materialism, and a rise in being more connected outside the home. Along with that, homogeneous suburbs will give way to diverse neighborhoods with more multifamily, multigenerational households. Walking and being outdoors will lead to more parks and greenways. There will be lots more home gardens, community gardens and neighborhood workshops.

On the technology side, buildings will be better insulated and more air-tight, with integrated energy recovery systems, and high-efficiency heat pumps, for space heating and water heating. The house systems will include the family's electric cars and bicycles. Houses will be built to utilize sunlight for light, heat, and electricity, and outside air for ventilation and cooling. Overall we'll live in homes and neighborhoods that better fit our changing norms and visions of happiness and sustainability.

WHAT IS SUSTAINABILITY?

Sustainability emerged in the late 1980s from two other movements – environmentalism and human rights. The classic definition from the U.N.:

> *Sustainable development … meets the needs of the present without compromising the ability of future generations to meet their own needs.*
> (World Commission on Environment and Development)

It combines the idea that every person has basic human rights and *needs* for human fulfillment, along with a recognition that our efforts to live decent lives today can compromise what is possible in the future. Though we often think of sustainability being all about the environment, it is a more holistic answer to the question of how can we all live decent lives here on Earth. It recognizes that a healthy planet is needed for decent lives, now and into the future.

HOW DID WE GET HERE?

There were three key changes that all began with the Scientific Revolution in the 1500's. Things were happening in 16th century Europe that were blowing peoples' minds. The Protestant Reformation was underway, taking power from the Catholic Church, and emphasizing the power of each person to interpret scripture. Then Copernicus claimed that the Earth and other planets orbited around the sun. Think about it. Your daily experience of the Sun moving around the Earth is now in conflict with this new philosophy called science.

As the life of the mind, exemplified by logic and reason, was elevated, the life of the body and its felt connections to the living world was diminished. Spirit was gradually withdrawn from the world, left to reside only in humans. We began to see the world as merely a giant storehouse of stuff there for our taking.

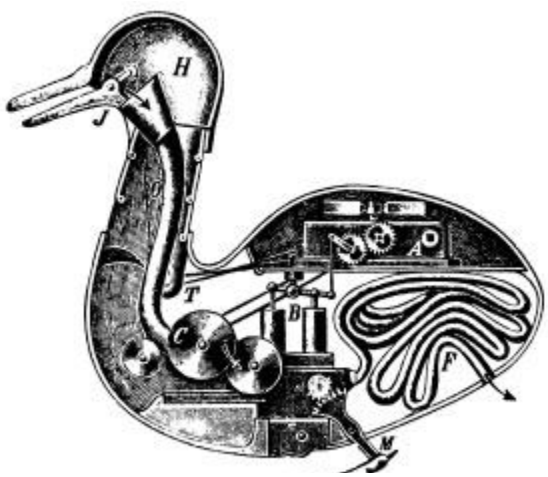

Figure 1 Descartes held that non-human animals could be reductively explained as automata (DesCartes).

Scientists were describing the creatures around us as nothing more than machines with feathery, furry, and scaly coats. The universe was just a gigantic machine, with its parts whirring around in space. The world became less meaningful as its life and spirit were withdrawn from human attention.

Then came another change that rocked the world – the idea of capitalism and its emphasis on material wealth and growth. When Adam Smith published *The Wealth of Nations* in 1776, the state controlled and regulated most of production and trade. With all of the respect that science and rational thought commanded at the time, Smith looked for basic rational principles of economics that were similar to scientific principles that were believed to govern and regulate the universe. His basic premise was that wealth was produced by land, labor, and capital, represented by the total output of goods and services. This concept of measuring wealth by total output, or production, came to be the standard we rely upon today, Gross Domestic Product (GDP).

Smith also proposed what has come to be known as the *virtuous cycle*. It is founded on the concept of *division of labor*. Instead of a worker making an entire product, a shoe for example, he only cuts the material. Another worker does the stitching, and another the sole, and so on. By each worker focusing on only one task, they can get really good at it, and do it fast. The result is that more shoes can be made by the same number of workers. Productivity increases and the increased profit can be reinvested in more productivity. It tends to ignore that a shoemaker's sense of accomplishment will be greatly diminished to be only a stitcher, or nailer. Now even people began to be treated like machines.

This system depends on growth and further productivity gains. Another fundamental change is that having more material goods and a less burdensome life became possible for a growing number of people. This shifted our attention from a good life after this one, to a good life right now. And it worked … for some of us.

It all literally picked up steam during the third key period in history, the Industrial Revolution. In the late 1700s and early 1800s in England, textile production that was typically done by craftspeople in their homes, was moved to factories and large weaving machines that could produce much more fabric per person. People began to move to the growing cities, further removing themselves from even domesticated animals. Yet for all of the growth and changes at the time, nobody could have imagined the next phase of the Scientific-Capitalistic-Industrial epoch.

The steam engine. Up until its development in the 1700s – for pumping water out of coal mines – the physical work of humanity was mainly provided by animals. That is the way it had been forever. Sure there were exceptions, like wind/water mills, and sailing ships, but the daily work to pull plows, harvest crops, and move about was animal power, including humans. The coal being mined at the time of the steam engine was used solely for burning to make heat for human comfort and for industry.

With the steam engine, we could now use heat from burning fuel to make work and power. The new coal-burning engines were put in factories, in ships, and then trains. Then came cars. Then electricity, delivering the awesome power to our homes.

Before engines and electricity, a horse was an important element of society. We even established the standard unit of power as a *horsepower*, meant to represent the rate a horse could work for some extended time. A horse is a powerful creature, especially when compared to us. A horsepower is equivalent to 746 Watts, or ¾ of a kilowatt. A human can steadily produce about 1/10 horsepower, or it takes 10 people to produce the daily work of one horse.

Look at what we are used to today. My electric leaf blower, plugged into an ordinary wall outlet, consumes 1,500 Watts of power. It is like having two healthy horses at my beck and call whenever I flip the switch. Two horses! My lawn mower is five-and-one-half horses. Even my small Kia Soul has 142 horses, and some would consider that not enough power. A 777 jet has a power equivalent to 220,000 horses. All in a culture that seldom experiences a living creature called a horse.

We think that is normal. What else do we think is normal after these three key periods in history?

- We need to have the power of hundreds of horses in order to be happy.
- We need growth in order to be happy.
- An easy life filled with conveniences is a normal aspiration.
- The other-than-human world is barely alive, spiritless, and mainly of value because of its use to humans.
- The benefits of modern society are worth the sacrifices.
- Sure there is still suffering, but that will be solved with more growth, and better technology.

SO WHAT'S WRONG?

This modern worldview does have its shimmer. If I'm in the lucky minority that has money and power, I'm materially well off. I have a nice house, at least one car, lots of gizmos and gadgets, good health insurance, and plenty of food. I may work long hours at a job that is not really fulfilling, but I justify it in the name of progress. To the average person in the wealthier countries, life is pretty good in these ways. Beyond stating the obvious about the majority of the world's people who are not materially well off, it's relevant to note that many of us who are materially well-off are less than satisfied. We have not found satisfying meaning in this convenient, well-stocked life. We're feeling a little duped. There's got to be more to life than maximization of personal preferences, and survival of the fittest.

But what also is wrong are the routine sacrifices we make of the more-than-human world: mountaintop removal, tar sands, climate change, eutrophication, species extinction, deforestation, etc. The best measure of all of those sacrifices is the ecological footprint [2]. Ecological footprint (EF) is a measure of the total bioproductive land and sea area that it takes to provide your resources and assimilate your wastes. In the United States, we typically have an EF that if everyone on Earth lived like us, it would take five planets.

Well that's a problem for a sustainable future.

About a year ago, I exchanged emails with an economist colleague who had published a report that claimed that the more money people make, the more satisfying is their life, and there is no evidence of satiation (Sacks). In other words, more money makes people happier, and this holds true for rich and poor. Their basic argument was that the best thing we can do regarding happiness is to continue to grow the economy.

I took their dataset and added in data on EF and got the result shown in Figure 2. The left vertical axis is the "satisfaction ladder score," the most widely used indicator of life satisfaction (0 is the worst life imaginable and 10 the best). This is the data that Sacks had published.

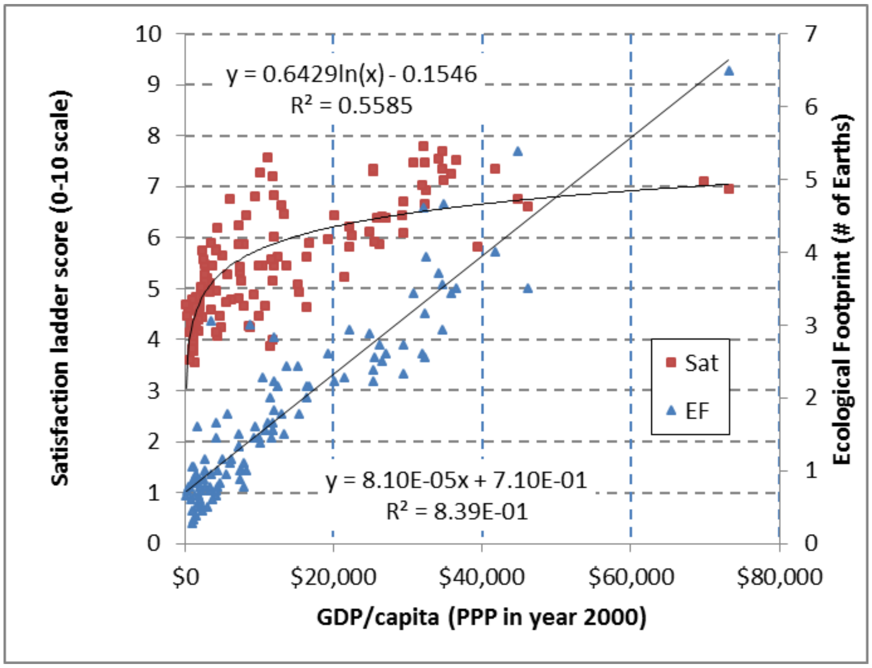

Figure 2 Country average life satisfaction and ecological footprint correlated to per capita GDP.

The right vertical axis is EF. Anything above one is not sustainable. When I pointed out that while country-average life satisfaction goes up with income, so does EF. In fact, it crosses one planet at a GDP/capita of about $4,000. The response was that the authors had never heard of EF.

Before we leave this graph though, there's three more relevant observations. One is that while satisfaction does correlate with income, it only explains about 56% of the variation in life satisfaction. There's a lot of other factors, one of the most important being the number and quality of relationships. Sustainability brings our attention to human relationships, as well as the larger world.

Secondly, there is an interesting grouping of countries with relatively low incomes, ~$10,000, that have satisfaction levels at the same high level (6-8) as countries with 3-4 times the income. These countries are for the most part in Central and South America. Clearly there are cultural, ethnic, and/or geographical factors that influence satisfaction. One could argue that instead of increasing income in countries like the U.S. (GDP/capita of $42,000, ladder average of 7.35), we should decrease income to countries like Venezuela ($11,200, 7.58). But that ignores all of the other factors that affect satisfaction.

A third observation is that while satisfaction goes up a lot at low incomes, it tends to level off as income increases. In fact, the two countries with the highest incomes, Luxembourg and Qatar, have satisfaction scores that are lower than many of the other countries with lower incomes. How could the economists have said that there is no evidence of satiation? Because they plotted satisfaction versus the log of income; see Figure 3.

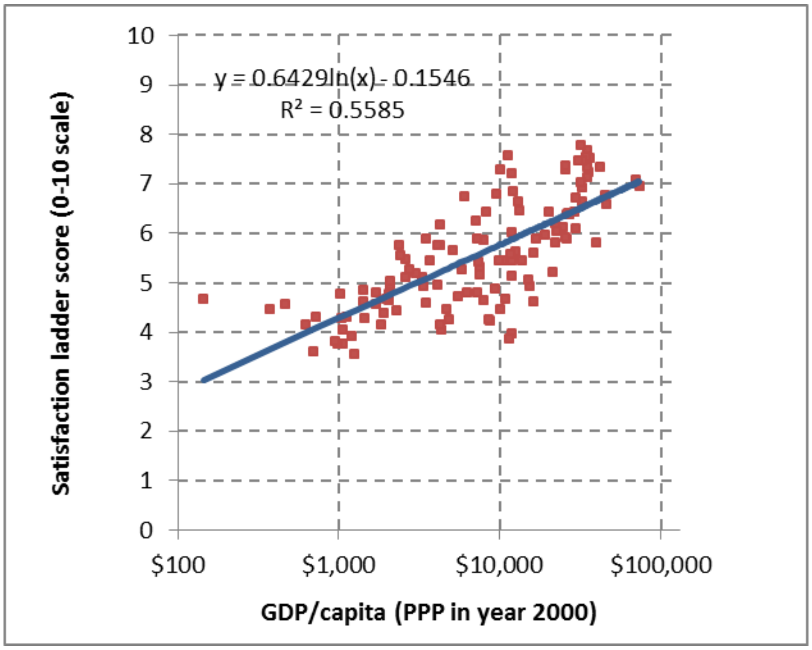

Figure 3 Country average satisfaction plotted versus log of income.

What changes here is that you don't see the leveling off. What the log plot does is make the data look like satisfaction just goes up and up with increasing income. It doesn't.

What it does say is that it takes ever increasing amounts of income to have a certain increase in satisfaction. As shown in Table 1, to go from 4 to 5 on the ladder score, the correlation equation says that income must go from $772 to $3,823, an increase of $3,051 and a factor of 4.9. To go from 5 to 6 requires an increase to $18,938, an increase of $15,115 and a factor of 4.9. Another way of saying that is that if a person making X amount a year wants to increase their life satisfaction by one ladder level, their income would have to increase by about a factor of nearly 5! That's pretty crazy, and a weak recommendation for making more money to be more satisfied with your life. Note that according to the correlation, to get to a ladder score of 9 would require an income of $2,300,000!

Table 1 Predicted ladder scores and associated income.

Ladder	GDP/capita
4	$772
5	$3,823
6	$18,938
7	$93,825
8	$464,840
9	$2,302,956
10	$11,409,535

Another way of looking at the correlation is suppose that someone made $500,000 a year. The same amount of increase in income that could raise that person's satisfaction, say one-tenth of a ladder level, could do the same for five people making $100,000.

Of course, while income does have some effect on life satisfaction, there is a lot more to it.

To conclude this section on what's wrong, we are exceeding the Earth's capacity to supply our resources and assimilate our wastes. The biocapacity of Earth is like our own household budget. If we spend more than our budget, we need to borrow but eventually need to live within our means. Right now, we're living on borrowed time. The global ecological footprint is now 1.6 Earths.

GETTING TO SUSTAINABILITY IN OUR HOMES

In the U.S., even if there was no growth in consumption, we need to reduce our environmental impact by a factor of 5. And we need to develop ways to ensure that every American has the capability to live a fulfilling life. Well that's a tall order. What might it mean for housing?

Sustainability draws our attention to the way one action affects another, and one technology connects to others. We begin to see that next to how many children we have, where and how we choose to live are the next biggest factors in our ecological impact. And where and how we live are also big factors in our happiness and life satisfaction.

> *Imagine. It's a beautiful July day in Pennsylvania in the year 2050 as I walk out into my yard to gather the wash from the clothesline. All around me the landscape flourishes. There's fruit on the peach and apple trees, and lots of little green walnuts on our young walnut tree. The sweet cherries are just finishing, but there's lots put away for the winter. After getting the wash, I pick as many juicy raspberries as I can on my way to move the "chicken tractor" to its new spot. But before moving it I gently retrieve 3 eggs from the nests. The four hens, Delores, Chickie-baby, Gaga, and Belle, are out in their yard pecking and scratching away …*

You're probably thinking: Hey, what does my yard and what's growing there have to do with housing and sustainability? Consider this. For the average American, what we eat and the way it's produced requires 7 units of fossil fuel energy for every 1 unit of food energy that we obtain from the food. And with more people and a worldwide increase in meat consumption, it's going to get worse globally.

Luckily here in Pennsylvania, we have a long tradition of growing and preserving food. Except for the chickens, that description of my yard describes the yards I knew growing up in Hanover in York County in the 1960s. Plus most of the alleys had mulberry bushes that were usually filled with sweet little berries for much of the summer.

The enlargement of home to include not just our house but also the yard where it lies, is a re-cognition of the interrelatedness of life, and a re-engagement with the processes of life. Sustainability has the greatest potential in our ability to see connections, and to see the bigger picture while also paying attention to the places we live.

It sounds like a step backward – the idea of growing food in our yards and preserving it for the winter. Why is that?

Part of our vision of material progress that we take for granted is that physical work is a burden, and that we should make life easier and more convenient. It sure is easier to just stop by the supermarket and buy a frozen dinner to microwave for dinner, than to plant a garden, care for it, clean the produce, preserve it, and then prepare it. Just like it's easier to just stuff wet clothes from the washing machine into a drying machine, turn it on, and pull out the warm clothes, than to carry the wet clothes outside, hang it on the line, and then gather it in when dry. And yes it's easier to turn the thermostat for heat than to chop wood, store it, bring it inside, light a fire, and keep it going. Easier yes. But what becomes of us humans if life was so easy?

I picture the people in the movie Wall-E who are very overweight and just float around in their levitating chairs watching a computer screen and drinking slushies. They live in space because they've destroyed life on Earth.

Part of the message of sustainability is that this disconnection from the living world that sustains us is how we became so unsustainable in the first place. The world matters. We are an integral part of that world, and we matter too.

In a similar way to including food when we think of where to live, we'll also pay more attention to transportation and services. For many, the idea of living someplace that requires driving a car will turn from an asset to a liability. So the old real estate adage of "location, location, location" may need another "location."

SELF-HEATED HOUSES

Here's a little secret that most of us in the high-performance home field know. A well-insulated, air-tight (with energy recovery), smaller home can pretty much heat itself. In Pennsylvania.

Note that I did not say that it does not use electricity. In fact, the increased electricity use for electrical devices, and its associated heat, is what has reduced the need for additional heat. Even with high insulation and air tightness, a home will still lose some heat in cold weather. A lot of that heat comes from all of the electrical uses around the house. Think about it. For most appliances that are not exhausted, all of the electricity that goes into them becomes heat inside the house. While thermal integrity has steadily increased over the last 40 years, there has been an increase in the number of electrical devices, and that translates to more heat.

Figure 4 shows a breakdown of the modeled electricity use in a 1,200 ft^2 high-efficiency ranch home in Philadelphia heated with a high-efficiency heat pump. The heating only accounted for 7% of the annual electric load. That's good news and bad. It's good because it means less fuel burned to heat the house, or less electricity used to run a heat pump. It's potentially bad for two bigger picture reasons. One is that at best, the heat given off by our electrical devices is 100% efficient. On the other hand, a high-efficiency heat pump can operate at an effective seasonal heating efficiency of

250%. I'd much rather heat with that heat pump than with my TV. But of course, the TV provides me some other service than simply heat (or does it?).

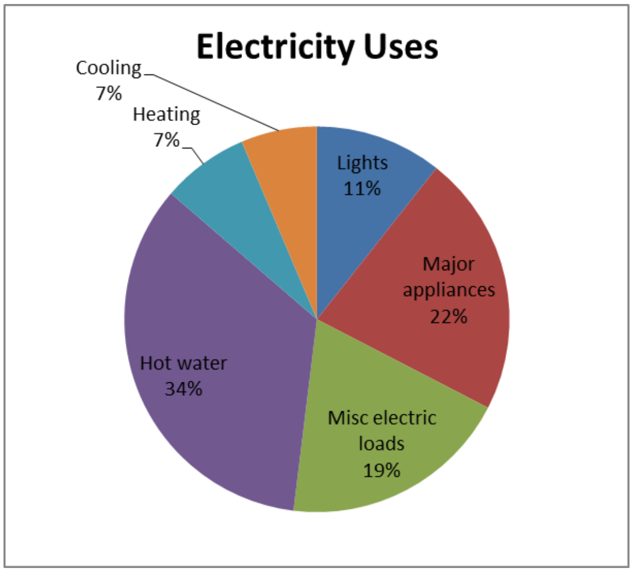

Figure 4 End uses of electricity in a small, high-performance home.

WATER HEATING

In a high-performance home, the energy required to heat water for use around the home is the largest heating load. We've got to be smarter about heating water than using electric resistance elements.

I started practicing engineering during the heyday of solar activity in the 1970s. One of the technologies promoted then, and just as relevant today, is solar water heaters. These thermal systems heat water, or antifreeze, in a collector outside, and then pump that fluid inside to be stored in a tank. The systems typically provide for 2/3 of the annual water heating needs. A typical family of four would need two collector panels, each about 4'x8'. Cost is about $5,000 to $8,000 and annual savings are about $200-$400 (compared to a conventional electric water heater).

A new player in water heating is the heat pump water heater (HPWH). Instead of electric resistance coils to heat the water, a heat pump is used. The heat pump obtains heat from the air surrounding it, so it cools the surroundings. In humid conditions, it also dehumidifies the surrounding air. This presents some interesting challenges in comparing it with a conventional electric (resistance) water heater, and with a solar water heater.

There's two basic places to put a HPWH, in the conditioned space, like an interior mechanical closet or in a conditioned basement, or in unconditioned space, like a basement. If you put it in conditioned space, then the heat it "pumps" into the water comes from the house heat system. So the overall efficiency depends on both the HPWH and the house heating system.

HPWH in Conditioned Space

For heat pumps, the common measure of efficiency is the COP, Coefficient of Performance. It is defined as the heating or cooling rate divided by the electrical power, and it is a dimensionless number – the same units are used for heating/cooling and electricity. The COP depends on the outdoor and indoor conditions, so for estimating seasonal performance, we use HSPF for heating, and SEER for cooling.

HSPF = heating seasonal performance factor = $COP_{avg,htg}$ (3.413 Btu/Whr)

SEER = seasonal energy efficiency ratio = $COP_{avg,clg}$ (3.413 Btu/Whr)

The HSPF for a heat pump is lower than the SEER because the temperature differences are greater in the heating season, e.g., 70-30=40 ^oF, than in the cooling season, e.g., 90-75=15 ^oF. Plus the heat pump must defrost when heating, and can use supplemental electric resistance heat in very cold weather. These days an efficient heat pump has an HSPF > 10 ($COP_{avg,htg}$ = 2.9) and SEER > 20 ($COP_{avg,clg}$ = 5.9).

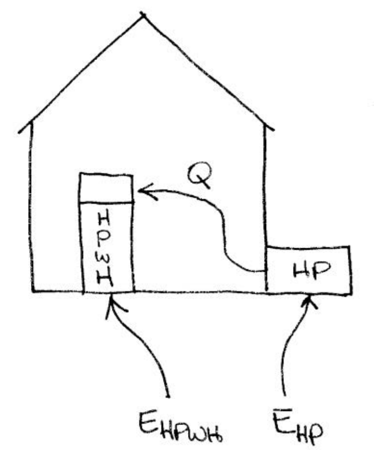

Figure 5 Schematic of house with a HPWH in conditioned space.

The easiest case to consider is a house with electric baseboard heat. A HPWH in this house, in the winter, will operate at an effective efficiency of 100%. As you can see in the diagram, the heat, Q, it pumps into the water was obtained from the baseboard (not heat pump in this case) at 100% efficiency, and the added heat from the compressor in the HPWH is also 100% efficient. So there is no difference – in the heating season – between a HPWH and a regular water heater, for a house with electric baseboard (or ceiling cable) heat. There is some cooling benefit in the cooling season.

Now when the house is heated with a heat pump, the thermodynamics works out to this:

$$COP_{TOTAL} = COP_{HPWH} [COP_{HP} / (COP_{HP} + COP_{HPWH} - 1)]$$

Let's say $COP_{HPWH} = 3.0$, then Figure 6 shows the overall system COP_{TOTAL}.

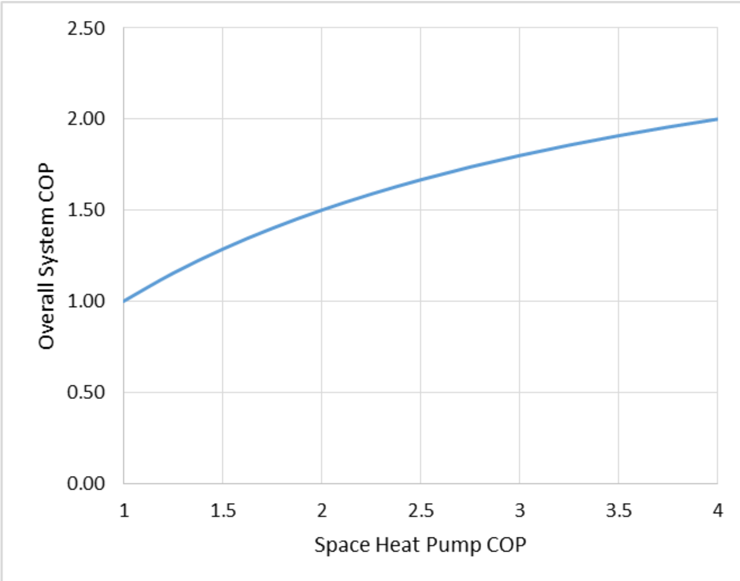

Figure 6 Overall COP for a HPWH with COP of 3 located in conditioned space.

The system efficiency is not as good as the HPWH itself, but it is still better than 1. Note too that even though the HPWH has a COP of 3.0, the overall system COP is no higher than 2.0, when the space heat HP has a COP of 4.0. For a seasonal COP of 2, the overall system COP is about 1.5.

HPWH in Unconditioned Space

What happens when the HPWH is in an unconditioned basement? Well there are two basic situations here. One is where the unconditioned basement is insulated from the conditioned part of the house, like with insulation in the basement ceiling. The other case is where there is no insulation between the basement and the upper floor.

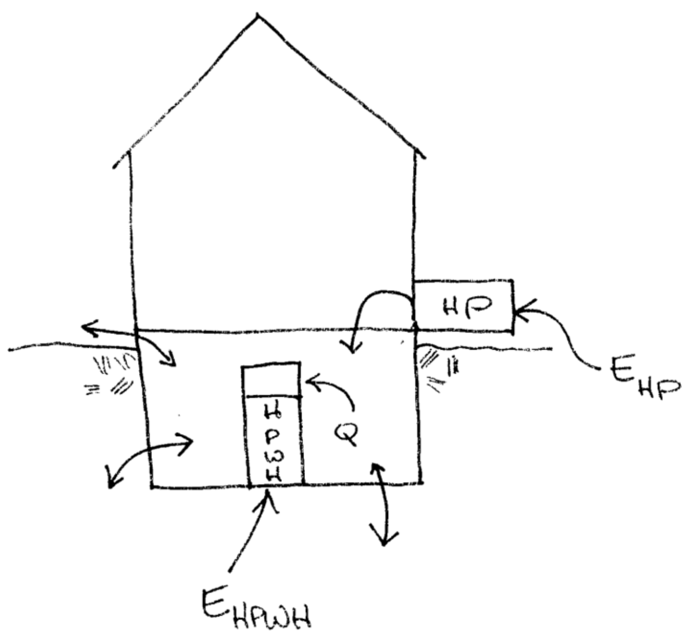

Figure 7 Schematic of a HPWH located in an unconditioned basement.

As you can see in Figure 7, the heat, Q, for heating the water comes from the basement air. That will end up reducing the temperature in the basement. The heat for the HPWH has to come from somewhere, so the basement air will be cooled, and that will draw heat both from the surrounding ground, and the conditioned spaces that are adjacent to the basement. When there is insulation present, the heat will be drawn more from the surrounding ground and the basement will get its coolest. There will be some additional heat that flows through the insulated floor. There is also a small amount of infiltration from outside.

When there is no insulation in the floor, the basement will not get as cool as heat will readily flow through the floor. But this reduced temperature will cause more heat to be needed than in the case of an insulated floor. Again, looking at the system effects is important to compare systems.

A year ago, two senior engineering students investigated the performance of HPWHs in unconditioned basements. They used a basic energy balance on a basement considering heat transfer from below-grade walls and floor, above grade walls and windows, the basement ceiling, and infiltration from outside. Here's what they found the effect to be on basement temperatures. These results are not intended to represent all possible situations, and the real basement will have thermal mass effects both in the masonry walls and floor, as well as the earth it is in contact with. Yet these steady-state results do provide some indication of the effect on the overall efficiency.

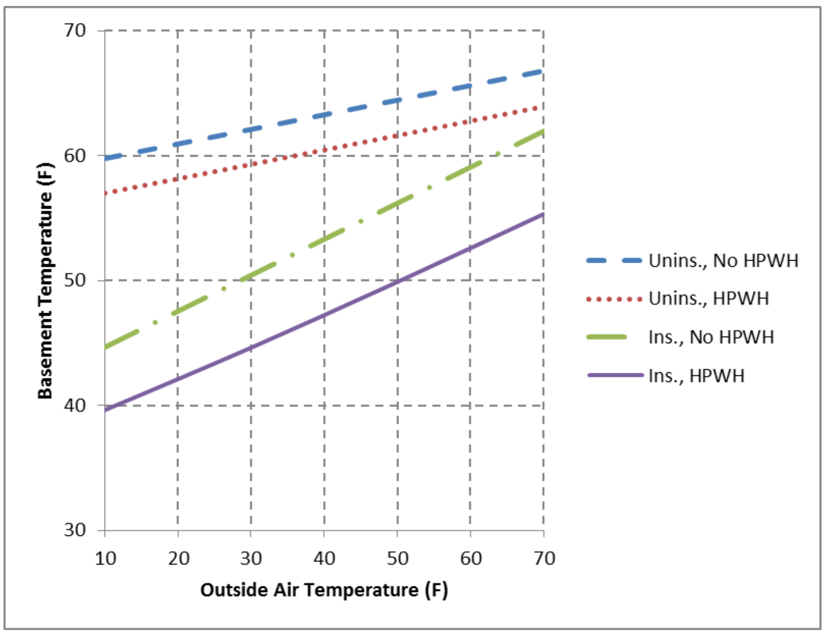

Figure 8 Unconditioned basement temperatures as affected by a HPWH.

Looking at the top two curves in Figure 8 for an uninsulated ceiling, you can see that the HPWH depresses the basement temperature by about 3 °F. That will result in an increased heat loss through the floor above on the order of 20% in winter, reducing the overall COP of the HPWH system.

Also for all cases, the steady-state basement temperature drops as the outside air temperature drops. This will reduce the HPWH efficiency in colder weather.

For the insulated ceiling cases, the basement is considerably colder. And the HPWH depresses the temperature 5-7 °F, about twice as much as for the uninsulated ceiling.

These temperatures were used with two types of space heating systems for the conditioned floor above, baseboard electric heat, and a high efficiency heat pump with a COP 0f 4.0 at 60 °F outside, and 2.0 at 20 °F. The COP characteristic for the

HPWH was obtained from one manufacturer's rated performance. It has a COP of 2.8 at 70 °F. The resulting overall system COP is plotted in Figure 9.

As we should expect, the lowest COP occurs when the basement ceiling is uninsulated and there is baseboard heat in the space above. A lot of the heat for the HPWH comes through the ceiling and the floor above. For this case, there is a slight improvement in COP over a conventional water heater (COP = 1), but only by about 25%.

If the basement ceiling is insulated with baseboard heat above, then there is marked improvement in COP, as less heat can come through the ceiling. Over the range of outside temperatures, COP is from 1.5 to 1.8 times conventional.

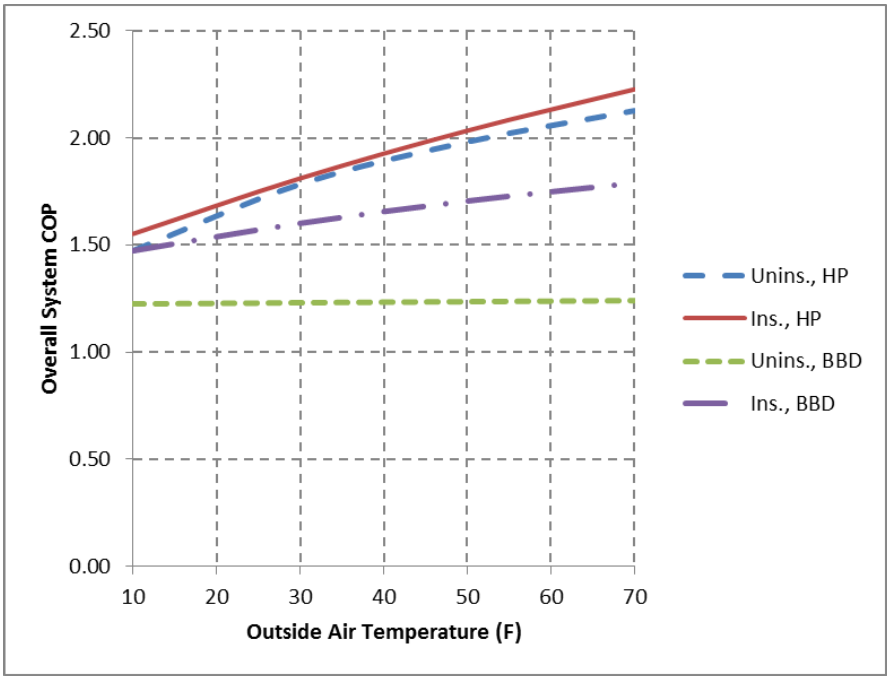

Figure 9 Overall efficiency of a HPWH located in an unconditioned basement.

When there is a heat pump in the conditioned space above, the highest HPWH efficiencies are obtained. Interestingly, there is little effect of the insulation in the floor. Here, the COP ranges from about 1.5 to 2.2 times conventional. Recall that the HPWH alone has a COP of 2.9 at room temperature. Also recall that for a high efficiency heat pump and the HPWH in conditioned space, the overall system COP was 2.0.

What about the cooling season? If the HPWH is in the conditioned space then it acts like a window air conditioner that dumps its heat into the water rather than the outside air. So if you need air conditioning, the HPWH provides a certain amount, and as a bonus heats your water too. If located in an unconditioned basement, it also helps to dehumidify the space.

By considering the HPWH as a system, we've learned this (for the heating season):

1. A HPWH is always equal to, or more, efficient than a conventional water heater with electric resistance elements.
2. How much more efficient depends. By itself, a HPWH has a COP of around 3. The specific model in this report had a COP of 2.9 at a surroundings temperature of 70 ^{o}F. It will not operate that efficiently though, because it draws heat from its surroundings. In the heating season, all or part of that heat comes from the house space heating system.

Table 2 Estimated system efficiency of a heat pump water heater in different circumstances.

<table>
<tr><th>Location</th><th>Type of Space Heat</th><th>Basement ceiling</th><th>System COP</th></tr>
<tr><td rowspan="2">Conditioned space</td><td colspan="2">Electric resistance</td><td>1.0</td></tr>
<tr><td colspan="2">Heat pump</td><td>1.5</td></tr>
<tr><td rowspan="4">Unconditioned space</td><td rowspan="2">Electric resistance</td><td>Uninsulated ceiling</td><td>1.3</td></tr>
<tr><td>Insulated ceiling</td><td>1.7</td></tr>
<tr><td rowspan="2">Heat pump</td><td>Uninsulated ceiling</td><td>1.9</td></tr>
<tr><td>Insulated ceiling</td><td>1.9</td></tr>
</table>

It is possible to compare HPWH with a solar water heater if we imagine that for the HPWH, we determine how big a solar electric array would have to be to provide the electricity that the HPWH system uses. Since the solar thermal water heater only provides about 2/3 of the annual needs, we'll have the HPWH system solar electric array sized to provide 2/3 of the annual needs. Then we're comparing apples with apples with solar as the source.

If we assume a typical new house with an efficient heat pump for space heat, then we'll assume the system COP is 2.0 (gives some credit to the cooling/dehumidifying benefit). A solar electric array size of 1,200 W would provide about 2/3 of the annual usage of a HPWH with a system COP of 2.0. At today's average installed cost of $5/W, that is about $6,000, plus about $600 extra for the HPWH, for a total of about $6,600. That's right in the ballpark of solar thermal system cost today. Solar electric costs will continue to come down so this system will look better and better down the road.

SMALLER HOUSES

In general, housing sizes have steadily increased, even though the number of people in each household has decreased; see Figure 10. Why? Is it growth for growth's sake, or do larger houses contribute to more fulfilling lives? This trend will surely reach a high point, and may be there already. Beyond a certain size, there is just too much house to clean, heat, and maintain. No matter what the Joneses are doing.

And even though our bigger houses may be the best insulated and tightly sealed ever, we still use more electricity than ever thanks to the many electrical devices in our homes, and a transition from fuel oil and natural gas to electric heat pumps. As shown in Figure 11, the significant increase in house size over the last 30 years has resulted in houses that use about 20% more energy than those built in the 1980s.

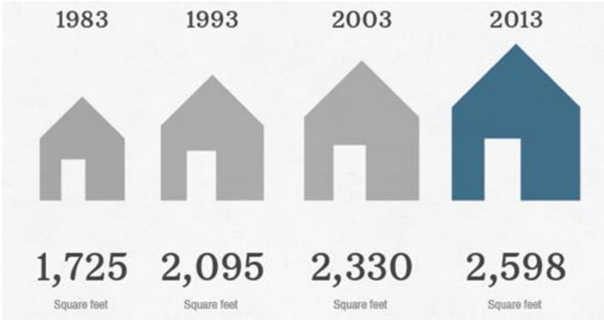

Figure 10 Average home size in the U.S.

One sign that our housing size expectations may be changing is the Tiny House movement. People are choosing to build and live in houses that are on the order of 500 square feet! In Portland, Oregon, one in ten new homes is less than 800 square feet. I love to watch this show on TV and observe both the ingenious ways of combining functions with compact furniture designs, and the change in lifestyle of the people who move into them.

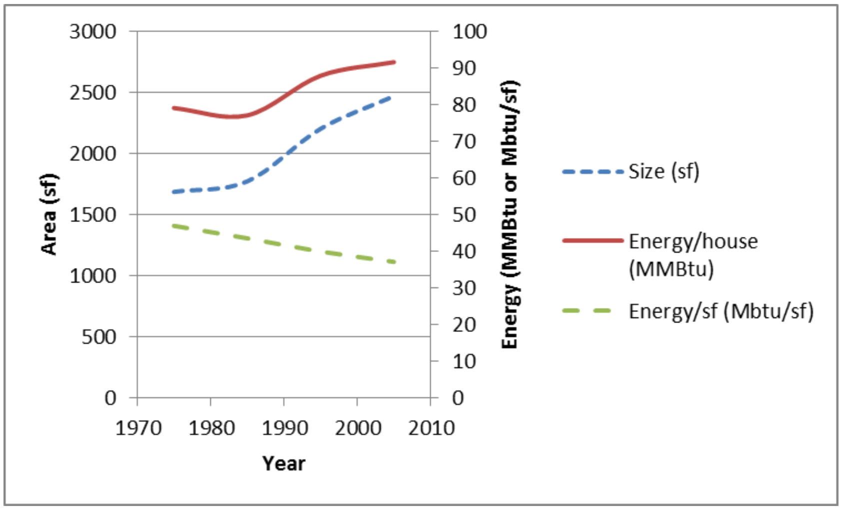

Figure 11 Trends in house size, energy efficiency, and overall energy use.

One of the biggest changes is that they spend more time outside their home. The money that they saved in the cost of their home allows the homeowners to invest in other ways to fulfill their lives: travel, education, gardening, cooking, less paid work, and more time with family. This is the human development side of sustainability.

Consider the bigger message here. People opting for smaller homes are living better, happier lives. They are reducing their negative impact on Earth too. From an economic standpoint they are paring down, what we might call *degrowth*.

In my book-in-progress, I imagine a time 50 years from now in the year 2066. As sustainability gets to be part of our way of life, our lives continue to change for the better. Suburbs like Park Forest here in State College, are rebuilt to better mirror our aspirations and human needs. Houses that are still in good shape are turned from 2,500 square foot, single-family homes into two to three-unit multifamily homes. Many of these units are multi-generational with grandparents, parents and an adult child and their family. Gradually, the average home size decreases to just around 1,000 square feet as shown in Figure 12.

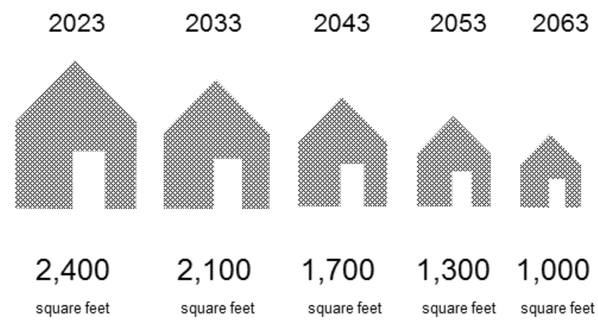

Figure 12 House size projection in a sustainable future.

Figure 13 Small house for added living space (http://www.medcottage.com/products.php)

Some small houses are added to yards where appropriate to add living options like this one already being offered today. This 299 square foot cottage is intended for accommodating an aging parent. It provides some independence while having them close by their families.

To help make smaller spaces more useable, companies will design and make multiple-use furnishings. There's pull-down beds, with desks when the bed is up. Expandable tables with chairs stored within. Architects and interior designers will use clever design to make the smaller spaces feel homey and comfortable.

Another big change imagined in 2050 is the greater prevalence of mixed-use of land. Now we have coffee shops, fix-it cooperatives, offices, micro-bakeries, tiny restaurants, and neighborhood gardens.

SMALLER REFRIGERATORS

Just like house size, I expect the size of our refrigerators to shrink. I did a survey of products in the internet and summarized their characteristics in Figure 14. One observation is that the largest one uses 2.4 times as much electricity as the smallest one shown. It's also interesting that the smallest unit is more expensive to purchase.

Figure 14 Range of refrigerator sizes in 2015.

CONCLUDING REMARKS

The triple play of the last 500 years of history – science, capitalism, and industrialization – has led to unprecedented material wealth, for some. Yet the very growth and consumption that fueled the economic success has also led to unprecedented environmental impact. The dream of sustainability challenges us to create a world where all people can live decent lives, and live within the planetary limits for a healthy Earth.

In the U.S., we need to build homes, neighborhoods, and communities that attend to the aims of sustainability. That will mean smaller, highly-efficient homes, more diverse neighborhoods, food-producing yards, and more time spent outside. Remember, we are talking about reducing our negative impact on Earth by a factor of 5. And that assumes no overall growth in income or consumption.

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Effects of Exterior Insulation on Moisture Performance of Wood-Frame Walls in the Pacific Northwest: Measurements and Hygrothermal Modeling

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ABSTRACT

Continuous exterior insulation on above-grade walls is becoming more common in many parts of North America. It is generally accepted that exterior insulation provides advantages for energy performance, by reducing thermal bridging, and for moisture performance, by warming the wood structural members, thereby reducing the potential for wintertime moisture accumulation. However, the effects of vapor-tight rigid foam insulation on the drying capability of the wall systems are not fully understood. In this study, temperature and moisture conditions in north-facing and south-facing wall assemblies with vapor-open and vapor-tight exterior insulation were monitored in a natural exposure test facility in the Marine 4 Climate Zone over a two-year period. The wall assemblies included interior gypsum board with latex primer and paint, 2×4 framing with nominal R-13 batt insulation, 11 mm (7/16 in.) oriented strand board, nominal R-5 exterior insulation, and white-color vinyl siding. Exterior insulation was either extruded polystyrene or mineral wool. Measurements and hygrothermal simulations indicated that walls with extruded polystyrene and mineral wool exterior insulation in north and south orientations perform similarly. Moisture content in wood framing and oriented strand board were within safe levels.

INTRODUCTION

Long-term moisture performance of exterior wall assemblies is a key consideration for contemporary energy-efficient housing. Designers and builders of wood-frame walls have a host of insulation materials and configurations to choose from. Continuous exterior insulation is becoming more common in many parts of North America. Although considerable research has been conducted on exterior insulation in wood-frame walls, further work is needed to provide a quantitative basis to minimize the risk of moisture performance and durability problems.

Climate characteristics can have a substantial influence on moisture dynamics in walls. Marine climates, as defined by Lstiburek (2004) and adopted by the U.S.

Department of Energy (n.d.), typically have cool, rainy winters and mild, dry summers. The moisture response of the building envelope depends on exposure to local environmental conditions, such as wind-driven rain, solar radiation, temperature, and humidity, as well as the interior humidity levels.

Moisture control strategies for exterior wall assemblies address the various sources of moisture interior and exterior of the building and the ways in which moisture migrates (TenWolde and Rose 1996). Exterior water management is critical to avoid bulk water intrusion. A continuous air barrier system minimizes moisture accumulation caused by uncontrolled air leakage. Vapor diffusion control strategies vary according to climate and properties of the materials in the assembly (Lstiburek 2004). In addition, wall assemblies should have the ability to dry out if they get wet (either during construction or during their service life). Drying potential is often a concern for wall assemblies that are insulated and air sealed to levels required by current model energy codes (Lstiburek 2013), such as the International Energy Conservation Code (IECC) (ICC 2015a). Drying potential depends not only on the configuration of the wall assembly but also on the climate. The marine climate of the Pacific Northwest has extremely low drying potential during the cool, rainy months (Desjarlais et al. 2001).

Continuous exterior insulation raises the temperature of wood structural members in exterior walls during cold weather, relative to walls without exterior insulation, thereby reducing the potential for wintertime moisture accumulation (Tsongas 1991, Straube 2011). This thermal effect reduces the vulnerability of the wall to water vapor migration from the interior carried either by air leakage or vapor diffusion. Exterior insulation materials of different types vary in vapor permeability; mineral wool, for example, is highly vapor-open whereas rigid foam insulation is typically vapor-tight. Vapor-tight exterior insulation may limit the outward drying potential of wall systems (Lstiburek 2013).

Hygrothermal modeling has been used to simulate drying of wall assemblies under specific climatic conditions. Smegal and Straube (2011) simulated the drying of plywood sheathing in 2×6 wood-frame walls in the climate of Portland, Oregon (zone 4C) with two types of exterior insulation. Walls with vapor-open mineral wool (MW) dried out faster than walls with vapor-tight extruded polystyrene (XPS). Glass (2013) found the same trend for 2×4 walls with oriented strand board (OSB) sheathing simulated in the mixed-humid climate of Baltimore, Maryland (zone 4A).

Two recent wall monitoring studies in the marine climate of the Pacific Northwest have investigated performance of exterior insulation in controlled test huts. Tichy and Murray (2007) examined a range of wood-frame walls with a test facility on the campus of Washington State University, located in Puyallup, Washington. They found that stucco-clad walls with 25 mm (1 in.) thick rigid XPS over OSB, 2×4 framing with nominal R-13 glass fiber batt insulation, and a “smart” vapor retarder resulted in lower moisture levels than a comparable wall without XPS but with 2×6 framing and R-21 batt insulation. The walls with XPS dried at a rate similar to the wall without XPS after the interior side of the OSB had been wetted with a controlled dose of water.

Smegal et al. (2013) compared three configurations of stucco-clad walls in a test hut in Coquitlam, British Columbia. All three configurations had OSB sheathing, 2×6 framing, and glass fiber batt cavity insulation. The first wall had stucco cladding installed over backerboard on 19 mm (3/4 in.) furring strips, creating a ventilated cavity. The second had the stucco cladding directly applied over a single layer of building paper. Both of these had an interior polyethylene vapor barrier. The third wall included 38 mm (1.5 in.) XPS to the exterior of the OSB sheathing with a corrugated housewrap between the two; this wall did not include interior polyethylene. Baseline OSB moisture contents were similar for the wall with ventilated stucco and the wall with XPS, but were considerably higher for the wall with direct-applied stucco. Controlled liquid-water wettings to the interior and exterior of the OSB sheathing were conducted five times over a period of two years. Following the interior wetting, the OSB sheathing in the wall with ventilated stucco and the wall with XPS dried at a similar rate, and both dried faster than the wall with direct-applied stucco. Following the exterior wetting events, the wall with ventilated stucco cladding dried more rapidly than the wall with XPS, which dried at a rate similar to the wall with direct-applied stucco. The wall with XPS, however, returned to a lower OSB moisture content than the wall with direct-applied stucco.

A joint research project was initiated in 2011 by APA – The Engineered Wood Association and the USDA Forest Products Laboratory to study the structural and hygrothermal performance of wood-frame walls with wood structural panel sheathing and rigid foam insulation (Yeh et al. 2014). This project builds on the studies discussed above by comparing 2×4 walls with no interior vapor retarder (other than latex paint) but with two types of exterior insulation: vapor-open MW and vapor-tight XPS. The project included two phases of hygrothermal monitoring in the Marine 4 climate zone. Phase I was conducted from February 2012 through February 2013 and Phase II from March 2013 through July 2014. An artificial water injection into the wall cavity was introduced in Phase II to simulate water leakage and to evaluate the rate of drying under natural conditions. This paper summarizes the project and additionally evaluates the capability of hygrothermal modeling software to predict the moisture performance of the wall systems.

EXPERIMENTAL METHODS

The evaluation of full-scale wall assemblies was conducted at the Natural Exposure Testing (NET) facility located on the Washington State University Agriculture Research campus in Puyallup, Pierce County, Washington (Tichy and Murray 2007). This location is classified as the Marine 4 climate zone (or 4C) in accordance with the IECC. The facility is about 15 km southeast of Tacoma, Washington.

Description of test facility. The NET facility was located to provide maximum exposure of test walls facing south and north. South-facing walls receive the highest exposure to wind-driven rainfall, which occurs primarily in autumn and winter. North-facing walls are exposed to limited wind-driven rain but lack direct exposure to sun in the winter, setting up an alternative critical condition. The building is in an open field with no obstructions within 400 m (1300 ft) of the south-facing wall. To the north, there are a few one-story buildings located 60 m (200 ft) or more away.

The NET facility is a 4.3 m × 21 m (14 ft × 70 ft) one-story building designed using open beam construction to maximize openings for test walls in segments (Figure 1). Each long side features 12 pairs of 1.2 m (4 ft) wide by 2.7 m (9 ft) high bays for installation of test wall sections. A 2 ft high insulated knee wall was poured with a slab on grade. The building's structural frame was constructed with structural insulated panels (SIPs). Two 10.7 m (35 ft) long structural composite lumber (SCL) beams were used to support the roof panels. SIP construction was used to facilitate air tightness and provide required insulation performance. Roof overhangs were limited to approximately 250 mm (10 in.) to allow appreciable exposure of the test walls to the weather. Gutters were provided to collect run-off rain water from the roof.

The NET facility is segmented into two 4.3 m × 10.7 m (14 ft × 35 ft) rooms with temperature and humidity control systems for each. This was done to allow creation of different interior environments in each of the two rooms when necessary. Each room is equipped with an independent electric heating unit, wall mount air conditioner, and humidifier/dehumidifier. A plan view of the building is shown in Figure 1 and the southwest elevation is pictured in Figure 2.

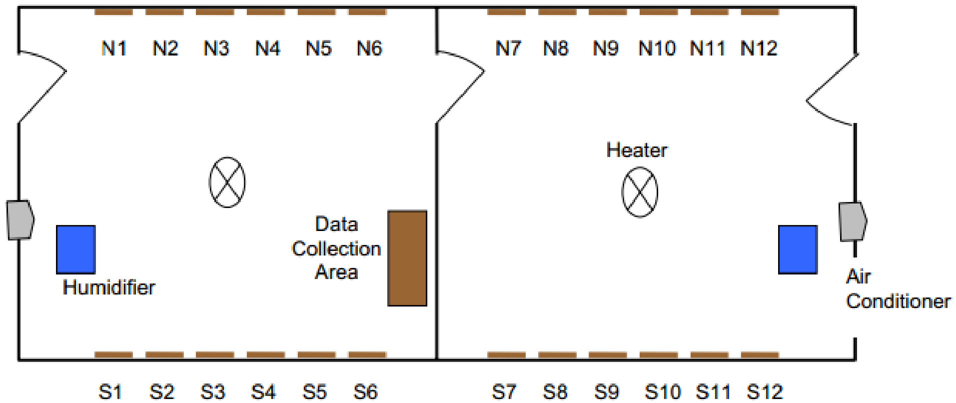

Figure 1. Floor plan of the NET facility

Figure 2. NET facility viewed from the southwest

Wall configurations. Two primary wall configurations were monitored for this study, each duplicated in north and south orientations (Table 1). The four wall assemblies were constructed based on a 4-foot by 9-foot design using standard 38 mm × 89 mm (nominal 2×4) kiln-dried Douglas-fir dimension lumber. The walls included a double top plate and a single bottom plate placed on a floor plate and rim board. This frame design provides two 368 mm × 2.32 m (14.5 in. × 91.5 in.) primary wall cavities that are protected from edge effects by smaller buffer cavities (Figure 3). The floor plate was insulated to the interior to separate the bottom plate of the test wall from the foundation.

Table 1. Test wall configurations

Wall	Orientation	Exterior Insulation	Water-Resistive Barrier
N7 S11	North South	25 mm (1 in.) XPS[a]	Taped XPS
N8 S12	North South	32 mm (1.25 in.) MW[b]	Spun-bonded polyolefin housewrap

[a] Extruded polystyrene
[b] Mineral wool

All assemblies had structural panel sheathing on the exterior of the framing consisting of 11 mm (7/16 in. Performance Category) OSB made primarily from aspen. Wall cavity insulation was glass fiber batt insulation with no facing in all cases; nominal thermal resistance was 2.3 $m^2 \cdot K/W$ (13 $h \cdot ft^2 \cdot °F/Btu$) for 89 mm (3.5 in.) thickness. All walls had 12.5 mm (1/2 in.) interior gypsum board, which was finished with one coat of latex primer and two coats of latex paint. None of the walls had any additional interior vapor retarder. Use of latex paint for interior vapor control in walls with sufficient exterior insulation is permitted by the International Residential Code (IRC) (ICC 2015b), which considers latex paint a Class III vapor retarder, having a dry cup vapor permeance in the range from 57 to 570 $ng/(Pa \cdot s \cdot m^2)$ (1 to 10 perms) (Lstiburek 2004).

For the walls constructed with mineral wool exterior insulation, a spun-bonded polyolefin house wrap was applied to the OSB sheathing prior to installation of the MW insulation. For the walls with XPS exterior insulation, no house wrap was applied; the joints between XPS rigid boards were taped with sheathing tape on the exterior surface to function as the water-resistive barrier. All walls were clad with vinyl siding, white in color, which was fastened through the exterior rigid insulation into the wood studs.

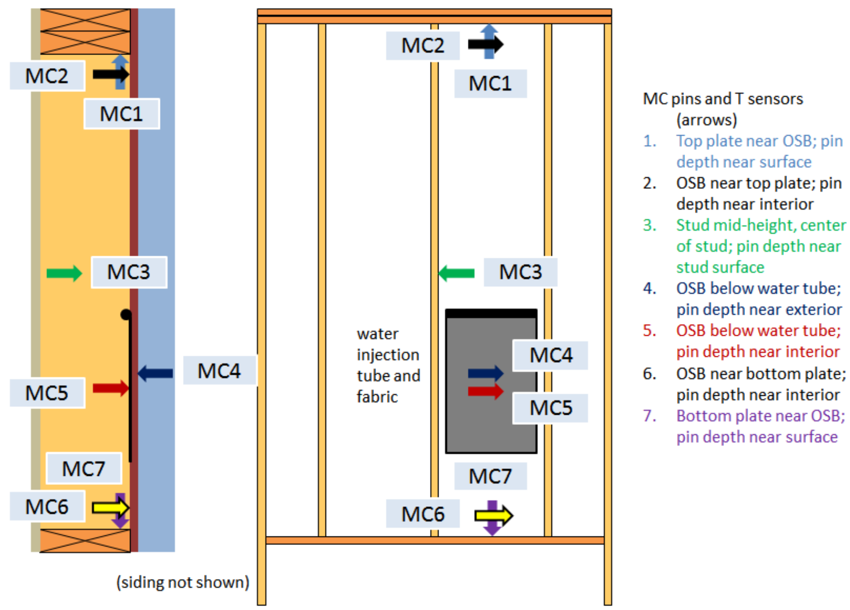

Figure 3. Placement of moisture content/temperature sensors

Wall assembly instrumentation. A data acquisition system was installed to monitor the hygrothermal performance of the test walls as well as indoor and outdoor environmental conditions. Sampling occurred every 5 minutes and values were averaged hourly.

Wood moisture content (MC) was measured in the framing and OSB sheathing at seven locations (Figure 3). Each location had a pair of moisture pins (brass nails) installed in the wood member 25 mm (1 in.) apart to obtain an electrical conductance reading related to substrate moisture content. The nails were coated with an electrical insulating coating to limit the measurement to the tip of the sensor. Pin pairs were typically inserted to a depth of 3 mm (1/8 in.) with the exception of the pair that was inserted to reach 3 mm (1/8 in.) from the exterior surface of the OSB.

Each moisture pin pair was partnered with a temperature sensor (thermistor) with an accuracy of 0.2°C (0.36°F). All moisture content readings were corrected for temperature and species based on Straube et al. (2002). The measurement uncertainty was estimated to be ±2% MC between 10% and 25% MC.

Relative humidity (RH) levels were also measured using capacitance-type humidity sensors at six locations in each wall assembly, with temperature sensors at the same locations. Further detail on these measurements can be found in the project report (Yeh et al. 2014).

Water injections. To provide additional field data on the drying performance of the test walls, Phase II of this study (March 2013 through July 2014) included simulated water leakage into the wall cavities. A method based on prior NET facility research experience was used (Tichy and Murray 2007). The method employed irrigation tubing and a medium that would retain water, located on the interior side of the OSB sheathing in each wall cavity, as shown in Figure 3. The process of injecting water into the wall cavities, however, was found to be less reliable than anticipated. In some cases the medium did not retain all of the water injected through the tubing, and water ran down to the bottom plate.

Over the test period, two targeted water injection periods were conducted. The first series of injections was performed from March 25, 2013, to March 29, 2013. Injections of 60 mL of water were made each day, resulting in a total of 300 mL on each wall over the course of five days. The second series of injections was performed from January 20, 2014, to January 24, 2014. 50 mL of water was injected into each of the walls in the morning and afternoon (total of 100 mL) each day for four days, followed by a single morning injection of 50 mL on the fifth day, resulting in a total of 450 mL for each wall over the course of five days.

Interior and exterior environmental conditions. A weather station was mounted on the test facility at the southwest corner (Figure 2). The station included an anemometer to measure wind speed and direction, a temperature and humidity sensor, a tipping-bucket rain gauge for vertically falling precipitation, and a horizontally installed pyranometer to measure solar radiation. Two additional vertically positioned pyranometers were installed on the north and south walls of the test facility to monitor solar radiation at the wall surfaces.

Exterior temperatures measured onsite were roughly similar to historical average values (Figure 4). Some summer months were warmer than average and some winter months were colder than average. Hourly values were recorded, but mean monthly values are plotted to show general trends. Interior temperature within the test facility was maintained year round at approximately 21°C (70°F).

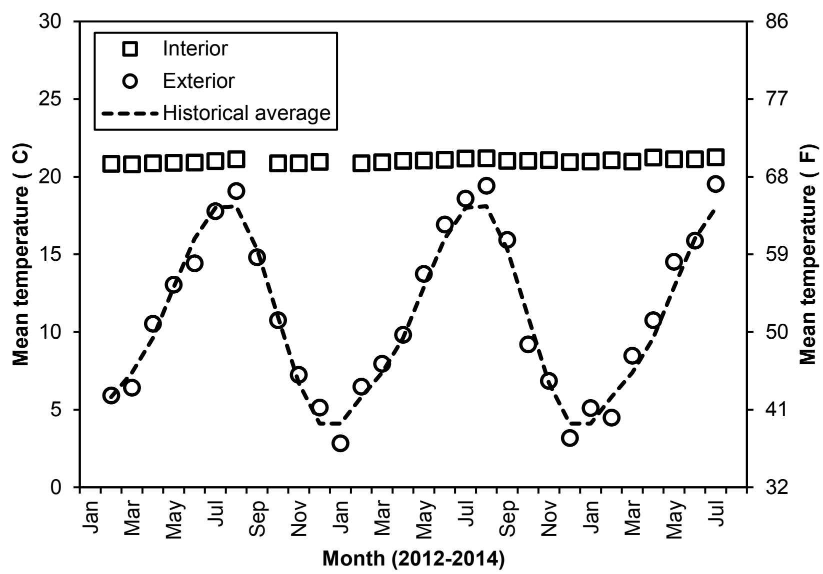

Figure 4. Monthly mean temperatures measured at NET facility and historical average for Puyallup, Washington

Precipitation measured onsite over the monitoring period was similar to historical average data, as indicated using monthly cumulative values in Figure 5.

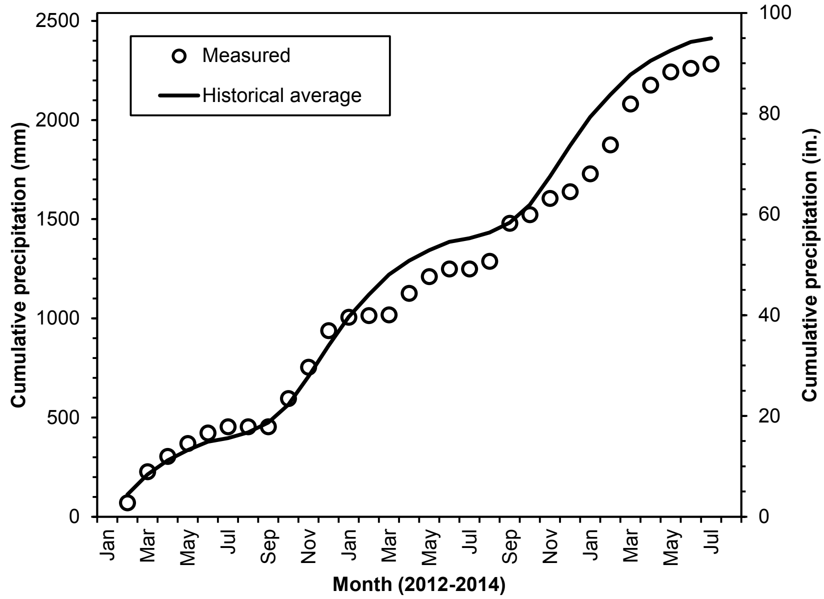

Figure 5. Cumulative precipitation measured at NET facility and historical average for Puyallup, Washington

Exterior and interior relative humidity levels are shown in Figure 6. Interior levels were maintained year round at approximately 50% RH, but there were periods during winter when RH levels fell because of brief loss of humidification. The interior RH levels, however, were similar to typical levels in residential buildings in this climate zone (Aoki-Kramer and Karagiozis 2004, Arena et al. 2010).

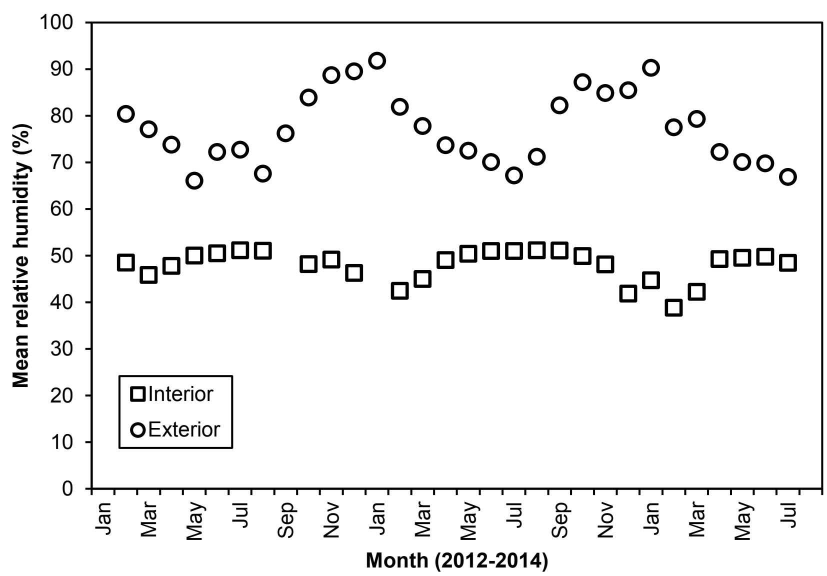

Figure 6. Monthly mean relative humidity levels measured at NET facility

Material property measurements. Laboratory tests were conducted to measure water vapor permeance and thermal resistance of some of the materials used in construction of the test wall sections. Materials were selected from the same batch of the product that was used to construct wall assemblies.

Test methods for water vapor transmission included the desiccant method (dry cup) and the water method (wet cup) of ASTM E96 (ASTM 2010b). For both methods, an environmental chamber was set at 23°C (73°F) and 50% RH. Specimens were cut to 135 mm × 135 mm (5.3 in. × 5.3 in.); edges were sealed with foil tape and then sealed to a metal dish with wax. Four replicates of each material were tested. Mean values are listed in Table 2. The measurements were in general concurrence with published values (ASHRAE 2013, Kumaran et al. 2002). Literature data for vapor permeance of OSB span a considerable range. The observed increase in vapor permeance from dry cup to wet cup measurements is consistent with previous measurements, and the measured values here fall within the upper part of the range of literature values (Glass 2013).

Table 2. Vapor permeance measurements

Material	Thickness, mm (in.)	Vapor Permeance, ng/(Pa·s·m^2) (perms)	
		Dry Cup	Wet Cup
Interior gypsum board	12.5 (0.494)	1670 (29.0)	2590 (45.1)
Interior gypsum board, one coat primer and two coats latex paint	12.7 (0.499)	150 (2.6)	470 (8.2)
Oriented strand board	11.8 (0.464)	100 (1.8)	420 (7.3)

Thermal resistance of rigid insulation materials was measured according to ASTM C518 (ASTM 2010a) with a mean temperature of 24°C (75°F). Specimens were 610 mm × 610 mm (24 in. × 24 in.). Six replicates of each material were tested. Specimens were stored in a laboratory maintained at approximately 50% RH prior to testing. Mean values and standard deviations are listed in Table 3. The measured values slightly exceed the manufacturer's stated nominal R-values (5 h·ft^2·°F/Btu).

Table 3. Thermal resistance measurements

Material	Thickness, mm (in.)	Thermal Resistance, m^2·K/W (h·ft^2·°F/Btu)
Extruded polystyrene insulation	26.1 (1.03)	0.904±0.003 (5.13±0.02)
Mineral wool insulation	32.7 (1.29)	0.969±0.006 (5.50±0.04)

HYGROTHERMAL MODELING APPROACH

The test wall configurations described above were simulated using WUFI® Pro 5.2 Software (Fraunhofer Institute for Building Physics, Holzkirchen, Germany) for one-dimensional transient heat and moisture transfer (IBP 2013, Künzel and Kiessl 1997). ("WUFI" stands for wärme und feuchtetransport instationär, German for "transient heat and moisture transport"). One-dimensional hygrothermal simulations are sometimes used by practitioners in North America for building envelope design analysis. In such cases actual material properties are not known with precision ahead of time, and practitioners rely on material properties from the literature or databases incorporated into simulation software. The objective of running these simulations was to evaluate the ability of hygrothermal simulations to predict OSB moisture levels in this climate for these wall assemblies given generic material properties and historic weather data.

Wall configurations are listed in Table 1. Each configuration was modeled as a multi-layer assembly, taking a one-dimensional section through the insulated cavity (rather than the framing). Each configuration was simulated in both north-facing and south-facing orientations. Material properties were assigned from the WUFI North America Database (IBP 2013); many of the properties in this database are taken from the work of Kumaran et al. (2002). Interior primer and paint layers on gypsum board were modeled as an interior surface diffusion resistance based on the mean of the measured dry cup and wet cup vapor permeance values. Vinyl siding was simulated using an equivalent vapor permeance, which is a simple method of modeling a cladding that is vapor impermeable but is back-ventilated by airflow. The equivalent vapor permeance was selected as 2300 ng/(Pa·s·m^2) (40 perms) (Glass 2013).

The initial moisture content of OSB was set to correspond with measured mean values in each of the wall assemblies at the beginning of Phase I. For materials other than OSB, the initial moisture content was set at equilibrium with 50% RH. Initial temperature in all materials was set to 21°C (70°F). Simulations had a start date corresponding to February 1, 2012, a one-hour time step, and an end date corresponding to January 31, 2013.

Interior temperature and relative humidity were set to be constant at 21°C (70°F) and 50% RH, approximately the same as measured values (Figures 4 and 6). Given that weather parameters measured onsite were similar to historical values, the exterior conditions for simulations were taken from a weather file for Seattle, Washington, built into the simulation software. Wind-driven rain on the walls was calculated according to ASHRAE Standard 160 (ASHRAE 2009), using horizontal rainfall, wind speed, and wind direction from the weather file. A rain exposure factor of 1.0 (medium exposure for buildings less than 10 m (33 ft)) and a rain deposition factor of 0.35 (for walls below a steep-slope roof) were assumed.

Drying behavior of OSB after the first water injection in Phase II was also simulated. In this case the OSB layer was divided into three parts: an outer 3 mm (1/8 in.) layer, a middle 5.8 mm (0.23 in.) layer, and an inner 3 mm (1/8 in.) layer. To simulate wetting of the OSB from the cavity side, the initial moisture content of the inner OSB layer was set to 25% MC, whereas the middle and outer layers were set to 10% MC. The increase from 10% MC to 25% MC roughly corresponds to 300 mL of water being uniformly distributed throughout the inner 3 mm (1/8 in.) of the OSB over the full height and width of the cavity. Simulations were run for north- and south-facing walls with a start date corresponding to March 29, 2013, the last day of the first series of water injections.

RESULTS AND DISCUSSION

The results discussed in this paper are limited to measured and simulated wood moisture contents. Further detail on temperature and relative humidity measurements can be found in the project report (Yeh et al. 2014).

Measured wood moisture content, Phase I. The test walls were subjected only to exterior and interior environmental conditions during Phase I; water was not injected into the walls in this phase. Wood moisture contents are plotted for the different sensor locations in each of the four wall assemblies in Figures 7–10. The sensor readings in OSB sheathing in each wall were then averaged so that the four walls could be compared directly, as shown in Figure 11.

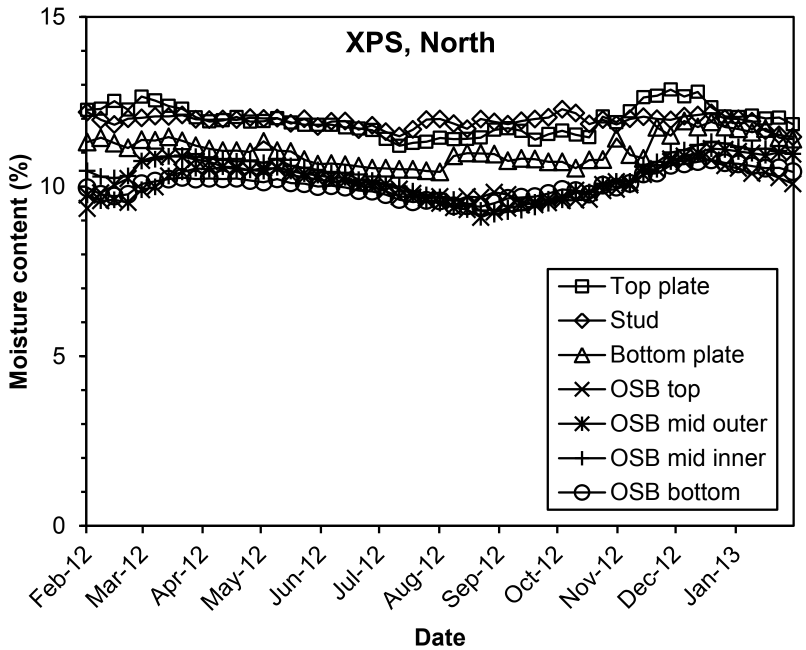

Figure 7. Measured wood moisture content in Wall N7

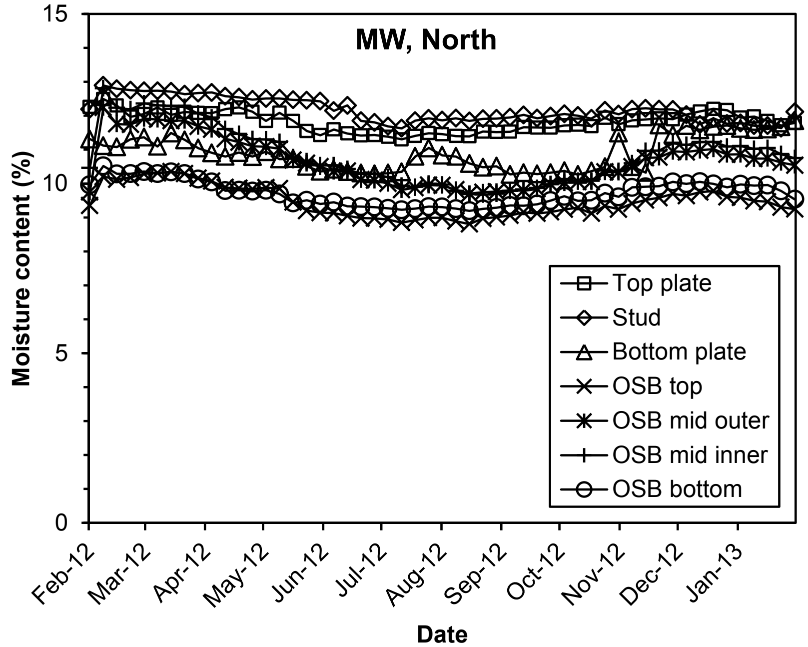

Figure 8. Measured wood moisture content in Wall N8

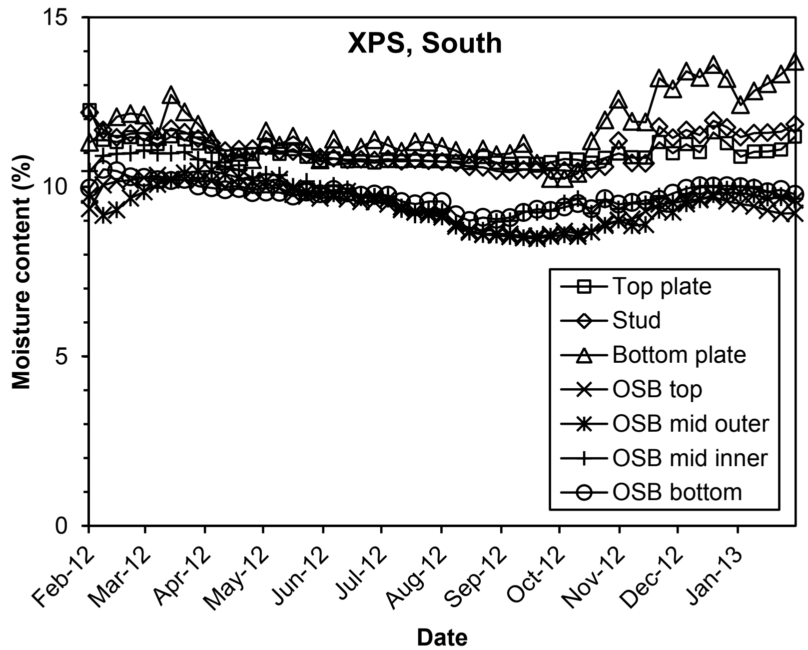

Figure 9. Measured wood moisture content in Wall S11

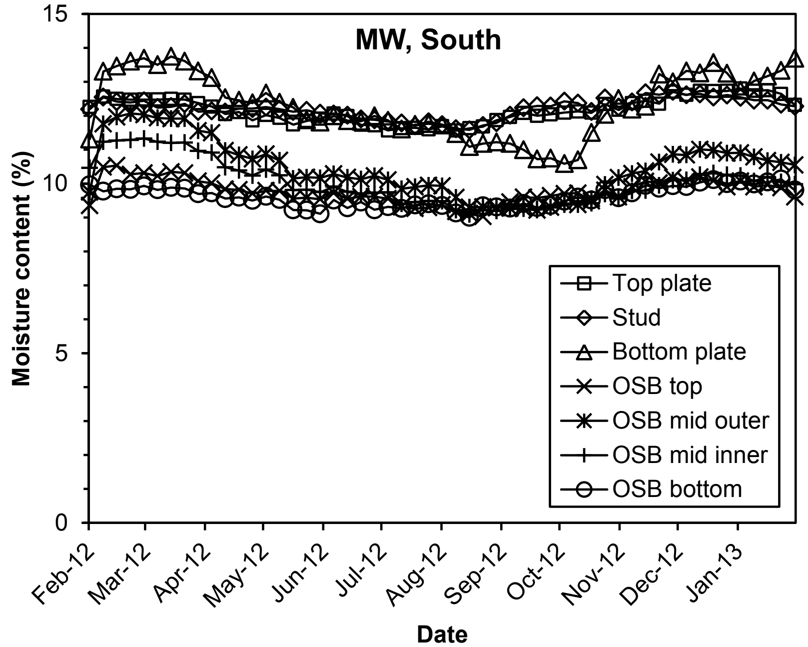

Figure 10. Measured wood moisture content in Wall S12

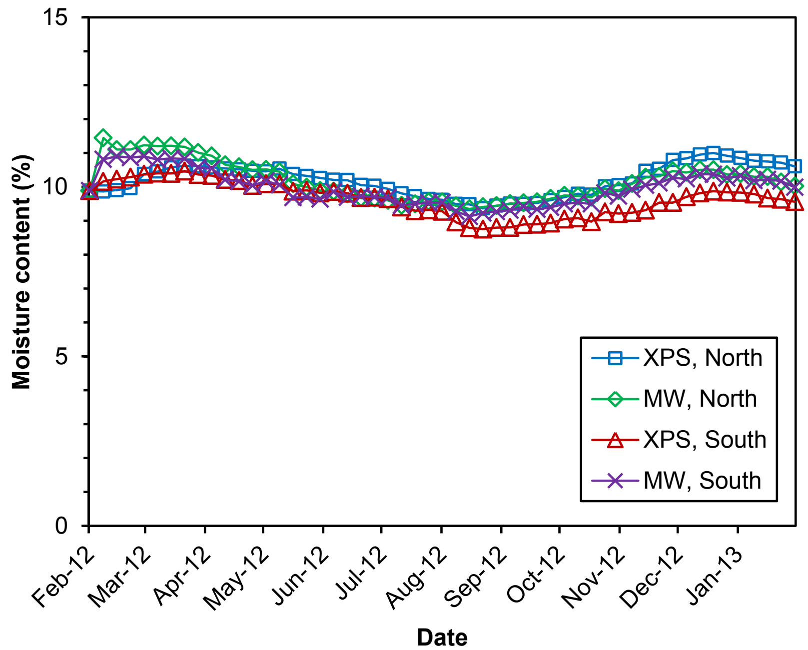

Figure 11. Mean OSB moisture content measured in Walls N7, N8, S11, and S12

In all four walls, wood moisture contents were below 14% MC, well within the range of safe moisture levels. Wall moisture performance was similar to measured values in previous studies in this climate for assemblies with good performance discussed in the Introduction (Tichy and Murray 2007, Smegal et al. 2013). Figures 7-10 indicate that moisture levels in framing generally were higher than those in OSB sheathing. This is a result of the fact that at a given RH level, the equilibrium moisture content of composite wood products is slightly lower than that of solid wood. Focusing on OSB moisture contents (Figure 11), the effects of wall orientation and exterior insulation were apparently insignificant. These observations are discussed further below in regard to hygrothermal simulations.

The seasonal trend in moisture levels is relatively small. Summer and winter values differ by less than 2% MC typically. For homes in the Pacific Northwest, moisture loading from the exterior and interior environments is most significant in the months of October through March. This is when there is greatest rainfall, highest outdoor humidity, and highest vapor drive from the interior. Drying typically occurs with the transition to warmer, dryer weather in spring and summer.

Simulated OSB moisture content, Phase I. OSB moisture contents from hygrothermal simulations for the four walls are compared with measured values in Figure 12. In general, the simulations correctly predicted the approximate magnitude of OSB moisture contents and the slight seasonal trend of higher MC in winter and lower MC in summer. The simulations, however, slightly over-predicted MC values for walls with XPS in winter and under-predicted MC values for all walls in summer (relative to measured values). Exact agreement between measurement and simulation should not be expected given that the simulations are one-dimensional and do not account for possible effects of air leakage, which can have a significant influence on moisture conditions.

Sensitivity analysis (Table 4) indicates that the winter peak MC in walls with XPS depends on the vapor permeance of the paint coating on the interior gypsum board and interior humidity levels. The peak winter OSB moisture content increases with increasing vapor permeance and increasing interior RH. The walls with MW exterior insulation are less sensitive than the walls with XPS exterior insulation because the vapor-open MW allows moisture to pass through the OSB to the exterior more readily. These trends are consistent with previous analysis for similar walls in a mixed-humid climate (Glass 2013).

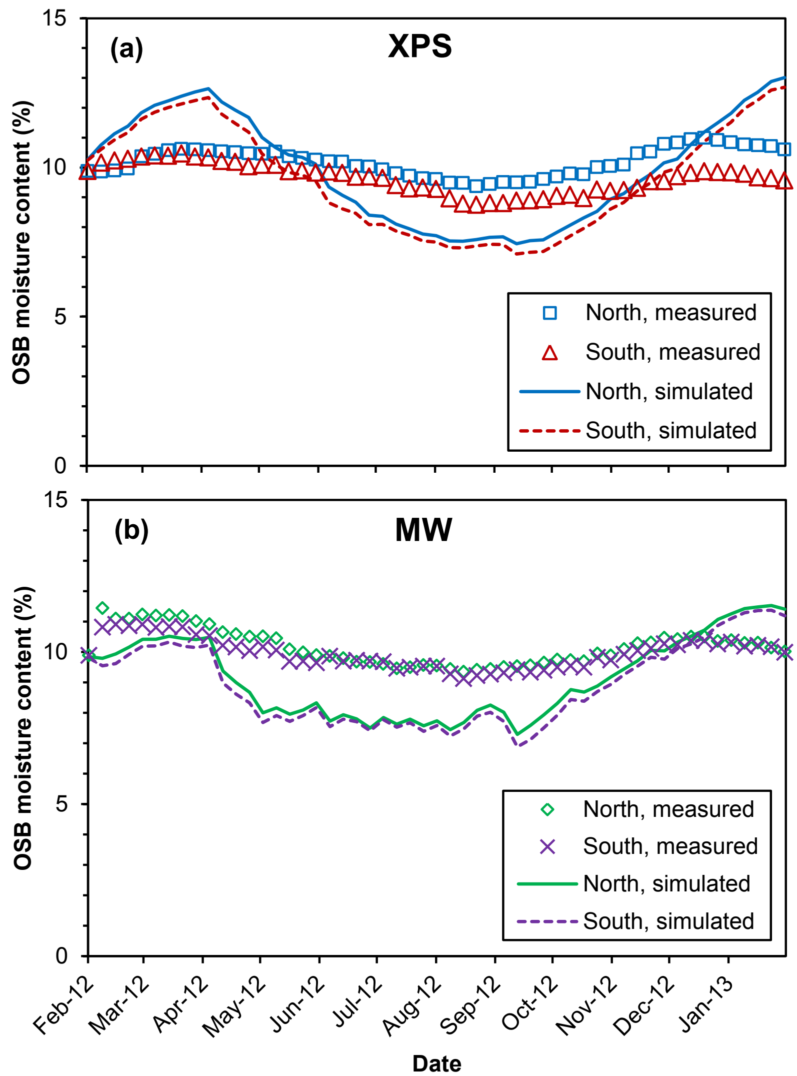

Figure 12. Measured and simulated OSB moisture content in walls with (a) XPS and (b) MW exterior insulation

Table 4. Effects of interior relative humidity and interior vapor permeance on simulated winter peak OSB moisture content in north-facing walls

Exterior Insulation	Interior RH	Interior Paint Vapor Permeance		Winter Peak OSB MC (%)
		ng/(Pa·s·m^2)	perms	
XPS	50%	290	5	13.1
	55%	290	5	14.9
	50%	570	10	14.4
	50%	1150	20	15.4
MW	50%	290	5	11.6
	55%	290	5	12.6
	50%	570	10	12.5
	50%	1150	20	13.2

Measured wood moisture content, Phase II. The wood moisture contents in Phase II were generally similar to those in Phase I except for periods following intentional water injections. As mentioned previously, the water injections were not as consistent as originally envisioned. Water flow rates were found not to be identical between test walls because of variation in the performance of irrigation tubing. In all wall assemblies the bottom plate moisture pins identified significant spikes in moisture content, presumably from injected liquid water running down the OSB sheathing to the bottom plates. The moisture pins in OSB sheathing at mid height and at the bottom also showed increases in moisture content, but were not consistent between the four wall assemblies. The four moisture content readings that were affected by water injections (MC4–MC7 in Figure 3, located in the OSB near the wetting device and the bottom plate and in the bottom plate itself) for each wall are depicted in Figure 13 as weekly average values. After the wetting events, wood moisture contents returned to pre-injection levels at different rates. Drying was typically faster following the first wetting (late March 2013) than the second wetting (late January 2014), presumably because of warmer weather in spring than in winter. The drying rates of the south-facing walls with XPS and MW were similar after both wettings. The drying rates of the north- and south-facing walls with XPS were similar after the first wetting. The north-facing wall with XPS, however, took considerably longer to dry after the second wetting. It is possible that this was a result of more of the injected water reaching the areas where the sensors were placed in this wall. The north-facing wall with MW showed a small response to the first wetting and almost no response to the second wetting, possibly because the injected water did not reach the areas where the sensors were placed.

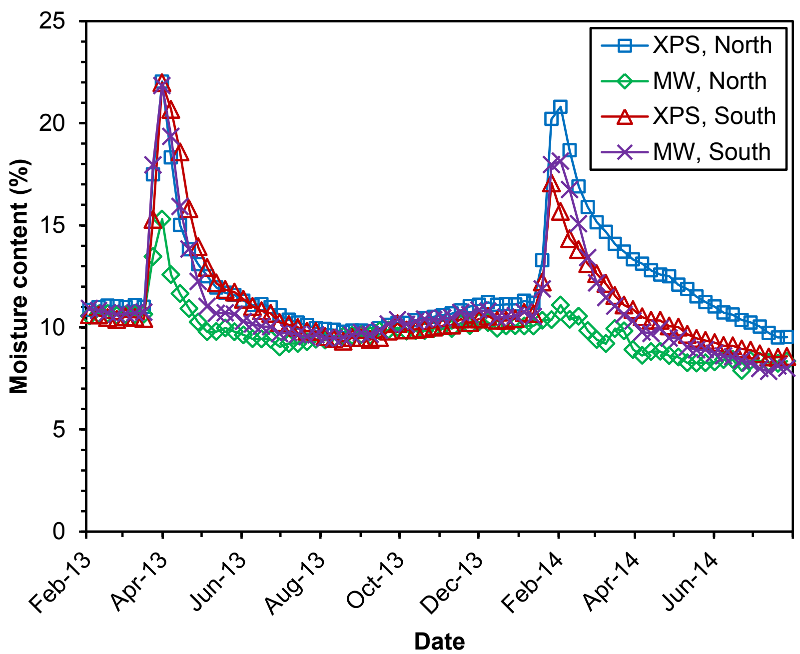

Figure 13. Measured moisture content in Walls N7, N8, S11, and S12 (average of readings in bottom plate and in OSB near wetting device and bottom plate)

Simulated OSB drying performance. Simulated moisture contents in the inner and middle layers of the OSB are shown in Figure 14. (The outer layer is not shown in the figure but behaved similarly to the middle layer. The south-facing walls are not shown but were similar to the north-facing walls.) The walls with vapor-tight XPS and vapor-open MW exterior insulation showed similar behavior in the simulations. The minor differences between the two walls suggest that drying to the exterior was not dominant. Within two weeks, the inner layer dropped to about 13% MC (from 25% MC initially), whereas the middle layer increased to about 13% MC (from 10% MC initially) in both walls. This indicates that some of the initial moisture in the inner layer was redistributed into the middle of the OSB. Drying to the interior through the vapor-open fiberglass insulation and gypsum board also occurred. This can be seen by comparing the water vapor pressure at the OSB surface to the vapor pressure inside the building. The temperature of the OSB surface at the start of the simulation was about 12°C (54°F); saturation vapor pressure at this temperature is 1407 Pa. The interior vapor pressure (corresponding to 21°C (70°F) and 50% RH) was 1248 Pa, so there was a vapor pressure gradient from the OSB to the interior. Although these simulations are one-dimensional and are not intended to capture the full behavior of the actual water injections, the simulations do provide some insight into the drying and redistribution mechanisms. Further experimental and modeling work is recommended to better understand and quantify redistribution and inward and outward drying in walls with various types of exterior insulation.

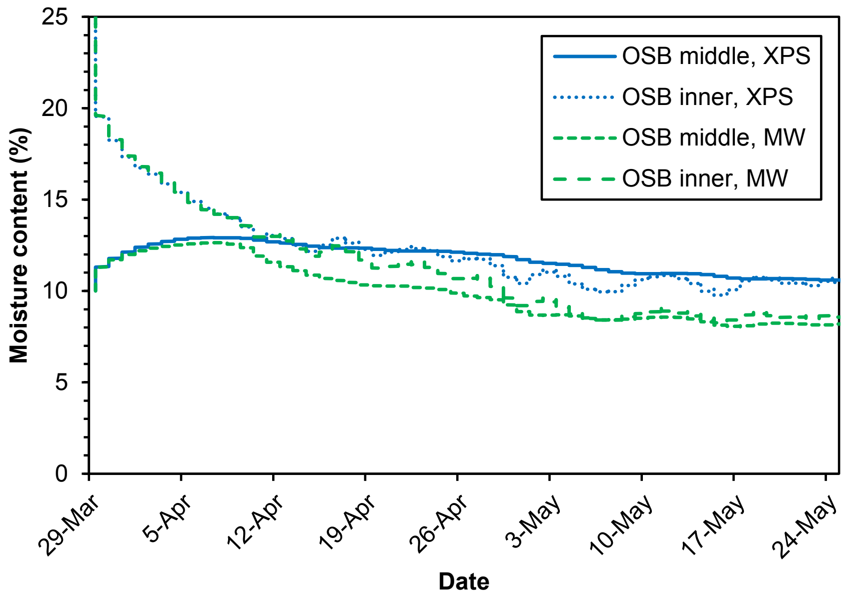

Figure 14. Simulated moisture content in middle and outer OSB layers in north-facing walls with wetting occurring in late March

CONCLUSIONS

Moisture and temperature conditions were measured in north- and south-facing exterior walls of a test facility in Puyallup, Washington (IECC Climate Zone Marine 4) over a two-year period. The wall assemblies included interior gypsum board with latex primer and paint, 2×4 framing with nominal R-13 batt insulation, 11 mm (7/16 in.) oriented strand board, nominal R-5 exterior insulation consisting of either extruded polystyrene or mineral wool, and vinyl siding.

Measurements indicated that walls with extruded polystyrene and mineral wool exterior insulation performed similarly in both north and south orientations. In all four walls, wood moisture contents were below 14% MC, well within the safe range for long-term durability. The seasonal trend in moisture levels was relatively small; summer and winter values differed by less than 2% MC typically.

Hygrothermal simulations correctly predicted the approximate magnitude of OSB moisture contents and the slight seasonal trend of higher MC in winter and lower MC in summer. The simulations, however, slightly over-predicted MC values for walls with XPS in winter and under-predicted MC values for all walls in summer (relative to measured values).

Intentional water injections into the wall cavities were conducted to evaluate the rate of drying under natural conditions. The quantity of water and distribution of wetting, however, were not consistent between the four wall assemblies, precluding direct comparisons of drying potential. Nonetheless, wood moisture contents returned to pre-injection levels within 4 to 6 weeks after the wetting events in all four wall assemblies. Further work is recommended to provide insight into moisture redistribution and drying mechanisms in wood-frame walls with exterior insulation.

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Building Code Impacts on Residential Electricity Usage

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ABSTRACT

Homes account for roughly 21% of energy consumption in the United States. However, most homeowners will not invest in energy efficiency, if there are not recognizable short term benefits. In an effort to reduce electrical consumption, municipalities have adopted increasingly stringent building codes, as it relates to home energy use. This study sought to explore the actual impact(s) of building code adoption on the consumption of electricity in homes, in Central Texas. Using smart meter data, collected over the last 20 years from the city of Georgetown, the following questions were addressed: 1) What is the a relationship between more stringent building codes and electrical consumption in homes? 2) Since the adoption of more stringent building codes, has electricity use been reduced? 3) Which building code caused the largest decrease in electrical consumption? The results of the study indicate that building code changes are related to significant electricity savings, with homes built under more recent codes using 35% less electricity than homes built in the early 1990s and 25% less than homes built in the 2000s.
Keywords: Sustainability, Electric Consumption, Electricity, Building Codes

INTRODUCTION

Energy is a commodity that is highly valued in most areas of the world. According to the United States Energy Information Administration, homes accounted for roughly 21% of the total national energy consumption in 2013. (United States Energy Information Administration [USEIA], 2014). So the implementation of energy conservation strategies in homes could lead to a substantial decrease of energy use. However, homeowners cannot be expected to make substantial investments if the benefits are not short-term (Meyers, Williams, & Matthews, 2009). Local governments on the other hand, can directly impact electricity consumption in homes through the adoption and enforcement of building codes. Through newer more stringent codes homebuilders are required to use materials and methods that use less electricity, which lead to long term electricity savings. Modeling has provided estimates of electricity saving through newer codes, so the researchers hypothesized that homes built to newer more stringent codes would demonstrate a lower usage of electricity. To quantify that hypothesis, the researchers sought to learn how much building codes reduced electricity consumption in actual homes. This study is significant as it provides a comparison of actual electric use based on a sample of homes constructed under different building codes. This information which could represent empirical support for municipalities to adopt newer more stringent codes and to better enforce existing codes as a measure to alleviate increasing electricity consumption. Further it could document money savings for home owners.

The specific research questions for this study were: 1) What is the relationship between more stringent building codes and electrical consumption in homes? 2) Since the adoption of newer building codes, what change in electrical use and thus cost has occurred in homes in Georgetown, Texas?

LITERATURE REVIEW

The literature regarding homes and the various approaches to examine their energy consumption are numerous, and help to display the evolution of energy use in homes. While some have simply considered the energy usage in homes, others have conducted research similar to this study where the impacts of codes on energy consumption were studied.

Improvements to the building envelope are important as the envelope is likely to be addressed by a building code. Cooperman, Dieckman, and Brodrick (2011) report that energy consumption can be reduced by 40% through window sealing, improved insulation, and roofing. Another study by Zhai, Abarr, Al-Saadi, and Yate (2014) also considered the building envelope. They reported that 12% of energy use goes to space heating, 12% goes to air conditioning and refrigeration, and 29% goes to other electrical needs, so controlling the envelope is a key question for reduced energy consumption. While they considered more extreme improvements on the envelope these studies demonstrate the reduction in energy possible.

Research conducted by Suter and Shammin (2013) took a different approach to observe the rate of saving energy through people's reaction to energy saving methods. They tested how much energy was saved by bringing energy consumption to the attention of the homeowners through incentives and programmable thermostats. Homes were equipped with better roof insulation and programmable thermostats in different areas to isolate the separate factors. Some people were informed of the effort to save energy and ways to achieve energy conservation. Another group was not informed of the test, and the last group was informed and offered financial incentives to save energy. The largest saving was achieved though offering financial incentives. The group of informed individuals achieved substantial savings but not to the same degree as the incentives group (Suter & Shammin, 2013). This study supports the results of others that a few changes to a house could make a difference in energy use.

Extreme improvements to a building's performance likely carry a large price tag, but changes that are typically implemented in building codes tend to be smaller which reduce the potential cost. Sadineni, France, and Boehm (2011) investigated the economic feasibility of energy efficient measures in residential buildings. They applied some basic upgrades to homes in the Southwest United States and calculated the payback period. The basic energy upgrades included upgrading the wall's R-Value to 17, window's U-Value to .65, Door's R-Value to 7, reducing the effective leakage area to 54.9 F-hr-ft^2/BTU, using a 15 SEER air conditioner, and increasing the attic R-Value. From the research they determined that these basic energy efficiency upgrades had a payback period of less than 10 years (Sadineni, France, & Boehm, 2011).

In addition to the building envelope, home appliances are also a large contributor to energy consumption, and can carry a significant price tag. McNeil and Bojda (2012) looked at the effectiveness of high energy efficient appliances. The cost effectiveness was evaluated for different appliances, including: refrigerators, electrical water heaters, gas water heaters, central air conditioning, unit air conditioning, and electric cooktops. This study produced results indicating the following savings by using more efficient appliances: 27% for refrigerators, 17% for room air conditioning, 53% for electric water heaters, 23% for central air conditioning, and 11% for gas water heaters (McNeil & Bojda, 2012). While more efficient appliances are more expensive, they can relate to substantial savings in energy consumption. While heating, ventilation, and air conditioning systems have code based requirements, other household appliances do not, as such appliances represent an option for additional improvement in the building codes.

While many studies have looked at specific improvements to increase energy efficiency, others have looked at building codes holistically to evaluate their effects. These studies have used a variety of methodologies but are all consistent in identifying a decreased level of energy usage. Raheem, Issa, and Olbina (2012) studied the potential energy savings of the proposed 2012 International Energy Conservation Code (IECC) for residential construction. They compared the 2012 IECC to the Florida Energy Efficiency Building Code (FEEBC). They conducted this examination by using Building Information Modeling (BIM) and running computer simulations to analyze the energy consumption on a model of the home before and after the IECC changes. The results showed that a residence in Miami was capable of saving 13.6% of Kwh per year which amounted to between $250 and $430 in savings per year. A simulation can be argued to inaccurately portray accurate consumption, but other studies using actual homes have been completed.

Jacobsen and Kotchen (2013) conducted a study in which they focused on how energy code changes translate to actual energy consumption in Florida. They reported a 6.4% reduction in natural gas consumption and electricity reductions between four and eight percent during hotter months. The study identified three major changes in the building code that would have the most influence on energy use. First, the use of an electric heat pump instead of older electric resistance heaters. Second, air distribution system requirements were changed from "leak free" system to a "leaky" (allowing homes to gain points for a leak- free system). The last significant change was an increase in the minimum solar heat gain coefficient in windows from .61 to .4 (Jacobsen & Kotchen, 2013).

In a study that used IECC 2003 and IECC 2006 as a standard to base their experimentation. Koirala, Bohara, and Li (2013) estimated the effect of IECC 2003 and IECC 2006 on energy consumption using the American Community Survey 2007. They report that homes could save roughly 1.8% of electricity and 1.3% of natural gas. Aroonruengsawat, Auffhammer, and Sanstad (2012) went on to study what kind of impact state building codes could have on residential electricity use. They measured the savings of electricity per capita to range from 0.3% to 5% depending on which state was analyzed. They reported that the main problem was that even if states created energy saving building codes, enforcing the codes became a problem.

The actual cost of increasingly strict building codes has also been researched. Home Innovation Research Labs (Home Innovation Research Labs [HIRL], 2015) conducted a study to determine the change in construction cost for a homoe, after a new building code has been adopted. HIRL selected four baseline homes to use for their study. Those four model types were: One-story house with slab foundation, Two-story house with slab foundation, One-story house with basement foundation, and Two-story house with basement foundation. These four types of houses were constructed under the 2012 International Residential Building Code (IRC). The study reported that based on the average square footage of the homes (2,607) the cost to construct under the 2012 code was $246,453. In the 2015 International Residential Building Code, 49 building code changes were identified. While some of the changes from 2012 to 2015 reduced the cost of construction, the overall difference was an increase of about $10,838, on a 2,600 square foot home.

While these studies have reported and drawn conclusions about the effects of building processes and codes on energy consumption, or reductions thereof. This study is unique as it empirically compares the incremental improvements available from one code to subsequent versions that were adopted.

The city of Georgetown adopted four different building codes over the course of twenty years, and the chance an energy savings occurs is very likely.

METHODOLOGY

This study used a quantitative approach to empirically compare building codes and their effect on electricity use. Utilizing empirical data a sample of homes from each of the different building code periods were compared. ANOVA was used to make comparisons of the electrical consumption data, other appropriate statistical tests were conducted as well and are detailed in the analysis section.

Actual electricity consumption in Kilowatt hours for the year 2014 is the data used for comparison. Because the City of Georgetown has officially adopted four different building codes, since implementing smart-meter use, a sample of over 400 homes was identified. Those 400+ were then broken into groups of 100 homes based on the time period they were built and the building codes in effect at that time in Georgetown. The four building codes include: First was the 1985 Southern Standard Building Code (SSBC) which was adopted in January 1987. The second was the 1994 Southern Standard Building Code with appendix C that adopted the 1992 CABO One and Two-Family Dwelling Code, along with the 1993/94 Book of Amendments which was adopted in September 1995. The third was the Amendments to 1992 CABO One and Two-Family Dwelling Code to Adopt and add energy conservation standards that were adopted in April 1999. The fourth and current code in Georgetown is the 2000 International Residential Code that was adopted in February of 2012. Table 1 summarizes the codes adopted and their time periods.

Table 1. City of Georgetown Adopted Building Codes

Code	Years of Use
1985 Southern Standard Building Code (SSBC)	1987 – 1995
1994 Southern Standard Building Code with appendix C that adopted the 1992 CABO One and Two-Family Dwelling Code, along with the 1993/94 book of amendments	1995 – 1999
Amendments to the 1992 CABO One and Two-Family Dwelling Code to Adopt and add Energy Conservation Standards	1999-2012
2000 International Residential Code	2012-present

Homes were filtered by their respective building code based on the construction date. If a building code was adopted in 1999, only homes built in the following year were included in the sample to ensure the home was built under the intended building code. To further ensure that homes were categorized under the correct building code, the date used was the date in which the certificate of occupancy was obtained.

The study was designed to mitigate the effects of uncontrolled variables, and to ensure that the sample could appropriately be compared, certain delimitations were imposed. electricity consumption varies greatly based on homeowner habits and uses. To avoid a skewed analysis from individual homeowner habits, sample groups of 100 were used. As a result an average electric consumption for those 100 homes could be determined and used for comparison. To ensure the homes in each group were comparable, the study was delimited to electricity consumed at the sample homes in 2014. Only homes between 1600 – 2000 square feet that were constructed between 1991 and 2013 were included in the groups, and homes that had undergone a major renovation were disqualified.

Data from the city of Georgetown was used because the utility data was readily available, but also because the researchers considered it to be a more accurate representation of electrical consumption. The City of Georgetown has used smart electrical meters since the early 1990's, as a result actual electrical use at each home was available and considered highly accurate because it was not subject to error by meter readers or average use calculations used by some utility companies. The electrical consumption data was obtained from Georgetown Utility Systems. The data provided was already broken down into Kilowatt hours consumed per month, average monthly Kilowatt hour use, and average Kilowatt hour use per square foot.

Which homes were selected for use was a multistep process. First groups of 125 homes were identified using the website www.realtor.com. The website provided build dates that allowed the researchers to initially identify each group and which building code period homes were built under. Using realtor.com also allowed the researcher to verify that the homes selected were in areas of the city serviced by Georgetown Utility Systems (not all of the City of Georgetown is serviced by one utility company). When build dates and utility service were confirmed, data from the Williamson County Appraisal District was used to verify that the information gathered from www.realtor.com., Specifically that the square footage of each home chosen, met the delimitations of the project. Further the Williamson County Appraisal District allowed the researchers to verify that no major renovations had taken place in the selected homes. By using a group of 125 homes, the researchers were able to remove any homes that did not meet the requirements set forth or for which electrical consumption data was not available, and still have sample groups of 100 homes.

The Hypothesis tested was:

$H_0: \mu_1 = \mu_2 = \mu_3 = \mu_4$ $\qquad$ $H_a: \mu_1 \neq at\ least\ one\ other\ \mu$

Where μ is the average monthly electricity use for the homes in each of the building code periods. The tests were conducted with 95% certainty. ANOVA was used because it is robust in cases of unequal variance or non-normal data.

ANALYSIS AND RESULTS

To test the hypothesis an ANOVA test was conducted to compare the mean electrical consumption in Kwh for homes in the four separate groups (each building code period) in 2014. Figure 1 displays a box plot depicting the difference in the group averages. One way ANOVA Tests were performed to compare the mean electrical use per square foot in Kw for each period to allow for consideration of home sizes. ANOVA Tests were also performed comparing the electrical use in Kwh for each month in 2014 to explore if there was any relation to building code and electrical consumption in different seasons of the year. In addition to the ANOVA tests Tukey HSD tests were conducted to determine where the differences between the groups existed. Games-Howel post hoc tests were conducted in addition the Tukey HSD because the assumption of equal variances was violated (Morgan, Leech, Gloeckner, Barrett, 2007).

A statistically significant difference was found among the four building code periods on electrical consumption in Kw, F (3, 396) = 18.490, p = .000. Table 2 shows that the mean electrical consumption for the 1985 SSBC is 983.5 Kw, 854.2 Kw for the 1994 SSBC, 853.9 Kw for the Amended 1992 CABO, and 635.7 Kw for the 2000 IRC. Table 3 displays the ANOVA results. Post hoc Tukey HSD Tests indicate that the 1985 SSBC differed significantly from all other code periods (1994 SSBC p = .034, Amended 1992 CABO p = .033, and 2000 IRC p = .000). The 2000 IRB was also significantly different from all other code periods (1985 SSBC p = .000, 1994 SSBC p = .000, and Amended 1992 CABO p = .000). The 1994 SSBC however was not statistically different than the Amended 1992 CABO.

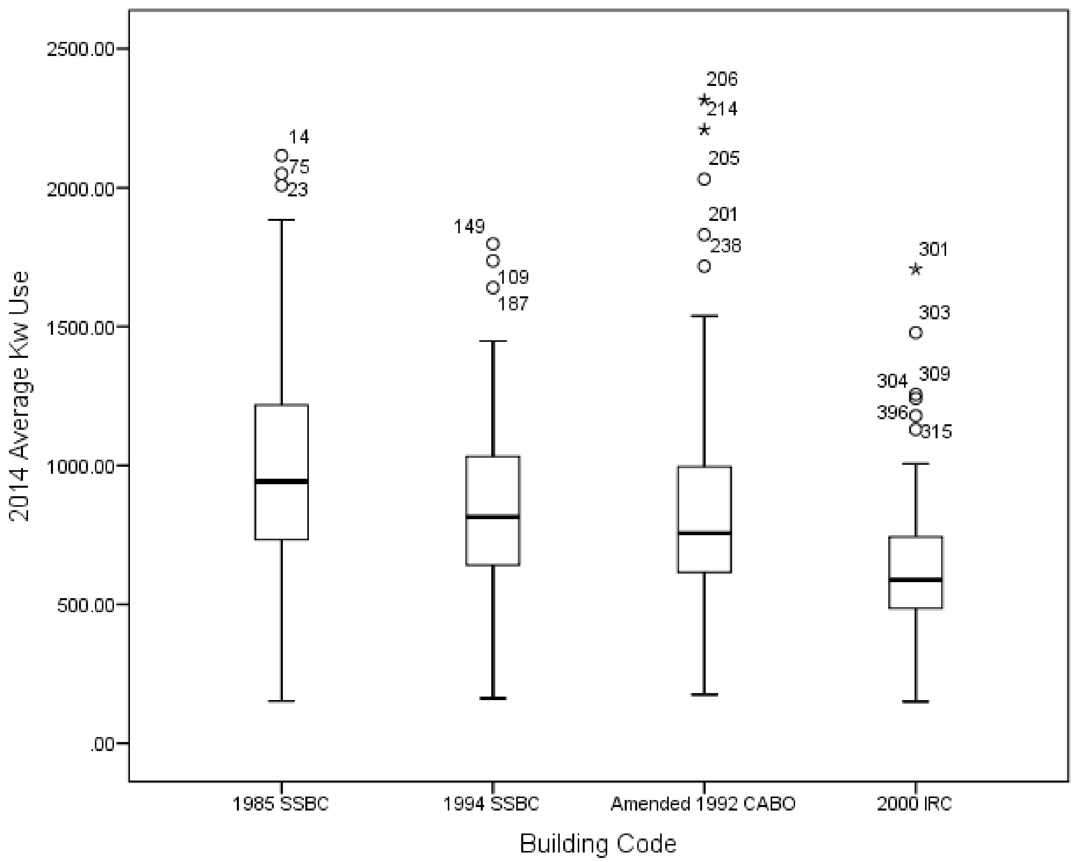

Figure 1. Boxplot of Electrical Consumption Data.

Table 2. Means and Standard Deviations Comparing Average Monthly Electrical Consumption in Different Code Periods and Monthly Electrical Consumption Per Square Foot.

Building Code	*n*	Average Kwh consumption		Average Kwh consumption Per Square Foot	
		M	*SD*	*M*	*SD*
1985 SSBC	100	983.54	368.63	0.56	0.22
1994 SSBC	100	854.17	313.98	0.48	0.18
Amended 1992 CABO	100	853.86	388.38	0.48	0.21
2000 IRC	100	635.68	255.36	0.36	0.20
Total	400	831.81	356.99	0.47	0.20

Table 3. One-Way Analysis of Variance Summary Table Comparing Building Code Periods on Average Monthly Kwh Consumption and Monthly Kwh Consumption Per Square Foot.

Source	*df*	SS	*MS*	*F*	*p*
2014 Average Kwh consumption					
Between groups	3	6247514.19	2082504.73	18.49	.000
Within groups	396	44600902.75	112628.54		
Total	399	50848416.93			
2014 Kwh consumption/SqFt					
Between groups	3	2.04	.68	19.18	.000
Within groups	396	14.04	.04		
Total	399	16.08			

A Games-Howell post hoc comparison showed slightly different results than the Tukey HSD. The 2000 IRC remained significantly different than all other code periods (1985 SSBC *p*=.000, 1994 SSBC *p* = .000, and Amended 1992 CABO *p* = .000), and the 1994 SSBC and the Amended 1992 CABO had no significant difference. However, using the Games-Howell, the 1985 SSBC was significantly different from the 1994 SSBC (*p* = .041), and 2000 IRC (*p* = .000), but not from the Amended 1992 CABO (*p* = .076).

A statistically significant difference was also found among the four building code periods on average monthly Kwh consumption per square foot F(3,396) = 19.182, p = .000. Table 2 shows that the mean Kwh consumption square foot for the 1985 SSBC is 0.56 Kwh, 0.48 Kwh for the 1994 SSBC, 0.48 Kwh for the Amended 1992 CABO, and 0.36 Kwh for the 2000 IRC. Table 3 displays the ANOVA results. Post hoc Tukey HSD Tests indicated the same building codes had statistically significant differences as in the comparison of Kwh use. The 1985 SSBC differed significantly from all other code periods (1994 SSBC *p* = .021, Amended 1992 CABO *p* = .026, and 2000 IRC *p* = .000). The 2000 IRB was also significantly different from all other code periods (1985 SSBC p = .000, 1994 SSBC p = .000, and Amended 1992 CABO p = .000). The 1994 SSBC again, was not statistically different than the Amended 1992 CABO.

A Games-Howell post hoc comparison was also conducted, because of unequal variance, and showed slightly different results than the Tukey HSD. The 2000 IRC remained significantly different than all other code periods (1985 SSBC p=.000, 1994 SSBC p = .000, and Amended 1992 CABO p = .000), and the 1994 SSBC and the Amended 1992 CABO had no significant difference. However, using the Games-Howell, the 1985 SSBC was significantly from the 1994 SSBC, but not from the Amended 1992 CABO (1994 SSBC p = .036, Amended 1992 CABO p = .062, and 2000 IRC p = .000).

These comparisons indicate a substantial average reduction in Kwh consumption through the adoption of the 1994 SSBC and 2000 IRC building codes, but no significant change in the adoption of the Amended 1992 CABO (from the 1994 SSBC). While the adoption of the Amended 1992 CABO resulted in no significant difference in electricity consumed (compared to the 1994 SSBC), the 1994 SSBC is related to an average reduction of 14% in electrical use, over the 1985 SSBC. An even larger reduction (25%) in electrical use is seen from the adoption of the 2000 IRC over the 1994 SSBC or Amended 1992 CABO.

The previous tests compared the average electrical consumption for one year. To explore the effects of the codes on electrical consumption in different times of the year, the monthly data was also tested using ANOVA. Analysis of the monthly data was performed to look for any significant differences in use related to seasons. Table 4 displays the means and standard deviations for each month under each building code in 2014. The results of the ANOVA are shown in table 5.

Table 4. Means and Standard Deviations Comparing Monthly Electrical Consumption in Different Code Periods.

		1985 SSBC		1994 SSBC		Amended 1992 CABO		2000 IRC	
Month	*n*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Jan	400	741.18	377.38	567.21	266.02	628.08	380.87	486.29	252.64
Feb	400	743.54	348.30	703.63	292.53	744.59	376.99	629.28	256.96
Mar	400	1057.07	416.68	1011.54	336.03	959.05	437.66	792.84	315.12
Apr	400	1538.18	538.89	1463.56	484.49	1347.72	571.39	1094.22	353.00
May	400	1477.09	538.05	1351.09	505.01	1237.82	544.97	981.66	425.43
Jun	400	1390.63	565.86	1190.56	471.66	1074.62	519.20	821.86	364.92
Jul	400	1093.62	448.29	915.20	419.95	863.93	475.03	601.50	306.113
Aug	400	784.60	359.38	659.13	324.50	660.21	393.19	471.59	243.51
Sep	400	644.92	311.24	535.99	277.85	576.19	331.04	415.69	221.21
Oct	400	683.40	392.33	542.62	278.42	615.26	377.00	414.47	270.41
Nov	400	807.25	573.03	631.43	367.38	769.32	517.19	461.85	329.51
Dec	400	867.18	582.04	677.15	417.06	769.27	526.06	456.46	365.02
Total		11829		10249		10246		7628	

Table 5. One-Way Analysis of Variance Summary Table Comparing Building Code Periods on Monthly Kwh Consumption.

Source	*df*	SS	*MS*	*F*	*p*
January					
Between groups	3	2782621.26	927540.42	8.79	.000
Within groups	396	41784441.30	105516.27		
Total	399	44567062.56			
February					
Between groups	3	878782.460	292927.49	2.82	.039
Within groups	396	41089010.50	103760.13		
Total	399	41967792.96			
March					
Between groups	3	3992726.21	1330908.74	9.22	.000
Within groups	396	57160599.54	144344.95		
Total	399	61153325.75			
April					
Between groups	3	11325920.72	3775306.91	15.47	.000
Within groups	396	96646152.72	244055.94		
Total	399	1.080E8			
May					
Between groups	3	13337589.53	44445863.18	17.39	.000
Within groups	396	1.012E8	255626.28		
Total	399	1.146E8			
June					
Between groups	3	16916475.72	5638825.24	23.86	.000
Within groups	396	93594053.55	236348.62		
Total	399	1.1.5E8			
July					
Between groups	3	12416977.36	4138992.456	23.76	.000
Within groups	396	68971401.07	174170.21		
Total	399	81388378.43			
August					
Between groups	3	4998519.39	1666173.13	14.87	.000
Within groups	396	44387038.09	112088.48		
Total	399	49385557.47			
September					
Between groups	3	2774608.27	924869.42	11.12	.000
Within groups	396	32926527.13	83147.80		
Total	399	35701135.39			
October					
Between groups	3	3970025.73	1323341.91	11.85	.000
Within groups	396	44222089.71	111671.94		
Total	399	48192115.43			
November					
Between groups	3	7349033.67	2449677.90	11.67	.000
Within groups	396	83099003.77	209845.97		
Total	399	90448037.43			
December					
Between groups	3	923723.85	3078574.62	13.35	.000
Within groups	396	91346072.06	230671.90		
Total	399	1.006E8			

A statistically significant difference was found among the four building code periods on Kwh consumption in every month (See Table 5), so a Tukey HSD was performed to explore the interactions in each month. Subsequently, because the assumption of equal variance was violated Games-Howell tests were also performed. The researchers point out however that while 11 or the 12 months were significantly different at *p* = .000, February did not show the same strong p value [F(3,396) = 2.82, p = .039]. As a result the researchers anticipated differences in February.

The Games-Howell and Tukey HSD generally agreed with each other in the month to month statistically significant differences. The Games-Howell indicated a statistically significant difference between the 1985 SSBC and the 2000 IRC (*p* = .044) in February, but the Tukey HSD did not produce a statistically significant difference (*p* = .060). Because the data violated the assumption of equal variance, the Games-Howel is the more reliable statistic. Not surprisingly, the 1985 SSBC had a statistically significant difference from the 2000 IRC every month.

The electrical consumption by month had statistically significant differences between the building codes in most months over the course of a year. And while a comparison between the 1985 SSBC and the 2000 IRC has value, differences between the 1994 SSBC and the amended 1992 CABO when compared to the 2000 IRC have even greater value. For the 1994 SSBC and the Amended 1992 CABO, there was a statistically significant difference from the 2000 IRC in all but the coldest months. The 1994 SSBC had no statistically significant difference in electrical use from the 2000 IRB in January (*p* = .125) or February (*p* = .227) of 2014. The Amended 1992 CABO had no statistically significant difference in electrical use from the 2000 IRB in February (*p* = .059), but did have a statistically significant difference in January (*p* = .012). In 2014, February was the coldest month of the year in Georgetown, TX. As a result it is likely that the cold is related to the lack of a significant difference between the electrical use from each code period to the next.

Table 6. Games-Howell & Tukey significance to the 2000 IRB.

Month	1985 SSBC			1994 SSBC			Amended 1992 CABO		
	Mean Δ	*G-H p*	Tukey *p*	Mean Δ	*G-H p*	Tukey *p*	Mean Δ	*G-H p*	Tukey *p*
January	-277.9	.000	.000	-80.9	.125	.294	-141.8	.012	.012
February	-114.3	.044	.060	-74.4	.227	.362	-115.3	.059	.057
March	-264.2	.000	.000	-218.7	.000	.000	-166.2	.013	.011
April	-434.0	.000	.000	-369.3	.000	.000	-253.5	.001	.002
May	-495.4	.000	.000	-369.4	.000	.000	-256.2	.002	.002
June	-568.8	.000	.000	-368.7	.000	.000	-252.8	.001	.000
July	-492.1	.000	.000	-313.7	.000	.000	-262.4	.000	.000
August	-313.0	.000	.000	-187.5	.000	.001	-188.6	.000	.000
September	-229.2	.000	.000	-120.3	.005	.018	-160.5	.000	.001
October	-268.9	.000	.000	-128.1	.006	.035	-200.8	.000	.000
November	-345.4	.000	.000	-169.6	.004	.045	-307.5	.000	.000
December	-410.7	.000	.000	-220.7	.000	.007	-218.8	.000	.000

On homes in the central Texas town of Georgetown, in 2014, statistically significant differences exist between average yearly Kwh consumption, average yearly Kwh consumption per square foot, and average Kwh consumption in most months when comparing one building code period to another. The study showed that there was a reduction in electrical use by homes built under newer building codes in The City of Georgetown. There was only one change in building code that did not result in a significant savings of electricity use in Georgetown homes. The 1994 Southern Standard Building Code containing appendix C with the 1992 CABO one and two family dwelling code did not have a significant savings after the adoption of amendments to 1992 CABO to add energy conservation standards. As should be expected, the savings were most substantial when comparing the oldest building code (1985 SSBC) to the newest building code (2000 IRC). The potential impacts of these differences are discussed in the conclusions.

CONCLUSIONS

This results of this study indicate that adoption of new building codes are an effective method to significantly reduce electrical consumption. However it also indicates that the differences between codes can be insignificant. While the 1985 SSBC and 2000 IRC were significantly different from the 1994 SSBC and the Amended 1992 CABO, The 1994 SSBC and the 1992 CABO were not significantly different in the electricity consumed by homes built under those code periods. The lack of a significant difference between the 1994 SSBC and the Amended 1992 CABO relating to electrical consumption is particularly interesting because the Amended 1992 CABO specifically included energy conservation standards. Never the less, average annual Kwh consumption in 2014, was less than one Kwh different from the 1994 SSBC to the Amended 1992 CABO. In comparing the average monthly usage data there was again no statistically significant difference, but there was some practical significance from one month to the next. In 2014 homes built under these two codes averaged a 75 Kwh difference per month. However that difference was split with homes built under the 1994 SSBC using less electricity in six months, homes built under the Amended 1992 CABO using less electricity in five months, and one month where the consumption was essentially the same. The interesting finding here is that the months where homes under each code used less than the other were not random, rather the 1994 SSBC homes performed better in the colder months, while the Amended 1992 CABO homes performed better in hotter months. Because Georgetown is a cooling dominated climate, a decision to adopt the Amended 1992 CABO with energy conservation standards is understandable as refrigerated air conditioning makes up a considerable chunk of home electricity consumption. However the data indicates that decision to change from the 1994 SSBC to the Amended 1992 CABO, and the related costs did not net the city a reduction in electricity consumption.

Electrical usage in February of 2014 was not significantly different between the 2000 IRC and the 1994 SSBC and the Amended 1992 CABO. And the mean difference between the 2000 IRC and 1985 SSBC only amounted to a difference of 114 Kwh, that was just barely statistically significant (p = .044). Normally January is the coldest month of the year in Georgetown, however in 2014, February was the coldest month. These findings indicate that while the changes in the 2000 IRC have had a positive impact in reducing the electrical consumption in warmer months, in colder months the code changes have little impact in reducing the electrical usage. As previously indicated, Georgetown has a cooling dominated climate, where more days each year requiring space cooling than space heating, so the consumption and use of electricity is lowest in winter months. As a result, adopting a code that provides a greater reduction in electrical use in warmer months is an appropriate strategy for this region. However, it is important to note that the building codes as implemented in Georgetown would likely be ineffective in reducing electrical consumption in a heating dominated climate.

This study did not consider the specific differences from one code to the next. However based on these findings the authors assert that the changes implemented between these codes have probably done little to affect the building envelope. In Georgetown space heating is predominantly accomplished via a natural gas fired furnace. Lighting, and appliance usage does not change significantly with seasonal temperature change, so the fundamental change from warmer months to cooler months is the energy source used for space cooling and heating, electricity is used in the summer for air conditioning and natural gas in winter for heating. As a result the authors believe that the primary cause of reduced electrical consumption has resulted from the installation of air conditioning systems with higher SEER (Seasonal Energy Efficiency Rating). So in seasons when the air conditioner is in use, a reduction in electrical usage in Kwh is seen, but in seasons when the air conditioner is not in use or used only minimally little change in electrical consumption is observed.

The City of Georgetown adopted the 2012 IRC in January of 2015, so at the time of this study, there was not electrical consumption data for homes built under that version of the code that could be compared to homes built under previous building codes. The authors intend to revisit this research in 2017 when a year's worth of electrical consumption data can be collected from homes built under the 2012 IRC and compared to homes built under the previous codes. Based on the percentage decreases in electrical consumption from the 1985 SSBC to the 1994 SSBC and Amended 1992 CABO (14%) and from the 1994 SSBC and Amended 1992 CABO to the 2000 IRC (25%) it is expected that the 2012 IRC could achieve a statistically significant reduction in electricity consumption from the 2000 IRC.

Without a return on investment increases in energy efficiency are challenging to implement. To consider the effects of reduced electricity use from building code in Georgetown some basic calculations were performed based on current residential electricity rates. In Georgetown the rate for residential electricity is $0.094/Kwh. So in the average home built under the 2000 IRC a home owner could expect to spend $246 less each year than owners of homes built under the 1994 SSBC or Amended CABO, and $395 less each year than owners of homes built under the 1985 SSBC.

Because of the variance in building code performance in colder and warmer months, the difference ranges from $10/month to $53/month, and averages to about $33 a month over a year. If homes built under the 2012 IRC have a reduction of 15% the difference in utility cost could equal over $40/month when compared to homes built under the 1985 SSBC. If an average reduction in electrical use like that seen from the 1994 SSBC and Amended 1992 CABO to the 2000 IRC (25%) occurred from the adoption of the 2012 IRC it could equate to $575 a year in savings to the homeowner. Table 7 displays these rates and projections.

Table 7. Actual and Projected Electricity Costs from one Building Code to another in 2014.

Month	1985 SSBC	1994 SSBC	Amended 1992 CABO	2000 IRC	2012 IRC 15% Reduction	2012 IRC 25% Reduction
Jan	$69.97	$53.21	$59.04	$45.71	$38.85	$34.28
Feb	$69.89	$66.14	$69.99	$59.15	$50.28	$44.36
Mar	$99.36	$95.08	$90.15	$74.53	$63.35	$55.90
Apr	$144.59	$137.57	$126.69	$102.86	$87.43	$77.14
May	$138.85	$127	$116.36	$92.28	$78.43	$69.21
Jun	$130.72	$111.91	$101.01	$77.25	$65.67	$57.94
Jul	$102.80	$86.03	$81.21	$56.54	$48.06	$42.41
Aug	$73.75	$61.96	$62.06	$44.33	$37.68	$33.25
Sep	$60.62	$50.38	$54.16	$39.07	$33.21	$29.22
Oct	$64.24	$51.01	$57.83	$38.96	$33.12	$29.22
Nov	$75.88	$59.35	$72.32	$43.41	$36.90	$32.56
Dec	$81.51	$63.65	$72.31	$42.91	$36.47	$32.18
Total	$1,111.89	$963.42	$963.13	$717.00	$609.45	$537.75

Beyond the value of $30 or $40 monthly in a home owner’s pocket, these savings in electrical utility expenses are important as they can serve as an argument for buyers of newer homes, built to more stringent codes, being able to qualify for a larger mortgage as they have more money available. By through decreased monthly utility costs homeowners would have more money available for a mortgage payment. These results represent averaged electrical usage numbers because the individual behaviors of occupants cannot be controlled, but nonetheless these results provide an empirically supported baseline.

Beyond the cost savings to the homeowner, for a utility provider that is directly tied to the municipality, like in Georgetown, these results provide empirical evidence supporting the adoption of the most up to date building codes. A statistically significant reduction in electrical usage related to a building code is data a municipality should consider in considering the adoption of building codes. Further this information has value as utility providers can better estimate electrical demand and cater generation to meet the demand.

This study represents a primary foray into electrical consumption in central Texas as it relates to building codes. As a result there are many areas that should be further researched. A few of those topics include: The comparison of these results to similar data from other climate zones. Analysis of homes built to the 2012 IRC and their electricity consumption. An analysis of the building code changes to define the changes that have led to reduced energy consumption. An understanding of the factors that lead municipalities to adoption, or not, new building codes. An evaluation of water and natural gas consumption in the same code periods to explore overall effects on energy consumption in homes.

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Theme: Low-Income and Affordable Housing

Capability Based Approach in Measuring Affordable Housing Policy in Urban India

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Abstract

Policy scientists often criticize policy analysts for narrowly focused means and rationality of policy analysis. The criticism largely focused on the recurring effort of analyzing policy based on utility, which is one-dimensional approach from the service provider perspective. But utility based approach never divulges beneficiary perspective, which is often neglected in the discussion. Be it developed or emerging economies, beneficiaries are often looked down upon devoid of any participation or voice in the quality or extent of the benefit. Considering the criticism, this paper tries to come up with an analysis strategy which would gratify the spirit of policy analysis, and help policy makers to understand the exact shortcomings of the policies.

Prime Minister Affordable Housing (PMAY 2015) policy is recently launched by the union government in India. Along with this newly introduced policy, this paper would consider 'National Urban Housing and Habitat Policy 2007' (NUHHP 2007) to understand the context of affordable housing in India. The program envisages a slum free India with inclusive and equitable cities where every citizen has access to basic civic and social services and decent shelter. It aimed to encourage states/union territories to tackle the problem of slums in a definitive manner. The objectives are to bring all existing slums, notified or non-notified within the formal system and enable them to avail of the same level of basic amenities as the rest of the town, redress the failures of the formal system that lie behind the creation of slums, and tackle the shortages of urban land and housing that keep shelter out of reach of the urban poor and force them to resort to extra-legal solutions in a bid to retain their sources of livelihood and employment.

The research opts for human capability as the measurement scale to identify policy well-being and considers state housing policies in identifying housing affordability for urban poor in India. In its methodology, the research introduces an advanced adaptation from Rawls' idea of justice, which considers 'temporal' duration in its impartiality based on his constructive idea of 'original position'. The duration signifies an individual or group is deprived of any utility or opportunity to enjoy utility. The concept of original position is the central to his idea of justice as fairness. In the recent times, Sen has discussed extensively on the issues of equality, justice and fairness. This research establishes an advanced adaptation of Sen's 'utilitarianism' and 'capability approach' to analyze RAY and identify housing affordability for urban poor in India.

Keywords: Capability approach, Utilitarianism, affordable housing, urban poor, fairness.

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1.0 Introduction

The term 'affordable housing' extensively features in government policy and financial transaction in any country. But housing affordability is very subjective and varies from place to place, even within a country. The main idea of housing affordability is to identify affordability to whom! Government sets the benchmark to define housing affordability and low cost housing. Generally government works on certain method to define affordability in its approach. India follows income approach to define economic sections' eligibility to access affordable housing. The union government considers area of individual dwelling units (DUs) to regulate access to affordable housing by economically weaker section (EWS) and low income group (LIG). Affordable housing projects are listed which uses at least 60 percent of the FAR/ FSI for dwelling units of internal area not more than 60 sq. mt. (MoHUPA, 2013). Union government defines EWS households as households having an annual income up to INR 300,000 (USD 4600) and LIG households as households having an annual income between INR 300,001 up to INR.600, 000 (USD 9200). States/Union territories (UTs) have the flexibility to redefine the annual income criteria as per local conditions in consultation with the union government (MoHUPA, 2015). Affordable housing regulation and supply network in India can be defined by the following diagram (Figure 1).

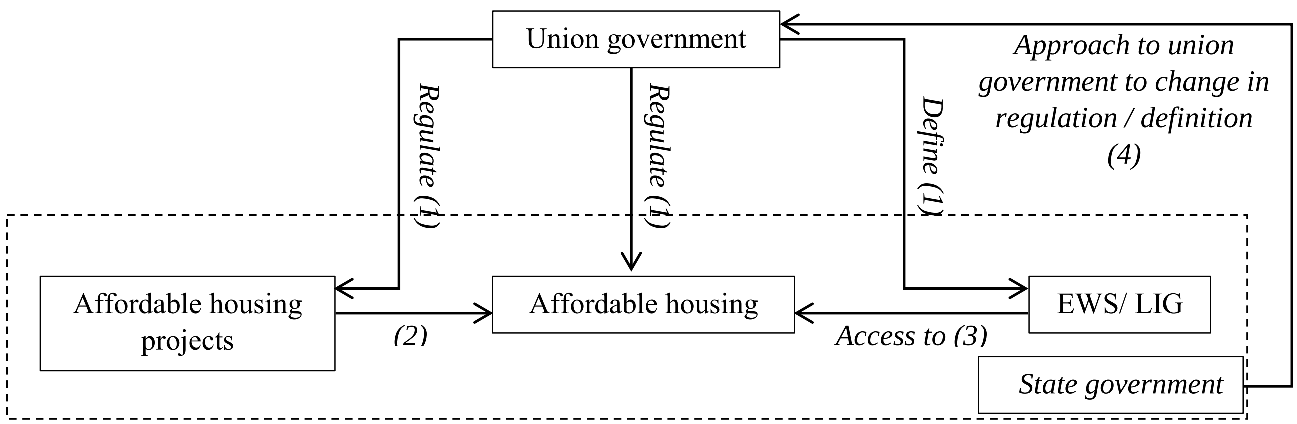

Figure 1: Conceptual Diagram of Affordable Housing Regulation and Supply Network in India

The union government regulates and defines affordable housing projects and affordable housing. These affordable housing projects can be promoted by public institutions, private institutions or PPP ventures. Affordable housing in independent projects or part of mixed housing project is also defined and regulate by the union government. Union government also regulate the eligibility to access these affordable housing by income approach. It distinguishes two categories in the name of EWS and LIG. The purpose of this distribution is to establish different magnitude of support (financial and regulatory) from the union and state government. But all housing activities take place under the physical boundary of individual states. Housing, land development and distribution are governed and monitored by state governments under their state law. If any state government wishes to make any changes in regulation or definition, it has to approach the union government with necessary justification for approval. The governance and financial distribution in Indian constitution make union government very strong in planning policy and allocation of budgetary funds. However the detailed governance framework is out of the scope of this paper. But this is not the sole approach to determine affordability. The process to determine affordability differs in other countries. United States which has similar federal governance structure like India adopts different approach in determining housing affordability. The government says housing is affordable if a family spends no more than 30% of their income to live there. This threshold is called "affordable rent burden". But in practice this 30% income varies in absolute amount. A household earning USD 1 million can allocate USD 300,000, whereas a household earning USD 30,000 can only allocate USD 9000 for house rent. To resolve this anomaly, the government calculates 30% affordability based on "median family income" (MFI). MFI is the median (and not mean) of family income distribution. Therefore different housing program targets different MFI categories. The advantage of this method is that each federal state or each city can calculate MFI of their own and can determine the range of affordable housing and its distribution to different family category. Theoretically, housing affordability should belong to almost all earning categories. Percentage of MFI can be used to identify housing affordability in different categories. But in India housing affordability is often perceived synonymous with low income housing.

In a prelude to the context of housing affordability, this paper will explore only affordable housing policy segment and not housing for slum. Although affordable housing ignite questions of affordability for whom! But affordable housing in India seems housing for urban poor (slum, EWS and LIG). Housing policy and perception is yet to be as comprehensive as US where affordability of every income group is considered. This paper establishes methodology to analyze affordable housing policy for EWS and LIG as it is the only affordable housing policy exists from the government. Two of the recent housing policy introduced during the course of past decade is discussed in this paper. Analyzing recent policies will apprise the government's perception on supplying affordable housing, and its approach towards mitigating housing situation. Conventional policy analysis considers utility based approach to determine performance of policy objectives. Utility based approach focuses on supply and demand while ignorant about the beneficiaries' ability to access utility or benefit. This paper will apply capability based approach to understand ability of policy beneficiaries' in accessing affordable housing in India. This paper also pens down subsequent discussions of the analysis. Theoretical argument of capability approach is not within the scope of this research but integration of capability approach will be discussed in this paper. The paper is structured in the following paragraphs affordable housing policy in India, capability based affordable housing analysis methodology, Methodology to analyse of affordable housing policy, and discussion & conclusion.

2.0 Affordable Housing Policy in India

The year 2007 is significantly noteworthy for history of Indian policy planning. 12^{th} five year commenced in 2007, where inclusive growth evolved as the kernel of Indian policy vision. NUHHP 2007 (introduced in 2007) outlined the country's ambition in achieving sustainable habitat and housing. The policy undertook nationwide study on housing & habitat and analyzed various contexts related to it. The policy discussed need of urbanization, balanced regional development, rural to urban shift of labor, housing and housing needs, magnitude of poverty, and various town development strategies. The relevant features of NUHHP 2007 only in affordable housing sector are listed below (MoHUPA, 2007);

i. Affordable Housing
    a) Accelerate the pace of development of housing and related infrastructure;

b) Create adequate housing stock both on rental and ownership basis with special emphasis on improving the affordability of the vulnerable and economically weaker sections of society through appropriate capital or interest subsidies; and
c) Use technology for modernizing the housing sector for enhancing energy and cost efficiency, productivity and quality. Technological advances would be disseminated for preventing and mitigating the effects of natural disasters on buildings, e.g., in case of earthquakes, floods, cyclones, etc.

ii. Increase flow of Funds
a) Promote larger flow of funds from governmental and private sources to fulfil housing and infrastructure needs by designing innovative financial instruments;
b) Remove legal, financial and administrative barriers for facilitating access to tenure, land, finance and technology; and
c) Shift to a demand driven approach and from subsidy based housing schemes to cost recovery cum subsidy schemes for housing through a proactive financial policy including microfinance and related self-help group programs.

iii. Spatial incentives
a) Innovative spatial incentives like relaxation of floor area ratio (FAR) to ensure that 20-25 % of the FAR are reserved for economically weaker section (EWS)/ low income group (LIG);
b) Transferable development rights(TDR) for clearance of transport bottlenecks in the inner-city areas; and
c) Availability of additional FAR in outer zones would be promoted with a view to meet the housing shortage amongst EWS/LIG;

iv. Increase Supply of Land
a) Facilitate accessibility to serviced land and housing with focus on EWS and LIG;
b) Suitable restructuring for enabling institutions at state and centre levels as well as the private sector for increasing supply of land.

In 2015 “Housing for all scheme” is introduced with the implementation of Pradhan Mantri Awas Yojana (PMAY 2015). The policy title can be translated into Prime Minister Housing Policy 2015. The policy identified three affordable housing strategies out of four strategies[2]. The strategies and its salient features are identified below (MoHUPA, 2015);

i. Affordable housing through credit linked subsidy;
a) Extension of credit flow to EWS & LIG for acquisition, construction of house;
b) Housing finance companies and other such institutions are eligible for an interest subsidy at the rate of 6.5 % from the government for 15 years or during the tenure of loan whichever is lower;
c) Ceiling of subsidised credit is INR 600,000 (USD 9250). Credit beyond this limit is non-subsidised. Ceiling area for EWS is 30 sq. mt. and LIG is 60 sq. mt.
d) The net present value (NPV) of the interest subsidy will be calculated at a discount rate of 9 %.

ii. Affordable housing in partnership; and
a) Affordable housing in partnership with state/UT, local government or private enterprises for EWS;
b) Union government support with INR 150,000 (USD 2300) per EWS family;

[2] "In situ" slum redevelopment being the other strategy.

iii. Subsidy for beneficiary led individual house construction
   a) Beneficiary belong to economically weaker section who possesses land but do not have required fund to construct houses or wish to enhance existing houses on their own; and
   b) Union government support with INR 150,000 (USD 2300) for housing construction for the EWS family.

Under PMAY 2015, all state government are required to draft 'Housing for all plan of action' (HFAPoA) and annual implementation plan (AIP) up to the year 2022, considering available resource and immediate priority.

3.0 Capability based affordable housing analysis methodology

Policy analysis framework is a set of causal linkages among the four components – policy, objective, strategy and constraints (Pearson, Gotsch, & Bahri, 2003) (Figure 2).

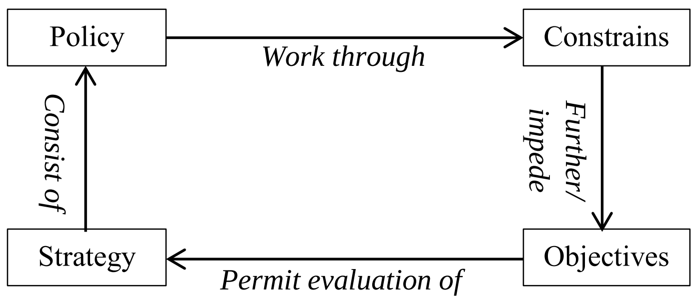

Figure 2: Causal linkages among policy components

Policy works through constraints to impede its objectives which in return permit evaluation of strategies; which consist of policy. The strategies consist of sets of policies that are intended to improve outcomes. The selected policies work through the constraints set by parameters. The constraints set by supply, demand, and world price conditions, either further or impede the attainment of objectives. An assessment of the impact on objectives permits an evaluation of the appropriateness of given strategies. Policy makers introduce policies generally to achieve precise objectives and design certain strategies. Constraints are varied and of many types. Constraints are the important practical consideration for policy planning. Initially many of the constraints are difficult to predict. Therefore policies always go through improvisations and reforms. If the whole process is considered as a system, some of the constraints are inevitable like financial constraints, legal constraints etc. Strategies mostly concerned about the method but policy is a combination of strategy and objective. Too much concentration on the strategy means the analysis would be more output centric while avoiding the process and objectives. Favourable output for some is not necessarily maximise benefits. Benefit maximisation only happen when it benefits all or most of the people. The role of a researcher or policy analyst is to look into the combination rather than only one aspect.

Policy analysts also work towards establishing analysis methodology to measure policy performance. The traditional method to measure policy performance is opulence/utility based measurement and monetization of policy implementation. Opulence (income, commodity command), utility (happiness, desire fulfilment), and wealth (income per capita) does not automatically imply better life[3]. Well-being or peace of people due to successful implementation from a policy deems more than achievement of utility in the context of housing policy. This paper has moved from an income or utility based approach to an overall analysis of well-being. It has presumed to work with a wide set of indicators that can assume quantitative or qualitative (dichotomous and ordinal) values or linguistic attributes such as good, bad, low, high and so on. Capability approach introduced by Professor Amartya Sen is a critique of traditional measure and an approach to measure policy based on its well-being to people or society[4]. The advantage of capability approach is that points out the exact reasons for policy fiasco and the causal linkages for the fiasco. The traditional method of utility based policy analysis considers single dimension or attribute which cannot substantiate the required outcomes to explain every theoretical argument.

Sen observes that the welfare and social safety from policy benefits does not necessarily permit liberty of a person from specific agony which is supposed to be resolved by policy benefit. The person does not mature any skill or minimum liberty to make an independent decision within the domain involving matters which has substantial consequence in her/his life. Policy planners often consider welfare or subsidy to extend support to deprived people and weaker section of the society. But seldom the approach of welfare and social safety (as a policy objective) unable to make her/him confident to perform the intended activity diligently and brings about additional social shame from the non-beneficiaries in the society. The manifest is seldom limited in the utility perspective of evaluating alternative social states. Sen eventually introduces that wellbeing of a person should be deemed to consist not in utility but in the opportunities people have to live the kind of life they have the reason to value. What matters is whether people can do and be the things they value and have reasons to value (Osmani, 2009). Sen uses the term “functioning” to represent a person’s actual achievement of a person’s doing and beings. The level of functioning can judge a person’s wellbeing. But choice of functioning is not entirely in her/his control given the resource constrains and additional difficulties. Sen specifies this opportunity set as “capability” of a person. In many instances capability of a person (the overall opportunity) needs to be considered rather than the particular combination of functioning. The concept of functioning is multi-dimensional than considering only utility. Functioning or wellbeing becomes measurable with a combination of vectors of measurement from different functional fields. Conceptually, a person to be happy needs to combine all the functioning that she value in her/his life. For example, a person’s wellbeing from the benefit of affordable housing policy can only be realised if she/he can construct the house, carryout any future modification or enhancement without any state support and become independent in accessing additional benefits commencing from other policies. In this context facilitating deprives to resolve her/his problem enables capability than direct welfare. Policy needs to be more concerned with expanding the freedom that we have reason to value, and enhancing the lives we lead and the freedoms we enjoy. But

[3] Sen observes that different people and societies typically differ in their capacity to convert income and commodities into valuable achievements. He cites the example of Gabon or South Africa or Namibia or Brazil, which are much richer in per capita GNP than Sri Lanka, China or the state of Kerala in India, but have very low life expectance at birth compare to the later. He begins by considering income or commodity and command like Adam Smith, which emphasizes that economic growth and the expansion of goods and services are necessary for human development but reiterates that mere wealth, is not good. Welfare approach is good in a sense that it provides additional benefit for the unprivileged people or group of the society. But at the same time it only concentrates on immediate happiness and desire fulfilment. Although it is important to take note of utility but utility or desire fulfilment is only one part of human existence. There are many other things of intrinsic values of human life like rights and freedom – which is totally neglected in welfare and utility based approach. It is difficult to conclude that human well-being only depends on opulence like income or commodity or utility happiness, (immediate) desire fulfilment (Clark, 2006).

[4] See (Sen, 1993), (Sen, 1997).

freedom alone can be the sole judge of well-being or individuals. The way freedom is achieved is also a key to overall development. An individual needs to enhance her/his own capabilities to achieve rather than depending on fulfilment of some utilities or inherit some primary goods. Capability can be seen as an inherit quality which enables individuals to choose many different functioning depend on their choices. But utilities do not offer any choices and concentrate within the offered utility to individuals. So the direct approach of development would be to focus on the "concept of functioning". The concept of functioning reflects various things a person may value doing or being. The valued functioning can be very elementary or basic ones to complex activities or personal tastes or advanced ones. In the present paper these two functioning(s) may be called "elementary functioning" and "advanced functioning". Functioning reflects the state of individuals and depends on variety of elements ranges from personal and social factors. An individual's "capability" refers to the alternative combinations of functioning that is feasible for her/him to achieve. Capability is thus a kind of freedom – the substantive freedom to achieve alternative functioning (Sen, 1999). For example, an individual belong to economically weaker section can choose to build her/his house or come out of informal settlements to rent a house with the help of her/his own with the help of certain factors like legal (with land allotment), financial (resource to buy/rent land, credit from financial institutions), and livelihood (secured job). These factors can be called as policy benefit/strategy or "functioning vector". In the process of evaluation these "functioning vectors" actually are individual dataset collected from secondary source which then transformed into a real number. And freedom of having own shelter of that particular individual depends on the selection of alternative functioning(s) of land, credit from financial institutions, and secured livelihood to repay the credit and sustain in life. While discussing capability approach, it can be seen that the evaluative focus of capability approach can be based on either "realized functioning" and the "real opportunity" she/he has. "Realized functioning" implies what a person is actually able to do and real opportunity implies the capability set exists for her to choose but for some reason or so she is unable to choose the functioning. The two forms of capabilities give different types of information – while the first one gives information about the things an individual does and the second one gives information about the things a person is substantively free to do but presently is not able to do for some reasons. Sen stresses the need for pragmatism in using the motivation underlying the capability perspective for the use of available data for practical evaluation and policy analysis. Capability and functioning remain intimately connected but capability is evaluated in the space of functioning thus functioning is integral element of capabilities (Comim, Qizilbash, & Alkire, 2008). Relation with capability approach and causal linkage of policy is given below. Policy and strategy wellbeing provide the means to achieve aimed target, which can be termed as realised functioning. Consequences of policy wellbeing proceed through obstacles (situational variable) to equip real opportunity to policy beneficiaries. Policy beneficiaries need to have the freedom to choose among the capability set to achieve the functioning set (or achieve functioning) (Figure 3). Analysis methodology developed in figure 3 adopts capability approach as the basis. The concept and the methodology conforms policy beneficiaries' option of availability of real opportunity/ capability set as policy consequences, and political, administrative, financial and legal freedom to choose among the capability set to achieve functioning. The framework inform whether the policy consequence extend opportunity for policy beneficiary and whether beneficiary have freedom to choose achievement or functioning set.

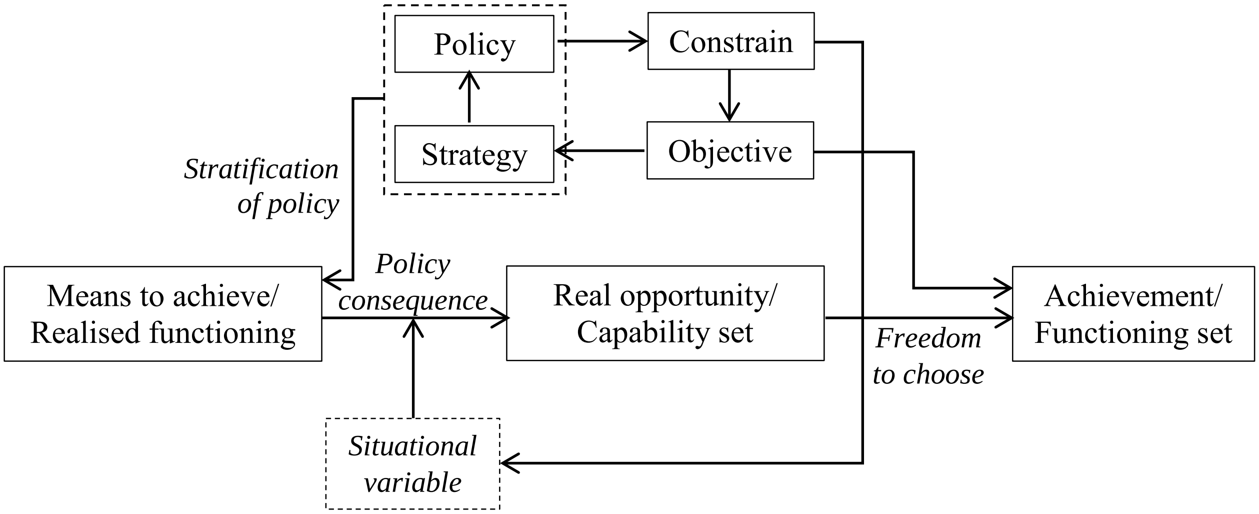

Figure 3: Relation with capability approach and causal linkage of policy

4.0 Methodology to analysis of affordable housing policy

Analysis of NUHHP 2007 and PMAY 2015 are initiated with stratification of both these policies in strategy and objective, and constrains (Table 1 & 2).

Table 1: Stratification of NUHHP 2007 policy into objective, strategy and consequence

NUHHP 2007		
1. Affordable Housing		
Objective	Strategy	Consequences
Creating adequate housing stock	Accelerate pace of housing and related infrastructure development	Opportunity of increased supply of housing
	Rental and ownership through appropriate capital or interest subsidies	Scope of housing affordability of vulnerable and economically weaker sections of society
Modernizing housing sector to enhance energy, cost efficiency, productivity and quality	Technological intervention in housing sector	Possibility for disaster resilience housing stock
2. Housing Finance		
Adequate fund flow to housing sector	Design innovative financial instruments	Possible improvement in housing finance
	FDI in housing sector	
Design suitable fiscal concessions	Appropriate monitoring mechanism	Opportunity to utilization of fiscal concession to deserving beneficiary
	Correctly targeted concessions	
Demand driven approach and cost recovery cum subsidy schemes	Microfinance and self-help group	Possible improvement in housing finance for urban poor
3. Supply of land & housing stock		

Facilitating access to service land	Utilization of vacant land belong to state or local government	Possible utilization of urban land for housing stock
	In situ slum rehabilitation	Opportunity for improvement in slum housing
Efficient utilization of urban land for enhanced area under housing	Review for enhanced FAR as per international standard	Scope for more built up area, or additional area as compensation of building housing for urban poor
	FAR incentive, TDR for housing supply to urban poor	

Table 2: Stratification of NUHHP 2007 policy into objective, strategy and consequence

PMAY 2015		
1. Affordable Housing through Credit Linked Subsidy		
Objective	Strategy	Consequences
Demand side intervention with expanding institutional credit flow to the housing needs of urban poor	Interest subsidy at the rate of 6.5 % for a tenure of 15 years or during tenure of loan whichever is lower	Opportunity to access housing loan up to INR 600,000 (USD 9250) by urban poor
	Housing loans for new construction and addition of rooms, kitchen, toilet etc.	Possible expansion of housing activity in urban areas for both new construction and addition
2. Affordable Housing in Partnership		
Supply side intervention with increased availability of houses for EWS category at an affordable rate	Central government's assistance of INR 150,000 (USD 2300) per EWS house	Confirmed financial assistance of USD 2300 per EWS house
	State/local government or private enterprise can plan AHP projects	Opportunity for AHP projects
3. Subsidy for beneficiary led individual house construction		
Demand side intervention to individual eligible families belonging to EWS categories with land/house to either construct new houses or enhance existing houses	Central government's assistance of INR 150,000 (USD 2300) per EWS house	Confirmed financial assistance of USD 2300 per EWS house
		Urban poor with land have the opportunity to construct house or house can enhance their houses

Policy consequences identified in the above two tables will extend real opportunity to the policy beneficiaries in choosing their desired functioning set. Now it depends on the beneficiaries' freedom to choose the functioning set. The scope of the present paper is not to analyse the housing policy but to establish the methodology which can be utilized for empirical analysis. Operationalizing capabilities is a challenge in itself. Comim's view of measuring capability seems to be effective and rational process in measuring capability (Comim, 2001). Measurement of capability has always remains a challenge for researchers around the world. There are many different ways through which the theory can be put into effect. Sen himself does not specify any specific measurement method as his preferential process. He lefts the decision on the individual researcher and the type of capability one wants to measure. If freedom is only instrumental importance and no intrinsic relevance for the wellbeing, evaluation of the capability can be done by option actually chosen or by maximally valued option from the capability set. However, if the freedom of choice is seen as a part of living and we think that “doing x” is different from “choosing to do x and doing it”, the entire set of options open to the person must be considered (Martinetti, 2000). Sen himself does not stress much only on freedoms to achieve citing the remarkable empirical connection linked with different types of freedom. To analyze housing policy, this paper recommends considering multidisciplinary set of attributes as affordable housing have both instrumental and intrinsic value.

Once the policy consequences and policy strategy is operational, the functioning set can be identified for empirical analysis. Policy beneficiaries need to have the freedom to choose the opportunity she/he feel necessary to achieve functioning set (Table 3).

Table 3: Arrangement of functioning sets and real opportunity for analysis

Functioning Set	Real opportunity
Opportunity to obtain shelter	Develop or maintain personal property
	Access to institutional credit to develop shelter
	Shelter development without job loss
	Ability of loan repayment
Private participation in construction housing for EWS & LIG	Government security on mortgage of EWS/LIG beneficiary
	Credit worthiness of beneficiary
	Recovery of investment
	Administrative, legal and financial security in investment

5.0 Discussion & Conclusion

Capability approach itself is a great challenge in transforming theoretical richness into measurable objectives. But great challenges bring more opportunity from its inferences. Selection of certain functioning and the choice of the most suitable indicators to represent them are problematic to choose. But if considered intimately, it does not seem to create much of a problem. Capability set is not directly observable and are constructed based on the basis of presumptions, as suggested in present research. Thus it might happen in practice that, the analysis may need to settle in relating wellbeing to achieve functioning set and observe functioning rather than trying to bring in the capability set (Comim, 2001). In case of design of public actions or policy planning, more helpful and effective information can be derived from an articulated picture rather than misleading indexes extract from traditional ways of analyzing utility or income or distribution (Martinetti, 2000).

Housing policy in India evolves significantly since the independence. Initial strategy was linked with direct assistance to provide housing and integrate housing as job benefit. But the supply was never adequate to outpace the rising demand. Even with moderate to low level of urbanization housing shortage had been a perennial problem in India. Gradually, the government realizes its limitation as provider and reorients its role as facilitator. Advent of economic liberalization and emergence of private enterprise help the government towards meaningful dissemination of its responsibility. Given the amount of demand and housing shortage, supply of adequate housing stock has always remained a challenge. The shortage of urban houses stood at 18.8 million units in 2012. With business as usual, the shortage can reach up to 34.1 million by 2022. The modified strategy of the government to act as a facilitator may encourage private enterprises to invest more in housing for urban poor and socially vulnerable group.

The most persistent challenge of this paper is to identify logical method to establish an analysis framework to explain the various modality of the theoretical contribution. The traditional method of utility based policy analysis considering single dimension or attribute cannot substantiate the required outcomes to explain every theoretical argument. The virtue of this noble theme demands some unique propositions as the framework of analysis. The paper highlights the necessity of embracing capability approach to measure wellbeing in establishing success from policy benefit. The paper also demonstrates the process by establishing two functioning sets with relevant opportunity that leads to achieve these functioning sets. Policy beneficiaries need to have the freedom to choose among the opportunities to achieve functioning set. The advantages of capability approach are that it is multidimensional, uses goodness instead of utility as a measurement indicator. Capability approach relies on different functioning which a people value in her/his life and the freedom people have to choose among different functioning. The housing policy can be termed successful if it can invigorate freedom among beneficiary to obtain shelter without direct benefit from the government. In some sense true measure of policy to invoke this freedom from the government benefit system and become independent rather being dependent on government help forever. It is beneficial for the government also, which finds it impossible to enable direct assistance to alleviate housing shortage. Rightfully, government has altered its approach to support more number of people. Facilitating policy benefit with financial, legal, administrative strategies allow private enterprises and investor to invest in affordable housing. And capability approach can be the ideal tool to measure the approach and suggest necessary modification in approach if any is required.

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Review of Test Methods for Selected Building Enclosure Component Types

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ABSTACT

Building enclosure physically separates the interior from the exterior of a building. It consists of walls, windows, doors, roofing and foundations, insulation, barriers, membranes and other components aimed at controlling heat, air and moisture that can flow through the building enclosure. Today's global environmental crisis has significantly drawn attention to green building design and construction. Since building enclosure and its performance seriously impacts the energy consumption of a building, and because there are great variety of material and system types that can be used in the enclosure, validation testing of building enclosure components is vital to ensure the energy-efficiency and durability of a building. There is a need for more widespread awareness of the test methods for different components of building enclosure as such understanding helps design appreciate the basis upon which they will be prescribing or specifying various product types. This paper provides a review of most relevant test methods for several residential building enclosure components types. The test methods discussed provide a means to evaluate performance of these components when subjected to various physical and environmental conditions. The review is introductory and can be useful to those without prior knowledge of such test methods.

The paper presents summary results of a review of several building enclosure component types including vapor barriers/ retarders, waterproofing membranes, air barriers/retarders and insulations along with relevant test methods. The paper includes a brief introduction of each building enclosure component type made by a selected number of manufacturers, including their uses, features and application approach. The main focus of the paper, however, is on the ASTM test methods for evaluating their important mechanical properties. For each particular ASTM test method, the paper summarizes test objective, apparatus, procedure and analysis of the results. The paper offers a quick overview of the tests each product goes through as per manufacturer website and introduces appropriate references for each test for follow-up reading.

1.0 INTRODUCTION

Today's global environmental crisis has drawn increasing attention to design of energy-efficient buildings. Among all building components, building enclosure has the greatest impact on the energy consumption of a building and because there are great variety of material and system types that can be used in the enclosure, testing for performance validation of building enclosure components is vital to improve and enhance the energy-efficiency and durability of a building. There is a need for more widespread awareness of the test methods for different components of building enclosure as such understanding helps design professionals appreciate the basis upon which they will be prescribing or specifying various product types.

The objective of this paper is to review standard test methods for building enclosure components and to provide a summary of most commonly used methods. Testing of enclosure components will improve the quality of systems that protect the building with respect to heat, air and moisture transfer and help energy performance. It is introductory and can be useful to those without prior knowledge of such test methods.

There are three different physical states of moisture: solid (ice), liquid (water) and gas (vapor). Water vapor primarily moves with air or by diffusion. Air movement accounts for most of the water vapor migration through a building, while diffusion through materials is a much smaller and a very slow process. Once air reaches its dew point, the moisture that the air can no longer hold will condense. This can happen in attics, foundations, and walls, and the result is wet framing and insulation with potential for mold grow. Moreover, the building will become less comfortable, and costly to heat and cool and less energy-efficient. Thus, a variety of building enclosure products have been developed to control moisture: Vapor barriers/retarders retard the diffusive water vapor migration; Waterproofing membranes are designed to prevent water penetration through the membrane; Air barriers control air movement through the envelope; Insulation reduces heat transfer or flow and helps avoid condensation. Among these products, vapor barriers/retarders and waterproofing membranes are both functioned to control moisture but with a difference: Vapor barriers/retarders prevent or retard vapor increment due to diffusion; Waterproofing membranes prevent penetration of water in its liquid state.

The paper introduces a selected number of products and ASTM test methods related vapor barriers/ retarders, waterproof membranes, air barriers and insulations.

2.0 VAPOR BARRIERS/ RETARDERS

As an important part of building enclosure, vapor barriers/retarders help reduce water vapor related problem in enclosure performance. Vapor barriers/retarders are generally applied on walls, roofs or under slabs. In this section, four representative vapor barrier/retarder products are introduced with corresponding technical data sheets included to help a better understanding of the test methods.

2.1 Introduction of Selected Vapor Barrier/ Retarders

AIR-SHIELD ™ Self-Adhering Air/Vapor and Liquid Moisture Barrier AIR-SHIELD is a roll-type air/vapor and liquid moisture barrier product. It will adhere to surfaces of precast concrete, cast-in-place concrete, masonry (concrete block), interior and exterior gypsum board, styrofoam, primed steel, aluminum mill finish, anodized aluminum, primed galvanized metal, drywall, and plywood (Figures 1 and 2).

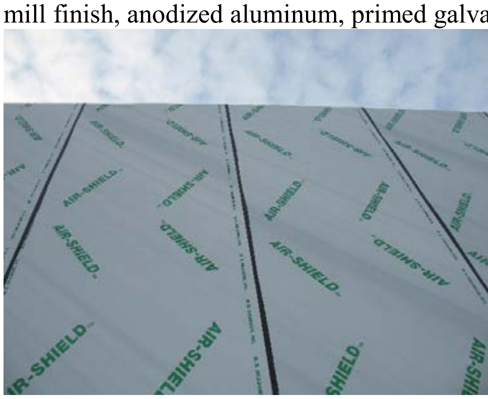

Figure 1 AIR-SHIELD ™ barrier product
(Courtesy of W. R. Meadows, Inc.)

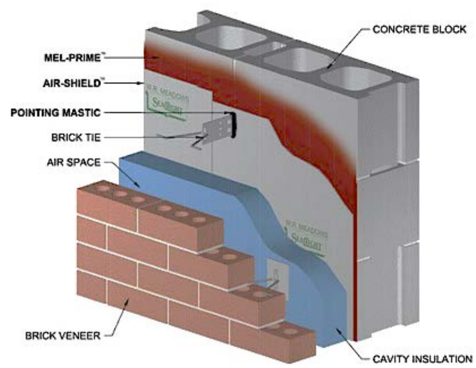

Figure 2 AIR-SHIELD ™ barrier in wall assembly
(Courtesy of W. R. Meadows, Inc.)

DuPont™ Tyvek® DrainWrap™ Moisture Barrier DuPont™ Tyvek® DrainWrap™ has a vertically-grooved surface that can provide protection against water on the wall assembly and facilitate drainage. The material fabric structure can help drying in the wall system and keep bulk water out but to allow water vapor to pass through it. (Figure 3).

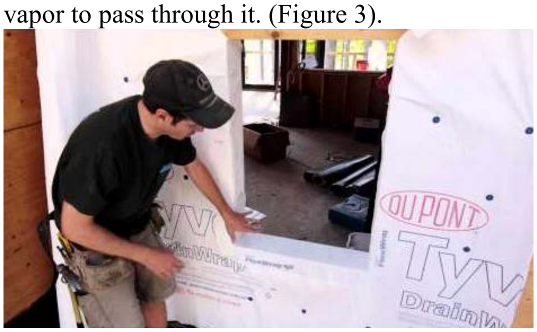

Figure 3 Application of DuPont™ barrier
(Courtesy of Professional Remodeler magazine/Photo: Erika Taylor)

Figure 4 Application of 3M™ barrier
(Courtesy of Panthereast)

3M™ Air and Vapor Barrier 3015 3M™ Air and Vapor Barrier 3015 is an air and vapor barrier membrane designed to allow application in temperature range between 0°F to 150°F. The membrane has self-sealing property against nail fasteners and penetrations. It can be installed onto wall with a rubber roller (Figure 4).

Stego® Wrap Vapor Barrier Stego® Wrap Vapor Barrier is a low permeance under-slab vapor barrier membrane. Stego® Wrap is installed over the area where the concrete slab is to be placed. Permeance, puncture resistance and tensile strength tests as well as other conditioning tests are conducted for Stego® Wrap Vapor Barrier.

Table 1 summarizes various ASTM tests the manufacturers have reported in their test data sheets. The test methods are explained in the next section.

Table 1 Summary of ASTM Test Methods for Vapor Barriers/ Retarders Products.

Properties	AIR-SHIELD ™ Self-Adhering and Air/Vapor Liquid Moisture Barrier	DuPont™ Tyvek® DrainWrap™ Moisture Barrier	3M™ Air and Vapor Barrier 3015	Stego® Wrap Vapor Barrier	GRIFFOLYN® Vapor Wall Retarders & Barriers
Water Vapor Permeance	E 96 (B)	E 96(A, B)	E 96	F 1249 E 154	E 96
Water Absorption	D 1970 D 570-81				
Air leakage/ Air Penetration	E 2178 E 283 E 2357	E 2178	E 2178		
Tensile Strength Film	D 412 D 882	D 882	D 882		D 882
Elongation Film	D 412 D 882	D 882	D 882		
Puncture Resistance	E 154			D1709	D 4833
Lap Peel Strength	D 903				
Lap Adhesion			D 3330		
Pull Adhesion			D 4541		
Tear Resistance		D 1117			
Surface Burning Characteristics		E 84	E 84		
Low Temperature Flexibility			D 1970		
Dart / Cold Impact Strength					D 1709
Nail Sealability			D 1970 E 331/547		

2.2 Test Methods for Vapor Barriers/Retarders

The major property of vapor barriers/retarders that need to be tested is water vapor transmission and its rate in that the performance of vapor barriers/retarders depends on this property of the material. Other properties include tensile strength, elongation and low temperature flexibility. Standards ASTM E96 and ASTM F1249 describe the test methods for water vapor transmission property.

ASTM E96: ***Standard Test Methods for Water Vapor Transmission of Materials***

The purpose of this test is to obtain values of water vapor transfer through permeable and semipermeable materials expressed in term of Water Vapor Transmission (WVT). It is applicable for specimens that are not over 1¼ in. (32 mm) in thickness. Two methods with different test procedures are introduced: the Desiccant

Method and the Water Method. The test procedure is explained in Figure 5.

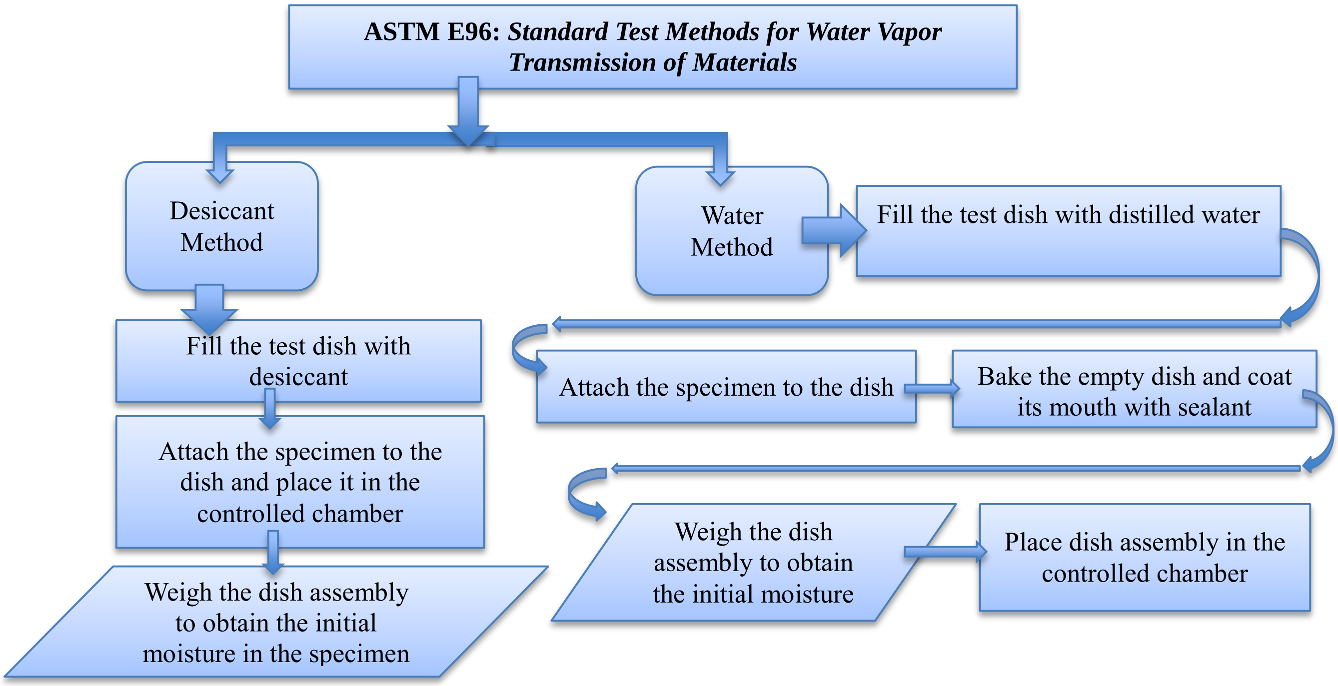

Figure 5 Flow chart of ASTM E96 Test Procedure

There are two ways of analyzing the results to obtain the Water Vapor Permeance:

- Graphic Analysis: Plot the weight against elapsed time (modified by the dummy specimen if used). Then inscribe a curve that tends to become straight. In this case, a nominally steady state is assumed, and the slope of the straight line is the rate of water vapor transmission.
- Numerical Analysis: A mathematical least squares regression analysis of the weight as a function of time will give the rate of water vapor transmission.

ASTM F 1249: ***Standard Test Method for Water Vapor Transmission Rate through Plastic Film and Sheeting Using a Modulated Infrared Sensor***

This test is to obtain values for the water vapor transmission rate (WVTR) through barrier material. Also, permeance of the film to water vapor, and for homogeneous materials, water vapor permeability coefficient can be determined in this test. It is applicable for flexible material specimens up to 3 mm (0.1 in.) in thickness.

The barrier material to be tested separates dry chamber from a wet chamber of known temperature and humidity, which make up a diffusion cell where the test film is sealed. The pressure-modulated infrared sensor measures the fraction of infrared energy absorbed by the water vapor and produces an electrical signal. Comparing the signal to the one produced by measurement of a calibration film of known water vapor transmission rate, the rate at which moisture is transmitted through the test material can be calculated.

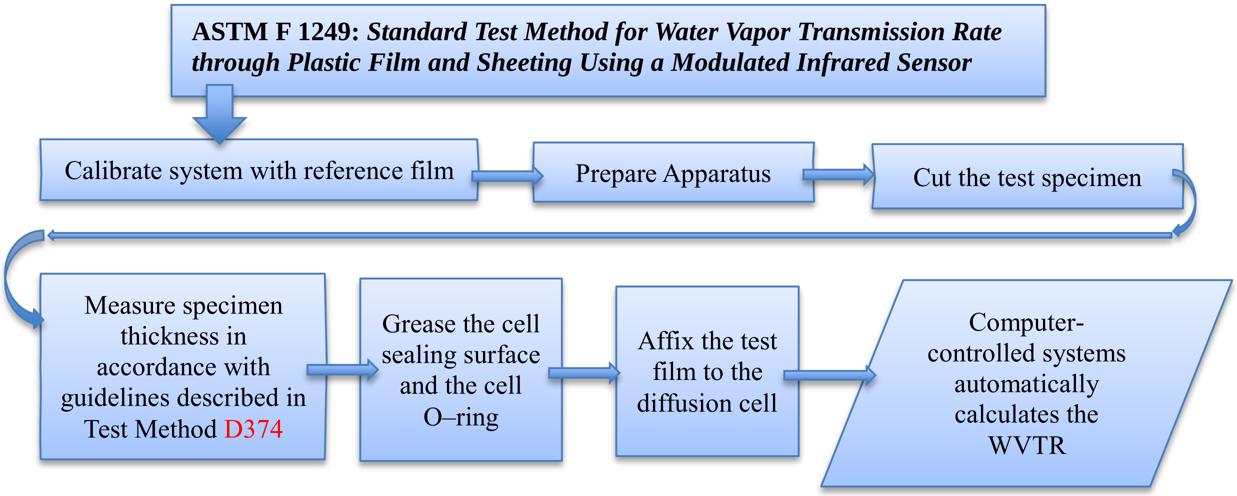

Figure 6 Flow chart of ASTM F 1249 Test Procedure

Summary of Test Methods for Water Vapor Transmission:
The methods are intended to allow approaching the actual conditions of use of vapor barriers/ retarders with test temperature and relative humidity conditions clearly stated.
Roof and wall vapor barriers/ retarders are generally tested with the method introduced in ASTM E96 Standard Test Methods for Water Vapor Transmission of Materials, while under-slab options are usually tested according to ASTM F 1249 Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor.

Tensile Strength The test methods applied to test tensile strength of vapor barriers/ retarders are described in standards ASTM D 412 *Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension* and ASTM D 882 *Tensile Properties of Thin Plastic Sheeting*.
The purpose of ASTM D 412 test is to evaluate the tensile properties of vulcanized thermoset rubbers and thermoplastic elastomers. Two types of test specimen are used corresponding to two different test methods.
1) Dumbbell and Straight Section Specimens— Test Method A Figure 7 explains the test procedure

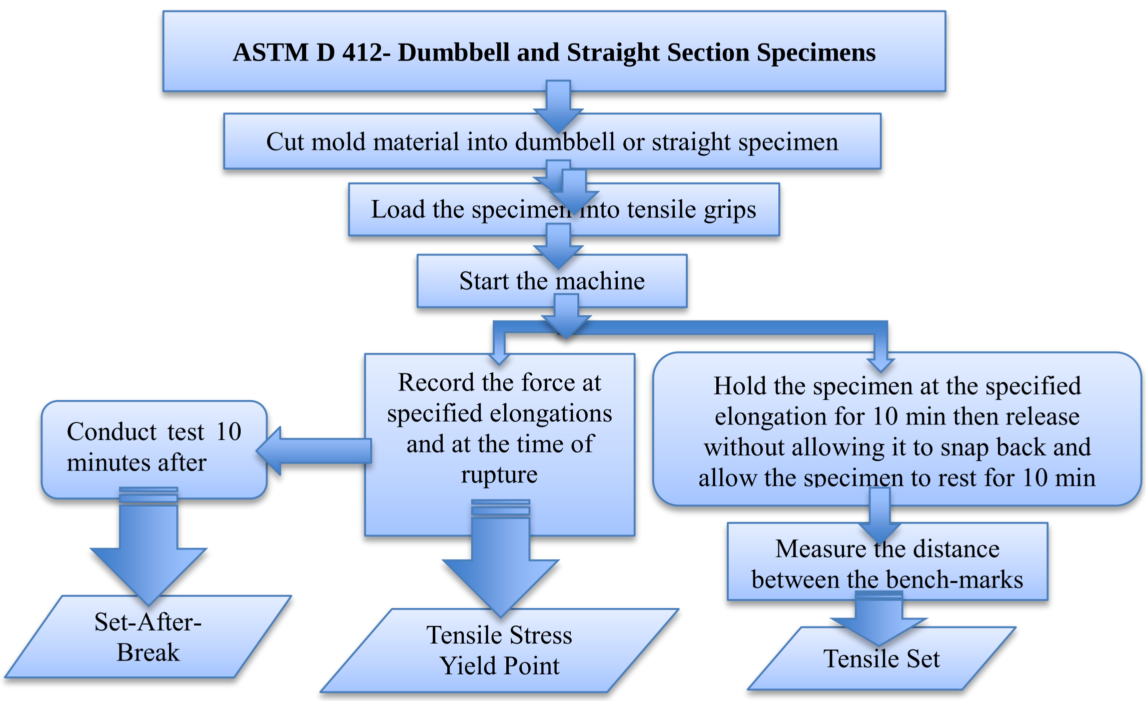

Figure 7 Flow chart of ASTTM D 412 Method A Test Procedure

2) Cut Ring Specimens— Test Method B One important characteristic for stress-strain properties of ring specimen is that the inside strain (or stress) is greater than the outside strain (or stress) because extending the ring generates a non-uniform stress (or strain) field, which is different from the dumbbell and straight specimens. But the stress-strain properties of ring specimens are calculated in the same manner for dumbbell and straight specimens. The test procedure is explained in Figure 8.

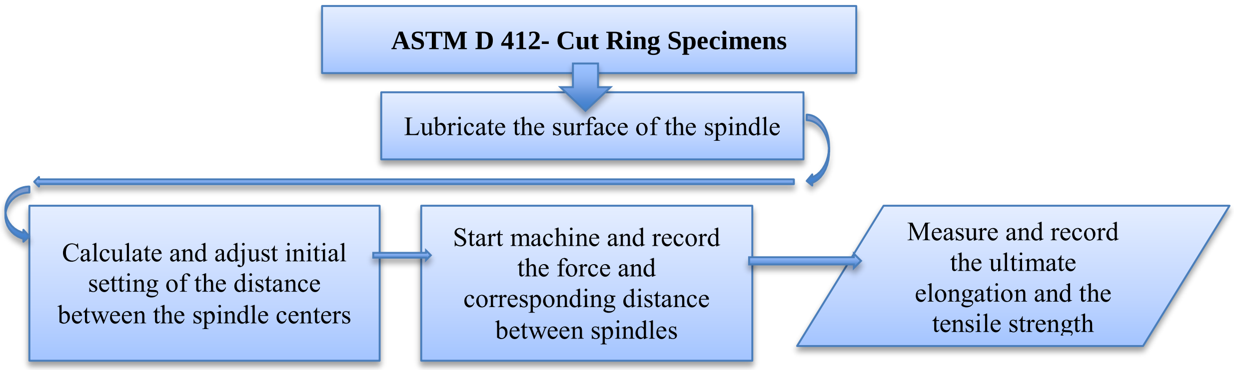

Figure 8 Flow chart of ASTTM D 412 Method A Test Procedure

ASTM D 882

The ASTM D 882 test is to determine tensile properties of thin plastic sheeting and films, with thickness less than 1.0 mm (0.04 in.). Figure 9 explains the procedure for this test method.

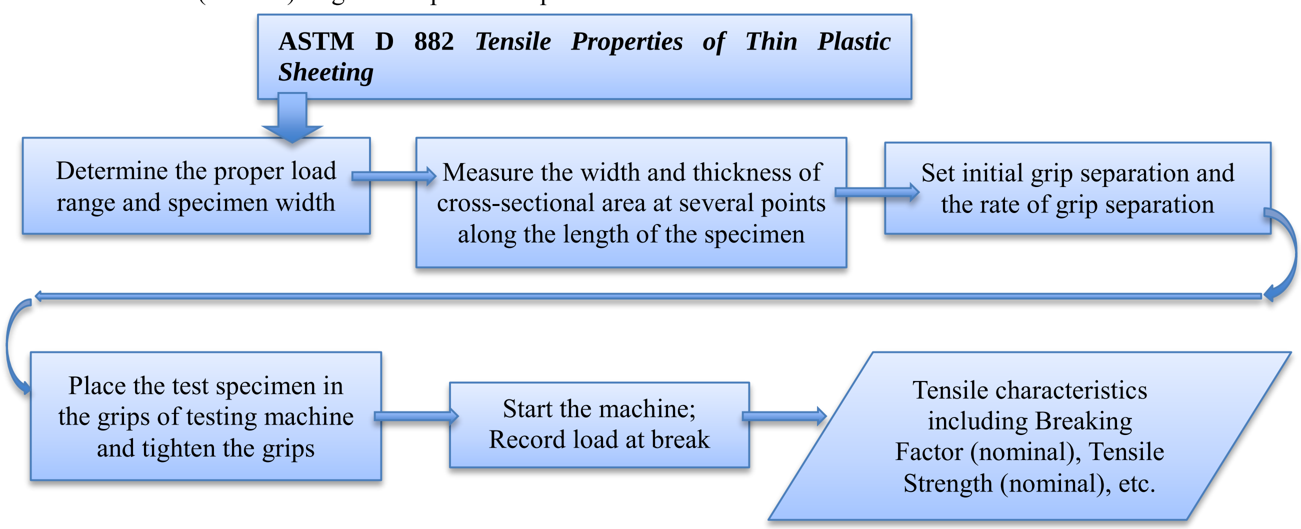

Figure 9 Flow chart of ASTM D882 Test Procedure

Low Temperature Flexibility

ASTM D 1970 ***Standard Specification for Self-Adhering Polymer Modified Bituminous Sheet Materials Used as Steep Roofing Underlayment for Ice Dam Protection*** This test method is to determine the low temperature flexibility of the underlayment sheets. This standard is for polymer modified bituminous sheet materials used as underlayment to prevent leakage from water back-up due to ice dams. The procedure is shown in the following flow chart in Figure 10:

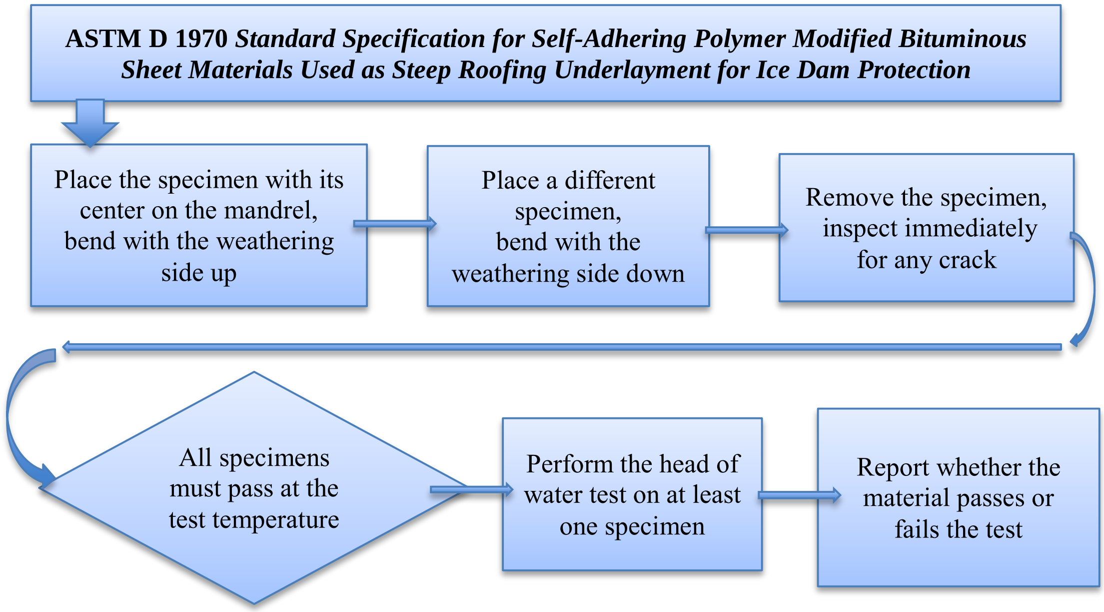

Figure 105 Flow chart of ASTM D 1970 Test Procedure

3.0 WATERPROOFING MEMBRANES

Waterproofing is used to prevent water intrusion into the structural elements of a building or its finished spaces. Building envelope systems including roof, siding, foundations, walls, basements, and all of the various penetrations through these surfaces need to have waterproofing material applied. Waterproofing membrane can either be applied to the interior, the exterior, or in places inaccessible by people. Types of waterproof membranes include applied or liquid membrane, film or sheet membrane, built-up or laminate membrane and injectable waterproofing.

3.1 Introduction of Selected Waterproofing Membranes

TAMKO®TW-60 Sheet Waterproofing Membrane TAMKO® TW-60 is a self-adhering rubberized asphalt sheet membrane with a polymer film on the surface. It can be applied as below-grade waterproofing of foundation walls, tunnels, earth shelters, ICF forms and similar structures (Figure 11-12).

Figure 11 TAMKO®TW-60 Sheet (Courtesy of TAMKO)

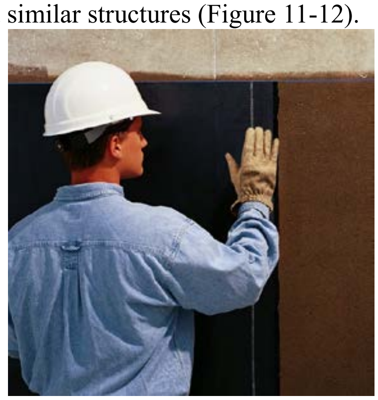

Figure 12 Application of TAMKO®TW-60 Sheet (Courtesy of TAMKO)

W. R. MEADOWS MEL-ROL Waterproofing Membrane MEL-ROL is a rolled and self-adhering waterproofing membrane composed of thick layer of polymeric waterproofing membrane on a cross-laminated polyethylene carrier film. It can be applied to waterproof foundations, vertical walls, and below-grade floors (Figure 13-14).

Figure 13 Installations of MEL-ROL Membranes (Courtesy of W. R. Meadows, Inc.)

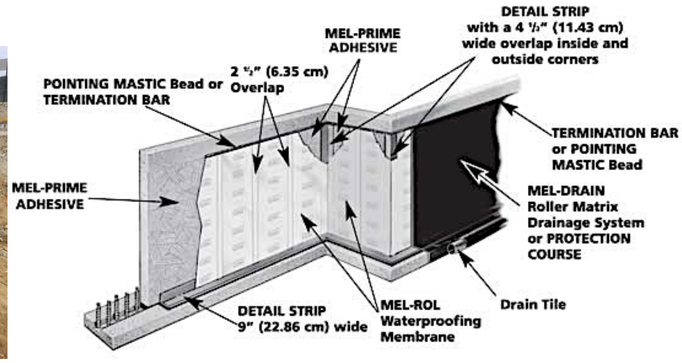

Figure 14 MEL-ROL Membrane Assembly (Courtesy of W. R. Meadows, Inc.)

GRACE Bituthene System 4000 Bituthene 4000 is a pre-formed below-grade waterproofing membrane comprised of a cross-laminated HDPE carrier film with a self-adhesive rubberized asphalt compound.

Polyguard 650 Waterproofing Membrane Polyguard's 650 Waterproofing Membrane is a below grade waterproofing sheet membrane material for both foundation walls and plaza deck applications. 650 Waterproofing Membrane for Foundation Walls contains a layer of polymerized asphalt formulation with a backing layer of polyethylene film.

REDGARD® Crack Prevention and Waterproofing Membrane RedGard® Crack Prevention Waterproof membrane is an elastomeric liquid product. It works by creating waterproofing barrier on interior or exterior substrates.

Table 2 summarizes various ASTM tests the manufacturers have reported in their test data sheets. The test methods are explained in the next section.

Table 2 Summary of ASTM Test Methods for Waterproofing Membrane Products

Properties	TAMKO®TW-60 Sheet Waterproofing Membrane	W. R. MEADOWS MEL-ROL Waterproofing	GRACE Bituthene System 4000	Polyguard 650 Waterproofing Membrane	REDGARD® Crack Prevention and Waterproofing Membrane
Tensile, Membrane	D 412 (C)	D 412	D 412	D 412 Modified Die C	ASTM D638
Tensile, Film	D 882	D 412	D 882	D 882	
Elongation	D 412 (C)	D 412	D 412	D 412	
Water Vapor Absorption		E 96, B		D 570	
Water Vapor permeability	E 96	D 1970	E 96 (Water Method)	E 96 Method B	
Flexibility	D 1970		D1970		
Low Temp. Crack		C 836			
Crack Cycling	C 836		C 836	C 836	
Peel Strength	D 903	D 903	D 903	D 903 D 1000	
Lap Adhesion	D 1876	D 1876	D1876		
Puncture Resistance	E 154	E 154		E 154 Blunt Instrument	
Hydrostatic Head	D 5385	D 5385	D 5385	D 5385-93	

3.2 Test Methods for Waterproofing Membranes

The most important property of the waterproofing is the water absorption rate. Also important is the thickness of the material and resistance to hydrostatic head. Others include tensile strength of membrane and film, flexibility, puncture resistance, crack cycling, peel adhesion and lap adhesion.

Water Absorption

ASTM D 570: *Standard Test Method for Water Absorption of Plastics* This test is to determine the relative water vapor absorption rate of all types of materials when immersed. The test procedures for different types of immersion methods are listed in Table 3 below:

Table 3 Summary of ASTM D 570 Test Procedures for Different Types of Immersion

	Procedure
Twenty-Four Hour Immersion	• Place conditioned specimen in distilled water maintained, entirely immersed • Remove the specimen one at a time at 24+1⁄2, −0 h, wipe off with dry cloth • Immediately weigh specimens to the nearest 0.001g
Two-Hour Immersion	• Tested as described in Twenty-Four Hour Immersion • time of immersion: 120 ± 4 min
Repeated Immersion	• 2-h immersion • Weigh specimen to the nearest 0.001 g • Replaced in the water • Weighed again after 24 h
Long-Term Immersion	• Tested as described in Twenty-Four Hour Immersion • Repeat weighing at the end of the first week and every two weeks until the increase in weight per two-week period averages less than 1 % of the total increase in weight or 5 mg
Two-Hour Boiling Water Immersion	• Place conditioned specimen in boiling distilled water, entirely immersed • Remove the specimens from the water and cool in distilled water maintained at room temperature at the end of 120 ± 4 min • Remove the specimen one at a time after 15 ± 1 min, wiped off with dry cloth • Immediately weigh specimens to the nearest 0.001 g
One-Half-Hour Boiling Water Immersion*	• Tested as described in Two-Hour Boiling Water Immersion • time of immersion: 30 ± 1 min
Immersion at 50°C	• Tested as described in Two-Hour Boiling Water Immersion • time of immersion: 48 ± 1 h • temperature of immersion: 50 ± 1°C • Omit cooling in water before weighing

Resistance to Hydrostatic Head

ASTM D 5385 : *Standard Test Method for Hydrostatic Pressure Resistance of Waterproofing Membranes* The objective of this test is to determine the hydrostatic resistance of a waterproofing membrane under certain laboratory condition. This test method is not applicable to systems that rely on confinement of the seams. The test procedure is explained in Figure 15. The head of water from the pressure the sample withstood and the mean and standard deviation of the head of water withstood can be obtained from the test.

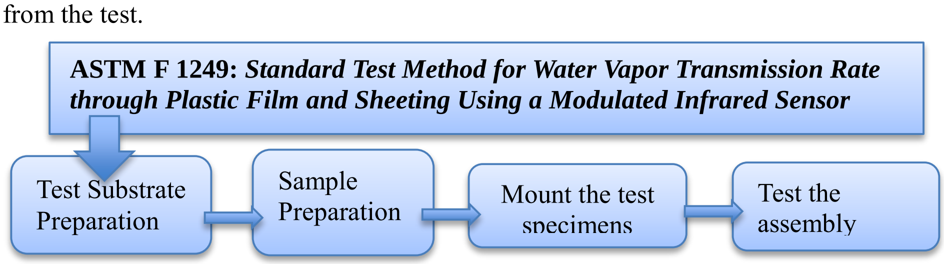

Figure 15 Flow chart of ASTM F1249 Test Procedure

Crack Cycling

ASTM C836: ***Standard Specification for High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane for Use with Separate Wearing Course*** Required properties and test methods for cold liquid-applied elastomeric-type membrane are presented in this specification including: 1) Hardness; 2) Weight Loss; 3) Low-Temperature Crack Bridging; 4) Film Thickness on Vertical Surface; 5) Adhesion-in-Peel After Water Immersion; 6) Extensibility After Heat Aging; 6) Stability. The Low-Temperature Crack Bridging Test is in compliance with the requirements of Test Method C1305.

4.0 AIR BARRIERS

Air barriers are significant to the energy-efficiency of buildings as air leakage directly influences the energy consumption of the HAVC systems. Thus, air barrier testing methods are vital to establishing installation guidelines for real practice. Based on the application methods, air barrier materials can be defined as fluid-applied, sheet-applied or self-adhesive membranes.

4.1 Introduction of Selected Air Barriers

GRACE Perm-A-Barrier VPL Perm-A-Barrier® VPL is a fluid applied, one component air barrier membrane as shown in Figure 30. It is vapor permeable but impermeable to liquid water.

DuPont™ Tyvek® Fluid Applied WB System DuPont™ Tyvek® Fluid Applied WB is a water and fluid applied air barrier as shown in Figure 16. It is based on silyl terminated polyether polymer technology to achieve low shrinkage during curing and elasticity. However, Tyvek® Fluid Applied WB is not approved for use on residential single family homes.

Figure 16 Application of DuPont™ Tyvek® Fluid Applied WB
(Courtesy of DuPont)

Henry® Non-Permeable Air Barrier Air-Bloc 06 WB Henry® Air-Bloc 06 WB is an elastomeric asphalt emulsion for use as air and vapor barrier membrane. It can be used for either above grade on construction surface to provide air barriers or below grade on foundation or footings as waterproofing membranes.

AIR-SHIELD TM Self-Adhering Air/Vapor and Liquid Moisture Barrier AIR-SHIELD TM is a sheet-applied air barrier product introduced in Section 2, which provides resistance to both vapor and air penetration. Refer to the previous part for detailed information.

3M™ Air and Vapor Barrier 3015 3M™ is also a sheet-applied product introduced earlier and functions as an air and vapor barrier. Refer to the previous part for detailed information.

Table 4 summarizes various ASTM tests the manufacturers have reported in their test data sheets. The test methods are explained in the next section.

Table 4 Summary of ASTM Test Methods for Air Barrier Products

Properties	GRACE Perm-A-Barrier VPL	DuPont™ Tyvek® Fluid Applied WB System	Henry® Non-Permeable Air Barrier Air-Bloc 06 WB	AIR-SHIELD TM Self-Adhering Air/Vapor and Liquid Moisture Barrier	3M™ Air and Vapor Barrier 3015
Air Permeance	E2178	E2178	E2178	E 2178-01	E 2178
Assembly Air Permeance	E2357	E2357 E283		E 2357 E 283	E 2357
Water Resistance	E331		D466		
Water vapor Transmission	E96 Method B	E96	E96		
Tensile Strength	D412				
Elongation	D412				
Low Temperature Flexibility	D1970				
Nail Sealability	D1970				
Adhesion Strength		D4541			
Tensile Strength		D412	D412		
Surface Burning Characteristics		E84			

4.2 Test Methods for Air Permeance Property of Air Barriers

Test methods for properties of air barriers including Tensile Strength, Elongation, and Low Temperature Flexibility have already been included in previous sections. The most important property that needs testing for products functioning as air barriers is air leakage resistance.

From the technical data of products introduced, the air leakage property of air barrier material, assembly and whole building all need to be tested, because testing of material property is not enough and actual installation and workmanship in the field are also critical to control air leakage of the building enclosure. Corresponding ASTM test methods are shown in Table 5.

Table 5 Summary of ASTM Test Methods of Air Leakage Property of all Levels

Air Leakage	ASTM Test Methods
Material	ASTM E 2178 Standard Test Method for Air Permeance of Building Materials
Assemblies	ASTM E 1677 Standard Specification for Air Barrier (AB) Material or System for Low-Rise Framed Building Walls
	ASTM E 2357 Standard Test Method for Determining Air Leakage of Air Barrier Assemblies (2011)
	ASTM E 283 Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen
Whole building	ASTM E 779 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization

4.2.1 Air barrier materials
Air leakage property on the material level is defined by air permeance, which is the rate of air flow per unit area and per unit static pressure differential. The standard test method used is ASTM E2178, *Standard Test Method for Air Permeance of Building Materials*.
ASTM E 2178: ***Standard Test Method for Air Permeance of Building Materials*** The purpose of the test is to measure the air permeance of flexible sheet or rigid panel-type building materials. Test procedure is explained in Figure 17.

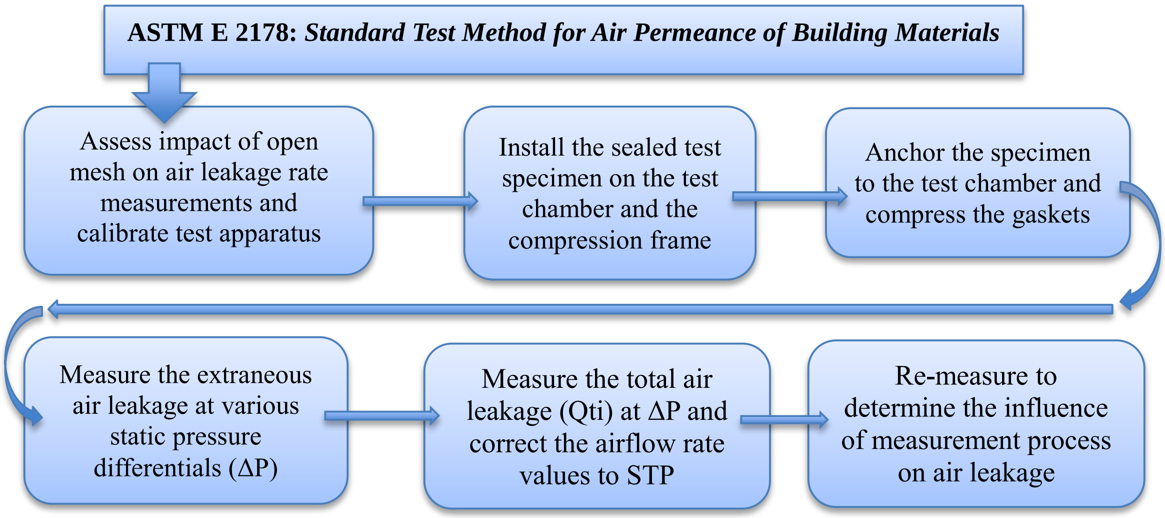

Figure 17 Flow chart of ASTM E2178 Test Procedure

4.2.2 Air barrier assemblies
Air barrier assembly is defined as the air barrier materials with air barrier accessories that provide a continuous designated plane. Test methods are intended to simulate the performance of various air barrier materials/accessories when combined into an assembly. For both accepted test methods ASTM E2357 and ASTM E1677 for air barrier assemblies, focus is given on ASTM E2357 since it is more stringent than ASTM E1677 and assemblies tested under its conditions can significantly outperform requirements under ASTM E1677 according to research results by Maria Spinu, 2009.
ASTM E 2357: ***Standard Test Method for Determining Air Leakage of Air Barrier Assemblies***
This laboratory test is to determine the air leakage rate of air barrier assemblies of building enclosure before and after exposure to specific conditioning cycles, which may be applied on site mockup.
The initial leakage test shall be conducted with 7 measurements across the sample in accordance with Test Method E283: *Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen*. Results shall be curve fit using a least squares procedure to establish the relationship between pressure difference and leakage. The reported air leakage rate of the specimen for both positive and negative cases, shall be the rate of the specimen after the structural (wind) loading conditioning.

4.2.3 Whole building air leakage
ASTM E779: ***Standard Test Method for Determining Air Leakage Rate by Fan Pressurization***
Fan-pressurization method qualifies the air tightness by measuring the air-leakage rates of the whole building under mechanical pressurization and depressurization. By measuring the airflow rate and the pressure differences at each pressure increment and collecting data for both pressurization and de-pressurization cases, the air leakage can be determined using the equations suggested in the standards.

5.0 INSULATION
Insulation is an important product for use in buildings applied in attic, ceilings, walls, roofs and sometimes basements to enhance thermal, acoustic, and sometimes fire-resistant property of these building components or spaces. There are essentially three types of insulation: loose insulation, rigid insulation and

spray foam insulation.

5.1 Introduction of Selected Insulation Products
5.1.1 Loose insulation

Cellulose Cellulose insulation is a loose fill product manufactured from recycled wood products, newspaper, for use in blown-in applications such as attics and wall cavities.

ULTRATOUCH™ CELLULOSE UltraTouch Nature Blend Cellulose is a loose-fill insulating product for attic applications. (Figure 18)

Figure 18 Application of UltraTouch ™ Cellulose

Figure 19 Application of UltraTherm™ Fiber Glass (Courtesy of Cerntainteed)

Fiber-glass Fiberglass (also called glass wool) is a commonly used insulation material made from fibers of glass and arranged in the texture similar to wool.

UltraTherm™ S&R Loose Fill Fiber Glass Insulation UltraTherm™ S&R Loose Fill Fiber Glass Insulation is designed for use in attic as shown in Figure 19.

Rock-wool Rock-wool insulation is made from actual rocks and minerals with extraordinary ability to block heat and sound. It is a mass of fine intertwined fibers, bound together with starch.

Rockwool Premium Plus™ Rockwool Premium Plus™ Insulation is a mineral fiber insulation manufactured in a granular form. The wall assembly section is shown in Figure 20.

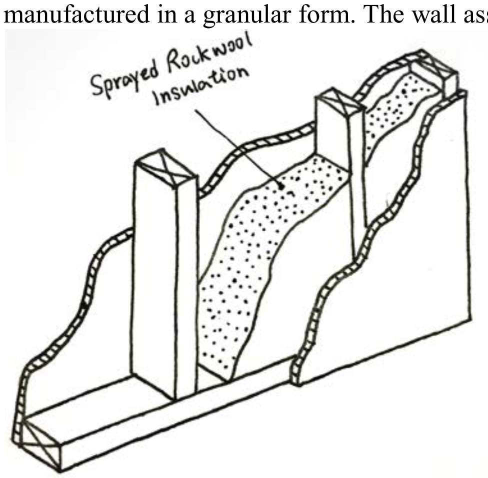

Figure 20 Section of Rock-wool Insulation

Figure 21 Installation of ThermalStar® X-Grade (Courtesy of Altas EPS)

5.1.2 Rigid insulation
Expanded Polystyrene (EPS)

ThermalStar® X-Grade® ThermalStar® X-Grade is an Expanded Polystyrene material insulation product for below grade applications as shown in Figure 21. It can provide thermal insulation and protection against backfilling for foundation walls.

Extruded Polystyrene (XPS)

FOAMULAR® 150 Rigid Extruded Polystyrene (XPS) Foam Insulation FOAMULAR® 150 is a rigid XPS foam insulation. The densely packed air cells within the foam insulation provide thermal insulating performance. It can be applied in attics, floors and walls, basement and crawlspaces, etc.

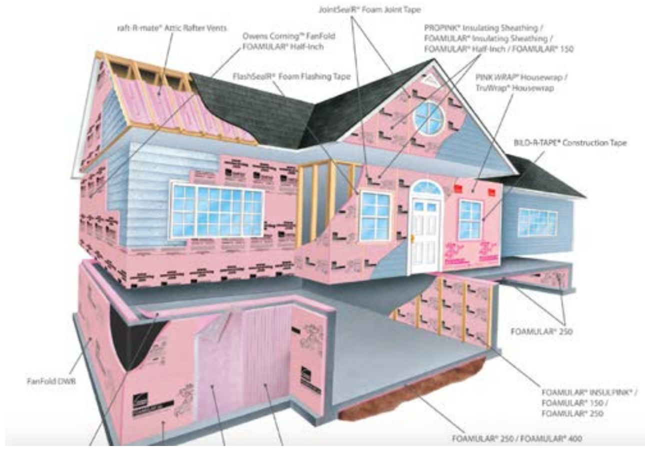

Figure 22 Section of Application of XPS Insulation
(Photo courtesy of Owens Corning)

Polyisocyanurate (ISO)
THERMAX™ Sheathing It is a rigid board insulation consisting of a glass-fiber-reinforced polyisocyanurate foam core and aluminum foil facers on both sides.

Figure 23 THERMAX™ Sheathing Product
(Courtesy of the Dow Chemical Company)

Figure 24 Section of THERMAX™ Sheathing
(Courtesy of the Dow Chemical Company)

5.1.2 Spray foam
STYROFOAM™ Brand Spray Polyurethane Foam (SPF) Insulation STYROFOAM™ Brand Spray Polyurethane Foam (SPF) insulation is a closed-cell, two-component spray foam barrier on the interior of steel stud walls. It can block air infiltration by filling gaps, cracks and penetrations. It needs to be applied by a trained SPF insulation applicator only as shown it Figure 25.

Figure 25 Application of STYROFOAM™ Brand Spray Polyurethane Foam
(Courtesy of The Dow Chemical Company |dowbuildingsolutions.com)

Table 6 summarizes various ASTM tests the manufacturers have reported in their test data sheets. The test methods are explained in the next section.

Table 6 Summary of ASTM Test Methods for Insulation Products

Properties	Loose insulation			Rigid insulation			Spray foam
	Cellulose	Fiber-glass	Rock-wool	Expanded Polystyrene (EPS)	Extruded Polystyrene (XPS)	Polyisoc-yanurate (ISO)	
	ULTRATOUCH™ CELLULOSE	UltraTherm™ S&R Loose Fill Fiber Glass Insulation	Rockwool Premium Plus™	ThermalStar® X-Grade®	FOAMULAR® 150 Rigid Extruded Polystyrene (XPS) Foam Insulation	THERMAX™ Sheathing	STYROFOAM™ Brand Spray Polyurethane Foam (SPF)
Density	C 739		E 605				D 1622
Thermal Resistance	C 518	C 518 C 687		C 518	C 518		C 518
Acoustical Performance		E 90 E 413					
Surface Burning Characteristics/ Fire Resistance	E 84	E 84	E 119 E136 E84	E 84	E 84		
Water Vapor Sorption	C 739	C 1104					
Water Absorption			C 553	C 272	C 272	C 209	
Water Vapor Permeance				E96	E 96	E 96	E 96
Odor emission		C 1304					
Fungi resistance		C 1338	C 1338				
Corrosiveness		C 764	C 665				
Compressive Strength				D 1621	D 1621	D 1621	
Flexural Strength				C 203	C 203	C 203	
Dimensional Stability					D 2126		

5.2 Test Methods for Insulations

The major properties of insulation products are its thermal resistance and acoustical performance. Other material properties including water vapor absorption, water vapor permeance, air permeance, and surface burning characteristics have been introduced in the previous sections.

Thermal Resistance

ASTM C 518: *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus* This test method can measure the steady state thermal transmission properties through thermal insulation specimen with high accuracy. The test procedure is explained in Figure 26.

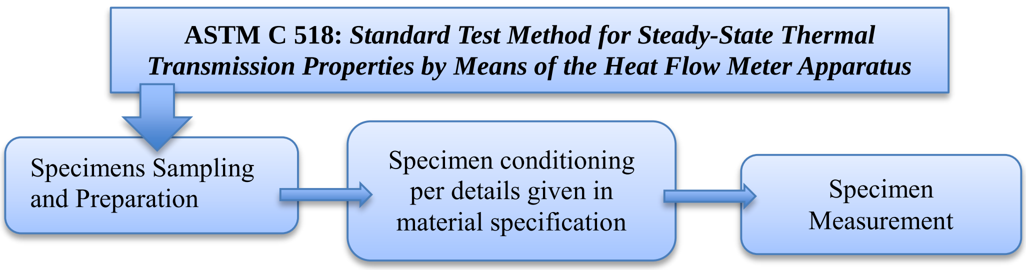

Figure 26 Flow chart of ASTM C518 Test Procedure

Acoustical Performance

ASTM E 413: *Classification for Rating Sound Insulation*

This test method calculates single-number acoustical ratings based on the reference sound insulation contour provided in the standard, which can be used to evaluate sound insulating performance of building insulation products. The test procedure is explained in Figure 27.

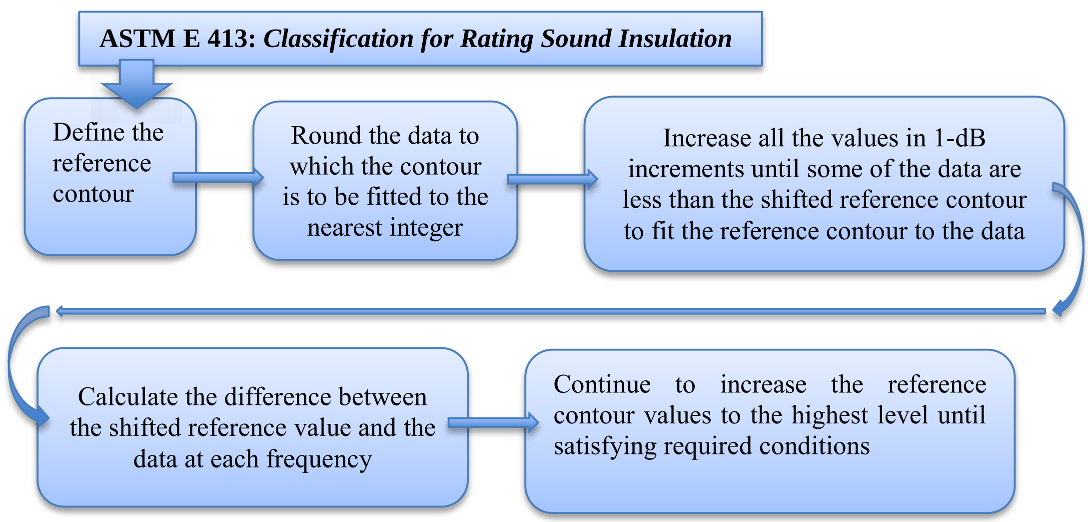

Figure 27 Flow chart of ASTM C518 Test Procedure

6.0 CONCLUDING REMARKS

The paper has presents a review of the most important components of a building enclosure: vapor barriers/ retarders, waterproof membranes, air barriers and insulation. Starting from the basics of a component, general ideas of what they are and how they function are explained. The review shows that some components have multiple functions, for example, vapor barrier and air barrier are sometimes the same layer as they can both prevent flow of vapor and air through the material. Multiple function property is also true for insulation, as it has to enhance not only thermal but also acoustic, and sometimes fire-resistance property. Through exploring the building enclosure component products in the market, the commonly used standard test methods can be generalized. Besides, information on where to apply in a wall assembly and how to apply the product is also provided by manufacturers. Test methods for a typical property can vary with different materials of the products and are stated in detail in ASTM Standards. Test methods are vital to establish installation guidelines in real practice. If the building enclosure components products are wisely selected and properly installed, they can work together to achieve low energy consumption and long-term durability. The performance of a building can be improved by measuring it. That is the meaning of studying test methods for building components. Many institutes and organizations are devoting their efforts into improving test methods for building enclosure components. In this paper, some articles and research papers on state of art studies and testing projects are also referenced for further reading.

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[6] ASTM E96/E96M−13, Standard Test Methods for Water Vapor Transmission of Materials.
[7] ASTM E154/E154M−08a, Standard Test Methods for Water Vapor Retarders Used in Contact with Earth Under Concrete Slabs, on Walls, or as Ground Cover.
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[11] ASTM D570 – 98, Standard Test Method for Water Absorption of Plastics.
[12] ASTM D1970/D1970M−13a, Standard Specification for Self-Adhering Polymer Modified Bituminous Sheet Materials Used as Steep Roofing Underlayment for Ice Dam Protection.
[13] ASTM D5385/D5385M−93, Standard Test Method for Hydrostatic Pressure Resistance of Waterproofing Membranes.
[14] ASTM E283 – 04, Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen.
[15] ASTM E779 – 10, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.
[16] ASTM E1677 – 11, Standard Specification for Air Barrier (AB) Material or System for Low-Rise Framed Building Walls.
[17] ASTM E2178−13, Standard Test Method for Air Permeance of Building Materials.
[18] ASTM E2357 – 11, Standard Test Method for Determining Air Leakage of Air Barrier Assemblies.
[19] ASTM C518−10, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.
[20] ASTM E84−14, Standard Test Method for Surface Burning Characteristics of Building Materials.
[21] ASTM E413−10, Classification for Rating Sound Insulation.

Co-Design of a Sustainable Affordable Housing Demonstration Project

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ABSTRACT

Housing affordability is a rising concern for many Americans, especially those of modest needs. The design and construction of energy and resource-conscious environmentally sustainable homes that are affordable in the short- and long-term are a paramount challenge. A Community Land Trust (CLT) is a private, non-profit organization whose goal is to acquire and hold land for the benefit of the community and to provide secure affordable access to land and housing for community residents. The mission of the State College Community Land Trust (SCCLT) is to "support vibrant neighborhoods by creating and maintaining sustainable housing opportunities for families and individuals who value living in the Borough of State College" (http://www.scclandtrust.org/clt/), a neighborhood with scarce opportunity for affordable, owner-occupied housing. Through a partnership with the Energy Efficient Housing Research group (EEHR), an outreach arm of the Penn State College of Arts and Architecture Hamer Center for Community Design, SCCLT is embarking on their first new building project – a zero energy ready residential duplex on a highly visible site in the property-constrained Borough. The duplex, once completed, will provide homes for two families of modest incomes and will be a demonstration for sustainable, affordable housing in the region. Fueled by challenges posed by the Department of Energy Zero Energy Ready Home program and *Race to Zero* student design competition, the "co-design" for the SCCLT GreenBuild demonstration project engages a diverse cross-disciplinary student and multiple-faculty team with community housing and construction leaders in an educational exchange centered on ideals for improving housing performance and community.

INTRODUCTION

> *Co-design is the process at which actors from different disciplines share their knowledge about both the design process and the design content. They do that in order to create shared understanding on both aspects, to be able to integrate and explore their knowledge and to achieve the larger common objective: the new product to be designed* (Kleinsmann and Valkenburg, 2008).

What role can co-design play in realizing needs for affordable housing? This question is asked in the context of an ambitious undertaking by the EEHR group at Penn State in the interest of researching new housing for the borough of State College that fills a distinct niche – providing design ideas for affordable housing that meets the needs of income eligible home owners, while educating the community and future visionaries of our built environment about the importance of long-term thinking and the impact of building design.

BACKGROUND

Penn State has a successful repertoire of affordable, sustainable housing demonstration projects including and evolving from the Solar Decathlon homes, American Indian Housing Initiative, Union County Energy Efficient Housing Program projects, and the GridSTAR Smart Grid Experience Center (see Figure 1). Each project demonstrates the importance of a holistic approach and the necessity for establishing local connections and reinforcing community development in realizing a replicable model for sustainable housing (Iulo et al, 2014). These pilot projects have provided insight for achieving more affordable and sustainable homes and potential for contributing to the very real problem of housing affordability in our own community.

2007 - MorningStar PA

2007 - MorningStar MT

2009 - Natural Fusion

2012 – GridStar

2012 - UCHA EEHP Duplex

Figure 1: Penn State Zero-Energy Home Demonstration Projects

The Energy Efficient Housing Research group (EEHR) at Penn State was established in part as an opportunity to reflect on past projects to inform success on future initiatives that can be of benefit to local communities. EEHR is a multidisciplinary team of faculty, graduate and undergraduate students dedicated to the investigation of energy efficient, affordable and sustainable housing - from design and construction methods through performance optimization – in order to inform better housing solutions and more resource conscious living. An approach that considers planning, design, construction, operations, monitoring, assessment and reflection is used to systematically consider affordable, sustainable, energy-efficient housing through an integrative design process. The projects undertaken by EEHR address applied strategies and solutions for realizing tangible examples for affordable, sustainable housing that are locally appropriate and address transforming markets and demographics. Over the past few years, EEHR has attracted interest from and sustained relationships with local affordable housing providers.

Figure 2: State College Community Land Trust mission and homes.

In December of 2013 the State College Community Land Trust (SCCLT) approached EEHR for guidance. Since the mid-1990s this non-profit housing assistance organization has been helping income-qualified individuals and families purchase homes in State College, PA (where Penn State is located). SCCLT helps to reduce the cost of buying a home by holding the land permanently "in trust," this means that while the house is sold to a homeowner, the land is leased long-term. The agreement allows the prospective homeowner to apply for a mortgage based only on the cost of the house, effectively reducing the cost of purchasing a first home by as much as 30 percent (www.scclandtrust.org). Moreover, it ensures that the home, when resold, remains affordable. Historically, SCCLT has purchased, renovated and resold existing homes in the Borough (See Figure 2), and initially they approached EEHR to learn about energy efficiency retrofit measures. Shortly after this initial meeting, SCCLT had the opportunity to purchase a highly visible and coveted borough site to embark on their first new housing construction project. Located in an R2 district, zoning for the 20,000 square foot lot size allows for the construction of a duplex (two connected dwelling units), which is consistent with the surrounding community fabric. SCCLT saw potential in the previously completed Union County Housing Authority Duplex to serve as a "blueprint" for their project. Consistent with the Union County Housing Authority's goals for the project, Union County's Energy Efficient Housing Program pilot project was documented by EEHR to serve as a model for other housing providers (Iulo and Quigley, 2013; Iulo et al, 2014). Although in practice it was feasible to adapt the Union County design – the size, budget, and goals for affordability were similar to those of SSCLT – theory about sustainability informed an alternative process. Tenets of sustainable development prioritize consideration for site-specific design strategies especially solar and a focus on local resources. Moreover, Penn State had the experience and interest to offer community design assistance. Therefore, it was determined that co-design of the project, through a university/community partnership, would be mutually beneficial.

Figure 3: Photo of the Penn State 2015 DOE *Race to Zero* Team

UNIVERSITY ENGAGEMENT

The SCCLT project serves as an opportunity for cross-disciplinary student and multiple faculty engagement that has the potential to leverage existing connections and inform involvement in ongoing educational and research initiatives. Partnership with Penn State provides the SCCLT with added value through design expertise, increased visibility, and potential project donations and sponsorship. The close working relationship with the SCCLT was one of the hallmarks of this project because of their demonstrated interest and common goal of affecting the community. They met the Penn State team with a partially conceived vision and list of what they wanted from the project. The integration between the students and the SCCLT was vast and critical. Most importantly, the outcome of this partnership with SCCLT – two homes for local families of moderate incomes – could not afford to be experimental. Therefore a rigorous process of curricular and extracurricular engagement to test viability was undertaken, involving:

Curriculum: Multiple opportunities for integrating this project into existing undergraduate and graduate curricula and studio coursework are being undertaken or explored. In the Fall 2014 Semester the project was incorporated into a comprehensive architectural design studio course required of fourth-year undergraduate students matriculated in the professional Bachelor of Architecture degree program. Students enrolled in this class provided initial research about the need for affordable housing in State College and provided the SCCLT with ideas for project program and suggested design alternatives. This preliminary work informed students, majoring in architecture and engineering, enrolled in a special topics class in the Spring 2015 semester focused on the design of Zero-Energy Ready Homes designed to meet the needs of the SCCLT "GreenBuild" project. Additional focused courses for the development of related design, mock-ups, detail fabrication, performance monitoring and on-going research about the eventual performance of the homes post-construction are projected for the future.

Student Design Competition: Concurrent to SCCLT approaching the EEHR the DOE was hosting the *Race to Zero* (formerly Challenge Home) collegiate competition. This competition was a perfect fit for the work the SCCLT already was interested in, homes that could be constructed for the current housing market and are consistent with goals for extremely low-energy living. Participation in *Race to Zero* promoted engagement across disciplines and attracted visibility for the project. Through the competition, students got to delve into the details of what it means to design for efficiency and affordability. An extensive network of industry partners informed the viability of the design, engineering and financing for the project. Penn State's team competition submission related rigorous building science research into the SCCLT GreenBuild design. Verification by 2015 DOE competition judges, experts in the housing industry and building science, allowed for some assurance that the future project can be successfully less energy-intensive without being unnecessarily experimental.

Test Bed: The SCCLT GreenBuild project is providing a test bed for research and collaboration where undergraduate and graduate students, faculty and industry partners are collaborating to explore ideas and test viable solutions for a real-world project. At its core this project is interdiciplinary. A group of over 30 students with various backgrounds in engineering, architecture and even business and finance came together to form a team of highly motivated and intelligent thinkers focused on a project specific to the SCCLT (See Figure 3).

[CO] DESIGN FOR A TRIAD OF INTERESTS

A process of interaction between "town and gown" has been central to this project from conception through visualization and will be necessary for successful long-term realization. Three parties were major design drivers: The State College Community Land Trust, representatives of future homeowners; the DoE *Race to Zero* competition guidelines and related *Zero Energy Ready Housing* standards for performance; and the Penn State team (See Figure 4).

Figure 4: Triad Diagram and related goals

H4 - Heritage Homes: High-Performance Living in Harmony with Community

"Good architecture learns from the past, responds to the present, and inspires the future" (Penn State, 2015). The project concept was informed by the triad in the interest of achieving cost-effective zero-energy homes, intended for a specific client in the community of State College, Pennsylvania, that showcase the expertise of a cross-disciplinary University team. The project title, H4, Heritage Homes: high performance living in harmony with community, eludes to the main goals for the project - to foster high performance living in an accessible and affordable way, tying these ideals back to what already makes our region great, all while making the best impact on the community we serve. The design of the duplex recalls the local history and traditions of the region's agrarian past through modern interpretations evocative of the iconic Pennsylvania Bank Barn and Farmhouse (See Figure 5).

Figure 5: "Heritage" influences. Sketches by Shivaram Punathambekar.

Consistent with sustainable-community thinking, the site that SCCLT acquired is located in the Borough of State College, within walking distance to campus and to multiple amenities and public transportation. The south-sloping site with views to surrounding mountain ranges is also prominently located on University drive, a well-traveled road with optimum exposure to the public (Figure 6). These factors make the location an ideal showcase for the importance of and potential for sustainable, low- (or zero-) energy design in our community. The concept of "heritage" ensured that the new concepts of energy efficiency and affordability did not land alien in the community of State College. Instead, by taking into consideration the surroundings and the history of the region the team was able to engage the community at the very core of the design.

Design and build a moderately priced, owner-occupied duplex utilizing advanced and long-term cost-effective green technology.

Develop a sustainable project "using best practices to create lasting environmental, economic, community and organizational vitality."

The Duplex:

2 Units, 3 Bedrooms, 1.5 baths with approximately 1250 square feet of living space in each unit.

Figure 6: SCCLT GreenBuild site and design goals.

With multiple facets to the project it was best to take an organizational approach to assure that all of the stakeholders were heard and equally considered. The Penn State team took direction from 7Group, borrowing the phrase "Engage Everyone Early on Everything" (7 group and Bill Reed, 2009). The multiple interests of the triad lead to interesting interactions that encouraged everyone to consider others objectives and sometimes question preconceptions. This interaction was a key component to the realization of a project that is more "holistically" considered. Throughout the process the project team was dedicated to a whole-house systems approach as defined by the Whole-House Systems Approach (2014). In addition to the building systems, this holistic approach considered all aspects of the sustainability "triple-bottom-line": Environmental, Economic and Social Sustainability. Tuesday evenings, from January through May 2015 the team of Penn State students and advisors, industry mentors and SCCLT members met to discuss the project goals and approaches to create cost-effective net-zero energy ready homes.

Methods used to engage the design team and the community played a major role in the quantity of feedback that the design team received which ultimately contributed to the quality of the design. Several large 'charrettes' - community design workshops where students, faculty, the SCCLT and local homeowner and industry representatives collaborated in order to determine the direction of the project - were the most successful examples of this engagement (Figure 7). The students employed questionnaires and developed informational packets to disseminate in order to evaluate preferences on aspects of the design including program, material selection and site design. These sessions were the team's most interactive opportunities to engage in dialoged break out sessions and solicit consensus votes to drive the process of design and decision-making. The charrettes were crucial to the project pace and informed the continuing work. In the short-term the community engagement workshops with the SCCLT and representative community members helped to ensure project success; for the long-term they may enhance the education of the future designers of our collective built environment.

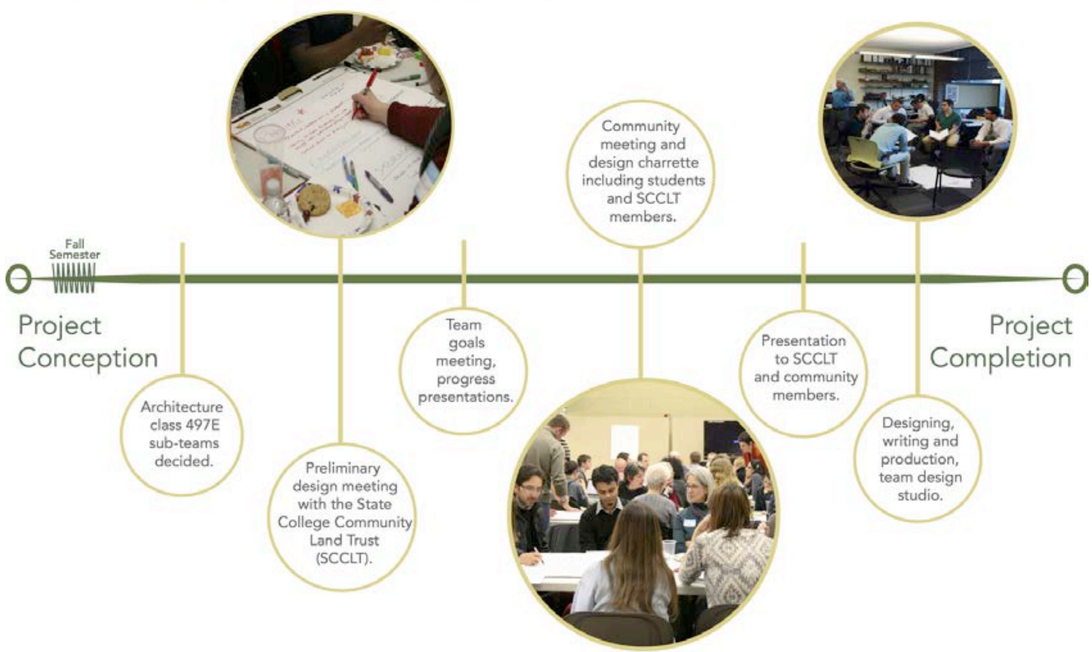

Figure 7: Project engagement timeline.

This project allowed students to connect with a real project for affordable housing - a sector of the built environment that rarely benefits from the intensive integrative process necessary to realize more sustainable results. The learning curve associated with this project is steep because of the significance of the subject and complexity of real-time data considered. Learning was enhanced by engagement with industry mentors. These mentors worked with many of the students, providing them context to help to ground their ideas and to answer questions they had never previously encountered in a classroom (Figure 8). Conversely, the students' presented progressive research. The benefit of this interactive learning is repaid to the community by harnessing young minds with the means to be on the cutting-edge of their selected fields.

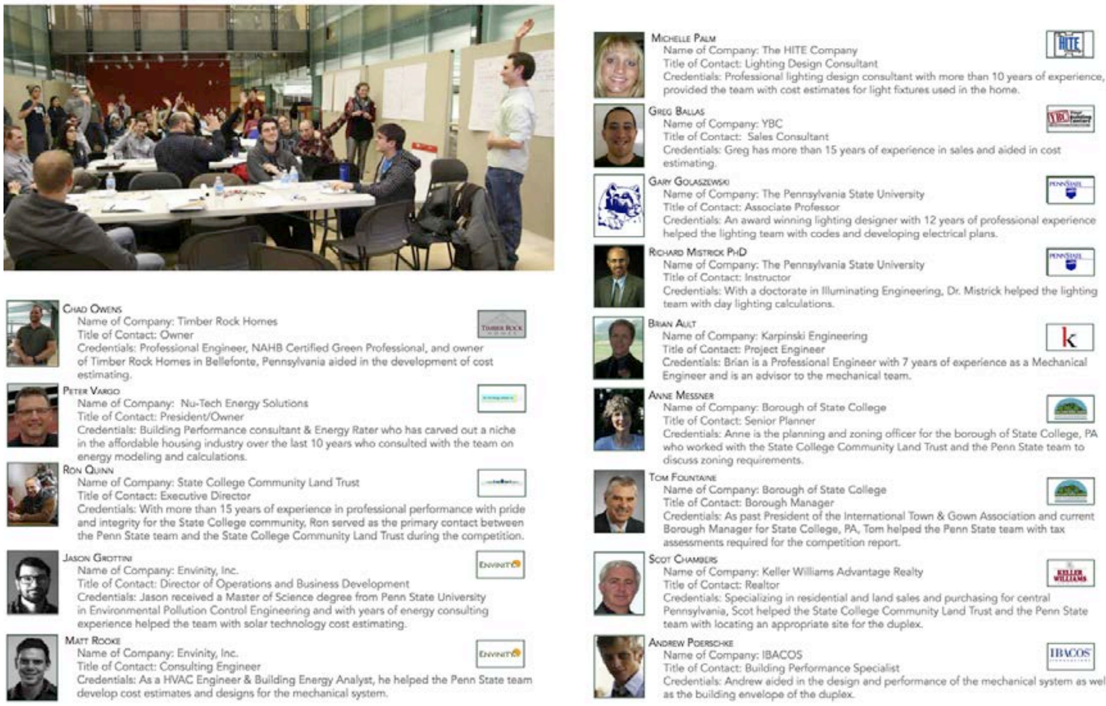

Figure 8: Penn State 2015 *Race to Zero* Industry Mentors.

Refinement of the design continued with a smaller group of students and staff, many representing members of the initial design team, facilitated through the Hamer Center for Community Design/EEHR. Once the substantial winter snow (present on the site throughout the Spring 2015 semester) melted, several meetings were held on the site to finalize information about project siting and program. Over the summer a smaller, focused group continued work to refine the design based on information provided during focused meetings with the SCCLT GreenBuild Committee, a subset of the not-for-profit SCCLT board tasked with taking a more fine-toothed look into the project outcomes. Currently the Penn State team is finalizing a detailed report of research and related design recommendations that will inform the future project. Based on this rigorous collective process of research and design GreenBuild presents a more thoroughly considered vision addressing factors impacting the future homeowners and the broader community.

The refined duplex design (Figure 9) has been preliminarily reviewed by Borough staff to be consistent with State College zoning regulations. A local engineer - an industry sponsor to the Penn State R20 team - has been identified to assist the SCCLT in moving the project forward. Depending on the success of a fund-raising campaign currently underway, the SCCLT plans to break ground for construction of the GreenBuild duplex in mid-2016.

CONCLUSION

In this co-design process politics and personal opinions had little to do with the progress of the project or the day-to-day decision-making. The continuity of presenting, problem solving and communicating happened through close and continued collaboration. The project empowered students to direct the decisions. The leadership and reporting structure was established early and this allowed for clear lines of communication as well as a clear view for other team members to take responsibility based on his/her role. For example, during the competition, there were sub-teams that helped steer the direction while collectively adding to the richness of the project. Faculty guidance and support from Penn State, Hamer Center/EEHR and PHRC (Pennsylvania Housing Research Center) was invaluable for the logistics and resources needed to organize and execute the tasks of the project.

Involvement on a meaningful 'real-world' project inspired students to work harder and be more engaged. The team became intimately familiar with and committed to community that they were affecting, instilling an accountability that few projects can match. The relationship built with SCCLT influenced enthusiasm for the project and inspired the team to ascent to personal sustainability goals while inspiring to those of the SCCLT and the community. Participants in this project share an unparalleled experience informed by a larger conversation, tuned to the engagement of building science leadership and energy-efficient affordable design communities, transcending individual contributions. The process undertaken in the interest of this demonstration project is built on collaboration and mutual goals. Participants engaged their local community to make a grass roots difference in what high-performance efficiency and sustainability means to State College while being able to situate themselves in a larger, international conversation about future goals and ways to get there.

Figure 9: Renderings of GreenBuild, clockwise from left: site plan, perspective looking north, and view of the duplex entry court.

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A Study on Residential Fires due to Electrical Faults in Hong Kong

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ABSTRACT

Accidental home fires lead to life and property losses. Electrical fault is one of the causes of residential fires, and its potential hazard is increasing as more electrical appliances are found in each household unit nowadays. Wiring has a higher possibility to be ignited. There were even cases reported that the television set caught fire. Possible reasons for electrical fires in residential buildings will be studied in this paper. Ignition of a television set by itself was taken as an example for experimental investigation. Television set can be a source of fire, insulation and wiring may be weakened and cause fire due to ageing problem. Although the possibility of ignition of a television by itself is low, it is recommended to plug off the socket from the power supply for isolation when the television is not in use.

INTRODUCTION

Statistical data compiled by the government authorities in Hong Kong and Taipei (e.g., Fire Services Department 2008-2010; Taipei City Fire Department 2010) indicated a high rate of residential fires in these two places. The accumulated percentage of fire events in domestic buildings and housing estates was up to 43% from 2008 to 2010 (Fire Services Department 2008-2010) based on the statistics by the Fire Services Department of Hong Kong. Residential fires caused by smoking (Runyan et al. 1992; Ducic and Ghezzo 1980; Chien and Wu 2008) were studied overseas in the past years. In recent years, more electrical appliances are being used in each family unit. The outer-casing of those electrical appliances and other related components such as insulator or even interior parts might be damaged by striking against hard objects, say by children repeatedly, resulting in defect or poor electrical connection. Increase in electrical loading might give potential fire hazard. Electrical fault is the most possible cause of fires (Taipei City Fire Department 2010). Therefore, more attention should be paid to electrical fault in residential buildings. It is necessary to investigate the possible reasons for electrical fires in residential buildings, including new cases such as battery fires (The Sun 2011).

Improper use of the electrical appliance is a major reason causing quite a number of electrical fires. Many users, particulary children and elderly, used to ignore the proper procedure of using electrical appliances as many of them never read the user manual. It had been reported that a new cellular phone was burnt because the user wrongly plugged the power input into other slots! Based on the findings of Smith and McCoskrie (1990), a fire might occur due to inappropriate electrical loading. Also, improper repairs by unqualified persons and removed or damaged insulation might increase the possibility of ignition. Further, electrical cables or wires have a higher possibility to be ignited as reported in the US fire statistics (Hall et al. 1983). Wiring will be discussed on having residential fires due to low-voltage power system faults. Three possible mechanisms that generate transient heat are by poor connection, arcing and overloading.

In this paper, electrical faults that cause residential fires are studied (Lee 2012). From the statistics published, television is a cause of fire in residential flats (Electrical and Mechanical Services Department 2002). A television set was selected for experimental investigation on possible ignition by itself.

POOR CONNECTION

Poor connection was identified (Hall et al. 1983) to be a prominent reason for electrical fires based on statistics from National Fire Protection Association (NFPA). It consists of wirings between the power supply and end-feed use and circuit inside the device. While poor connection exists, improper circuit alternation can induce extreme high temperature and may lead to ignition, depending on the condition of the surroundings. Improper wiring connection by unqualified persons, defective design and lack of maintenance migth lead to poor connection.

Variations among screw-clamp type connection, also push-in, back-wired receptacles are common reasons for poor connection (Smith and McCoskrie 1990). Similarly, deficient contact pressure between portions of male and female receptacles is prone to poor connection, where ignition or arcing will be resulted. Aging, initial design problem and corrosion might be the factors for having high resistance (Gillmana and Le May 2007). Stress between connecting segments may be loosened and lead to poor connection.

In some cases, unintended connection is prone to electric fault. Conductors inside wall or building structure may be pierced by nails or sharp metal components, forming unintended path of circuit and generate high temperature. Moist condition, such as in bathrooms or in springs (Lam 2011), is often a cause of poor connection.

Defective design is another severe cause. For rare condition, the resistance of two wires twisted together will also induce high temperature (Babrauskas 2003). Aluminum cable installation was the major cause of residential fires in the US in 1950s due to different thermal and mechanical properties of aluminum and other materials used in the contacting outlet (Smith and McCoskrie 1990). Fortunately, this trend stopped in late 1970s.

ARCING

When the electric field between two electrodes is sufficiently high, electrons in air will move faster and there will be elastic collisions. As field strength is increased, electrons will escape from the air molecule and move to the positive electrode. Glow discharge will sustain and heat is then emitted (Tleis 2009). Electric spark or arc will be created and may ignite nearby tinder-type materials. Open circuit or shorting more than one conductors together will produce arcing in air. Arcing can occur across carbonized insulation and in air.

Carbonization can occur by large potential difference among insulation materials of wiring. It can be divided into two classifications: wet tracking and dry tracking. Wet tracking is common due to existence of moisture universally, and it is focused in this paper.

Polyvinyl chloride (PVC), commonly applied for sheltering conductors, is prone to carbonization by comparatively low temperature about 200^{o}C (Babrauskas 2009). Pollutants such as moisture and dissolvable contaminates can step up the breakdown process. The carbonized insulation part becomes a semiconductor and allows current to pass across the insulator, such that an unintended path is formed. Scintillations or carbonization process can start (Babrauskas 2006) under low power level at lower temperature. If it takes place without obstruction, full arcing may be resulted and the high temperature might ignite nearby tinder-type materials.

Arcing in air, considering that a low voltage residential fire is involved, may not independently occur. By opening a circuit or shorting two conductors together, ejection by induced magnetic field will separate them and arcing exists.

However, the chance of ignition is very low. Possible reasons (Babrauskas 2009) are that arcing can only preserve for a very limited period, and arcing may scatter with extracted solid.

OVERLODADING

Overloading is a notable physical mechanism of electrical fire. The main reason for overloading is that the flowing current exceeds the maximum current carrying capacity of the wire or cable (Li 2010; Lau 1997; Wong 2011). Temperature will rise and cause overheating. When overloading occurs, the surrounding materials may melt due to excessive thermal insulation, or even ejection of hot particles if heat emitted from the wire is much higher than the melting point of the material, fire can be resulted. Wrong selection of wire cross-sectional area and improper protective devices sizing would lead to ignition due to these mechanisms. The latter is, modern circuit breaker gives inappropriate allowable period. Circuit breaker would permit an abnormal current, which exceeds the designed range to pass through. It will result in overloading, and it will be heated up (Lee 2012). In some cases, insulation of wiring may melt and emit hot particles, thus causing fire.

Stray current would cause overloading. One of the factors is current flow through an unintended part of circuit. For insulation failure, it can ignite nearby tinder or produce spark to have fire. Wrong selection of wire coss-sectional area and sheltering material would lead to ignition due to these mechanisms.

In fact, ignition might involve several mechanisms. All contributing causative factors were studied by Smith and McCoskris (1990). To sum up, there are two probable physical explanations for ignition by those factors.

DETERIORATION OF WIRING BY AGEING

According to Gosland (1956), the probability of causing fire by wiring which has been used for more than 15 years is roughly proportional to the age of installation. This indicates that the longer the period the wire is installed, the higher the incidence rate of fire. A possible reason is that conductors used for a long time would allow less electrons to pass through, so the maximum current carrying capacity of the wiring will be decreased year by year, resulting in similar case of improper cable sizing or overheating. The insulation material also has ageing problems such as lowered melting point or even easy to be broken.

However, very few articles documented this phenomenon due to difficulties in collecting wirings used for different lengths of years. The consumption pattern is also very different now from the 1950s, as mentioned by NFPA (2006). As electricity consumption is larger nowadays, wiring might have ageing problems in a shorter period, compared to the conclusion made by Gosland (1956).

Nowadays, the living style has been changed with the advancement of technology. The number of electrical appliances used in residential flats has largely been increased. It is common that each household has at least one television set for entertainment. Nevertheless, television can be a source of causing fire event. From the statistics by the Hong Kong government Electrical and Mechanical Services Department, nearly 30 cases of fire event were suspected to be related to television during 1998 to 2001 (Electrical and Mechanical Services Department 2002, 2007). Japanese statistics (Babrauskas 2001) indicated that one-third of the ignition of television were related to the transformer. Therefore, television will be another target to be studied for investigating the possibility of being ignited. In this paper, the old-style television, using cathode ray tube but not liquefied principle for giving audio, will be focused on.

Generally, transformers applied in televisions are flyback transformers, or called line output transformers. One of its characteristics is that it consists of small-size capacity but output voltage can achieve normal operation of cathode ray tube, which creates audio at monitor, of about 20 kV to 50 kV (Dixon 2001). However, small size contains thinner insulation of the outer shell. In case of overcoming high voltage with insufficient isolated protection, unintended path may be created by carbonized insulation, thus become a source of fire event. Besides, dust is likely to be accumulated due to electrostatic effect. Under heat-up condition, the dust layer can act as tinder to exacerbate the ignition process. It is mentioned that (Du 2011), to maintain operation of the television memory, current in secondary circuit will not be completely cut but kept in "standby mode", power is still being supplied from the socket outlet. For long-term operation, wiring inside the secondary circuit may overheat, thus it can be an ignition source that causes fire.

Experiments can be conducted to study the temperature and also the current variation of a television under standby mode with long-term observation. The results can be analyzed to find out the possibility of a television being ignited by itself.

AN EXPERIMENTAL STUDY

For the wiring part, the Code of Practice for the Electricity (Wiring) Regulation, published by Electrical and Mechanical Services Department (2009), gives guidelines on how to satisfy the requirements on electrical installation in Hong Kong. This Code of Practice summarizes all recommendations for new electrical installation and relative materials such as the checklist for testing and commissioning process and sample for correct cable sizing in Hong Kong. The situation of electrical installation especially for the wiring part in Hong Kong can be briefly known through reviewing the code. Some reasons for ignition can be roughly estimated. In this paper, by considering residential flats, only wiring and end-feed appliances will be focused on.

For studying the possibility of ignition of a television by itself, a television set (Lee 2012) with a video recorder as shown in Figure 1 will be used for investigation. It is a common type of television in residential flats appeared in 1990s. A layer of dust is accumulated on the outer shell as it has not been used for a long time. Therefore, dusty condition can also be demonstrated.

Figure 1. The television set studied

An experiment was carried out to investigate the current and temperature variation for a television in standby mode. The interior structure should be studied before starting the experiment. The main components of this television are flyback transformer, vertical cathode ray tube (CRT), horizontal CRT and coil.

The surfaces of all components, including the outer shell of the whole television, were connected to thermocouples, and fixed by aluminium sticker and glue. These components were connected to a data logger (serial: midi logger) to record the surface temperature. One thermocouple was fixed for recording the changes of ambient temperature as a control. The data logger took measurement at every 30 minutes interval. Transient temperature rise at vertical CRT, flyback transformer, coil and horizontal CRT are shown in Figure 2.

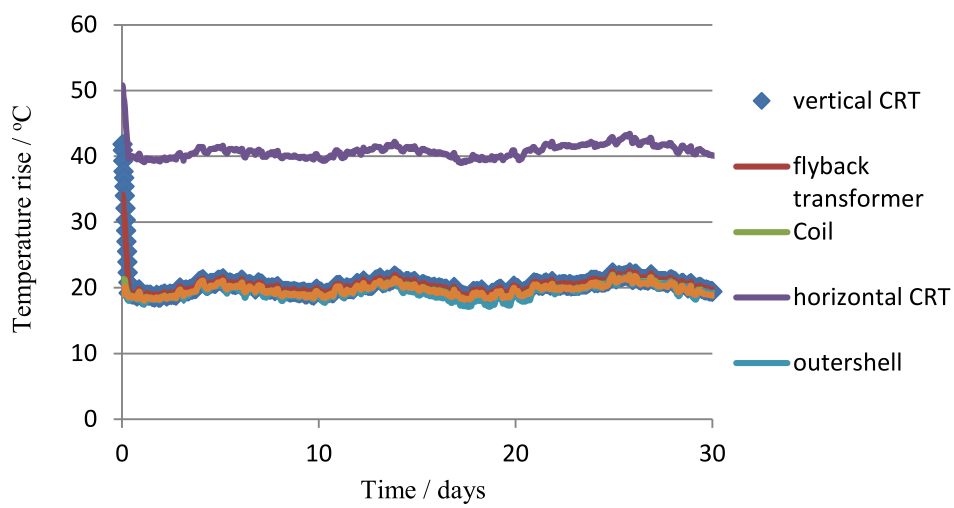

Figure 2. Transient temperature rise measured at different positions

A small resistor was added into part of the circuit for measuring current. Potential differences across the resistor were measured by adding a voltmeter with results sent to another data logger. This data logger recorded the voltage every hour. By known values of resistance and measured voltage, the current passing through the secondary circuit can be calculated by basic laws in electricity.

The experiment was conducted for 30 days without power interruption so that the standby mode was on for a relatively long period for obtaining accurate result. As a safety precaution, the variation of temperature and also the operation of all equipments involved should be checked daily. Temperature and result should be recorded in the log book and all connections between the television and data loggers should be inspected not to be loosened due to unwanted crash or other accident. This is to ensure that the television worked under normal condition, and to avoid real case of ignition.

The results on temperature rise at different parts of the television set and the current are shown in Figures 2 and 3, respectively. Analysis such as poor connection within plug and line can be done from experimental results. Approximate temperature and current can be found from literature review. Thus, the possibility of igniting the television can be estimated by comparison between criteria of average ignition and experimental result.

From temperature rise curves shown in Figure 2, flyback transformer, vertical CRT, coil and outer shell temperatures were all hotter than ambient. Temperatures were kept normally at 0.5°C higher than ambient temperature. The temperature of horizontal CRT was about 20°C higher than ambient temperature. One of the reasons is that the horizontal CRT is independent of the secondary circuit. Therefore, supply current can directly flow without passing through the flyback transformer. However, at 50°C, the horizontal CRT still had a very low possibility to be ignited since the formation of arc or spark are at about 190°C.

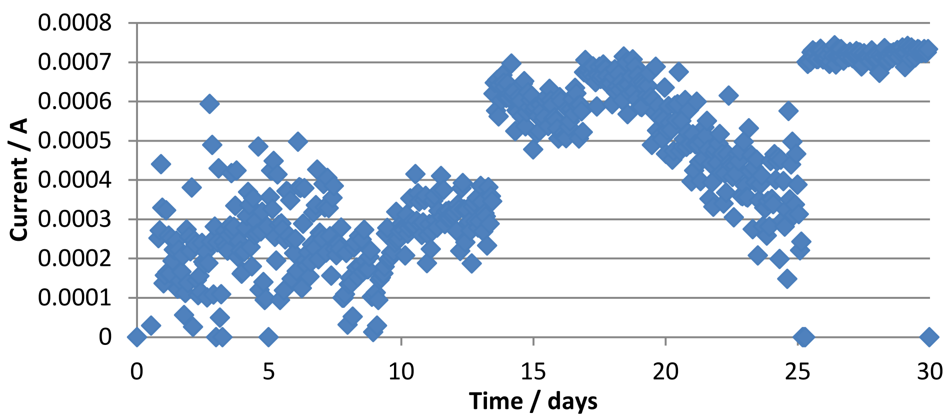

Figure 3. Transient current measured

The results showed an irregular increasing trend from the starting period (day 5 to day 15). However, the current decreased slightly at later stage as in Figure 3, though the value was still higher than the current measured in the first few days. At the end (day 25 to day 30), the current was stably kept at a relatively high level about 0.08 mA.

Compared to normal ignition due to electrical fault, the current from experimental result was still at very low values for ignition. Therefore, by considering temperature and current, the possibility of igniting a television in standby mode is very low.

LOCAL CODES

In Hong Kong, all wiring installation should be based on Code of Practice (CoP) for the Electricity (Wiring) Regulation 2009 Edition (Electrical and Mechanical Services Department 2009). All protective devices, inspection and testing criteria are recorded so that safety of installation should be ensured to reach an acceptable level in Hong Kong. It will be used to evaluate the possibility of causing fire due to wiring installation. As fires are caused by numerous reasons, the one having the highest possibility (poor connection) will be taken as the main reason to be evaluated.

Code 8 Isolation and Switching of the CoP for the Electricity (Wiring) Regulation (Electrical and Mechanical Services Department 2009) stated that the general circuit breakers should be installed to fulfill minimum requirements in Hong Kong. The connection method is also noticed. Only the first two sections of the 8A part will be focused on as wiring and appliances in residential flats will be concerned.

It pointed out that all appliances or equipment (including lighting) should have their own insulator, which means if wirings inside are connected wrongly, it should be cut by devices of appliance or even devices installed in ring circuit in some serious cases. It means double protection will be given. Another code will be introduced for earthing problems.

Code 13 to Code 15 (Electrical and Mechanical Services Department 2009) guided the wiring characteristics, installation method and also the condition of wiring installed so that the maximum current carrying capacity of the selected wiring will be much more than the current passing through under normal condition. Consequently, there will be higher chances of overheating. Basic protection will also be suggested for the electrical insulation. Types of tinder are listed to avoid placing them near wiring after reading. Therefore, even if spark is given out, fire will not easily occur by reducing tinder.

Code 26 (Electrical and Mechanical Services Department 2009) is on the requirements for specific installations and equipment; 26A(1) guided the number of socket outlets and also the maximum allowable connecting loads in one circuit of a domestic building. It is separated into kitchen, bathroom and other heavy load appliances. Following the guidance and considering interior separation in a flat, as loads are evenly distributed in each circuit during the design stage, overloading condition due to poor design and installation can be reduced. There are worked examples for application of the CoP and checklist in Appendices 12 and 13.

In these examples, especially 12(B), the progress of cable sizing and other equipments can be shown. By calculation, the design current can be found. By matching the cable information, the maximum allowable current of a cable can be found so that the possibility of overloading condition will be very low by using the same method. Checklist is for testing and commission for new low voltage installation. It provides the checklist of each part of circuit, so that for new installation, contractors can carry out installation according to this list for installation with supposed safety criteria.

To sum up, wiring installation guided by the CoP (Electrical and Mechanical Services Department 2009) should have a low possibility of being ignited. It is recommended that in the design stage, cable sizing procedure should include the consideration of aumoured method, installing condition of cable, etc. Special condition and also insulation material are included so that overheating or overloading situation due to inappropriate sizing can be greatly decreased. However, unclear indication is given for existing cables such as testing and commission period and also preferred time for a cable used, therefore ageing problem of wiring still cannot be completely solved by replacement on time. Physical damage is mainly considered as accident, which is unavoidable. Improper use is an uncontrolled factor which depends on the users and their living style.

Therefore, according to the CoP (Electrical and Mechanical Services Department 2009), overloading condition can be greatly avoided but still the problem due to human factors cannot be solved.

CONCLUSIONS

Electrical fault is a common cause of residential fires, and its potential hazard is increasing as more electrical appliances are being used in each family nowadays. Wiring has a higher possibility to be ignited. Physical damage and improper installation are some of the reasons causing electrical fires. According to the CoP for the Electricity (Wiring) Regulation in Hong Kong (Electrical and Mechanical Services Department 2009), overloading of wiring can be greatly avoided. However, some problems involving human factors still cannot be solved.

Television set can be a source of fire. For long-term usage, insulation and wiring may be weakened and cause fire due to ageing problem and also unintended path created by carbonization. Although television has a low possibility of being ignited by itself, it is recommended to plug off the socket from the power supply for isolation when not in use.

Fires caused by electrical fault were discussed in the literature (e.g. Fire Services Department 2008-2010; Taipei City Fire Department 2010; Runyan et al. 1992; Ducic and Ghezzo 1980; Chien and Wu 2008), but most of the work were focused on industrial fire investigations or fires by high voltage installation. Very few reported on fires by low-voltage installation in residential flats. More articles on this topic can be found in Mainland China, but many were reported 30 years ago. Taking into account the changes in life style, statistics or reasons behind the phenomenon might be different. However, updated statistics are not yet compiled. Battery fire and explosion is a good example (The Sun 2011).

Besides, the cases studied in this paper (Lee 2012) are mainly from Hong Kong. As the living style and electrical consumption habit are different in different countries, the conclusion drawn in this paper may not be applicable to other places.

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A Brief Discussion on Fire Safety Issues of Subdivided Housing Units in Hong Kong

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ABSTRACT

Subdivided unit (SDU) is a new type of residential housing affordable to the fundamental class citizens of Hong Kong. A flat is subdivided into smaller units in both domestic buildings and industrial buildings without government approval. Fire hazard of SDUs is a public concern, which should be assessed properly.

In this paper, fire hazards of SDU will be discussed. Fire regulations for SDUs by the local government will be summarized. Fire accidents happened in SDUs will be briefly reported. A survey was carried out on the potential fire hazards of SDUs located in eight residential buildings and two industrial buildings. Based on the surveyed results, recommendations were made along four areas on fire safety auditing; upgrading the design, installation and maintenance of appropriate fire safety provisions; raising the awareness of occupants on fire safety and providing suitable training; and the establishment of a Building Fire Warden System.

INTRODUCTION

Hong Kong is a densely populated big city with over 7 million registered residents, and another million of transient visitors. About 60% of the population stay in 80 km^2 of usable land (Grange 2004). Economics in Hong Kong is growing rapidly and so housing cost is very high. A residential flat cannot be cheaper than HK$100,000/$m^2$ (about US$13,000/$m^2$) of floor area. However, citizens prefer to stay close to their working areas to avoid having long traveling time.

Subdivided units (SDUs) then appear in downtown to provide low-cost housing. A residential or industrial flat is divided into many small units. There are about 280,000 SDUs (Platform of Concerning Subdivided Flats and Issue in Hong Kong 2012) with over 170,000 residents. Many problems were identified in SDUs, such as poor ventilation, fire safety and even overloading of the structure. After the fire accident in the Fa Yuen Street involving SDUs in 2011 (South China Morning Post 2011), citizens are alerted to the fire hazards in those buildings with SDUs. Problems on fire hazards have to be solved urgently as most of the SDUs do not comply with the fire safety codes (Buildings Department 2011; Fire Services Department 2012).

The fire hazards identified in buildings with SDUs include poor electrical wiring, unregistered electric meter installation, high amounts of combustibles stored with high fire load density (FLD), inadequate evacuation paths and blocked escape route. Illegal electrical wiring systems with unregistered electric meter installation can give (and had given) accidental fires due to electricity leakage or overloads.

In this paper, fire safety provisions in SDUs will be studied. The potential fire hazards in an SDU will be identified first. The amount of combustibles in a selected SDU will be surveyed. The current situation of SDUs in Hong Kong will be reviewed. Results of the study will be analysed. Recommendations will then be made for improving the fire safety in buildings with SDUs.

SDUs IN HONG KONG

SDU is defined (Buildings Department 2013a) by the government Buildings Department (BD) of Hong Kong as a unit that is subdivided into two or more separated rooms, and usually there is individual toilet or cooking place in each of the flat. SDUs without individual toilet or cooking place are known as 'cubicle apartments' or 'bedspace apartments' not defined in the Buildings Ordinance (BO) following the legislative council quota (LCQ11) (News.gov.hk 2012). Cubicle apartments are generally defined as a flat subdivided by wooden cubicles of simple construction and enable a unit to accommodate more than one tenant or sub-tenant. Bedspace apartments are known as 'caged homes' according to the BO, meaning that there are 12 or more bedspaces used as sleeping accommodation for individuals under rental agreements.

Statistics compiled by the government reported (Legislative Council Secretariat 2013) that there are at least 66,900 SDUs; and every subdivided flat is approximately subdivided into 3.6 units, with about 171,300 residents or 2.4% of the total population in Hong Kong. Over 55.4% of the 171,300 residents are living in SDUs with 7 to 14 m^2 floor area, and 10.8% are living in SDUs below 7 m^2. Housing shortage in downtown areas might be addressed by increasing the number of SDUs after sorting out the problems identified. Note that the main reason why citizens live in SDUs is for convenience, not travelling between their working or studying areas for over 2 hours a day with heavy traffic. The ordinary class of citizens cannot afford to drive, and the fares for public transport are high. SDUs are also found in industrial buildings which are not designed for domestic use. Some factories are in operation in industrial buildings with SDUs. Such SDUs have a higher risk to the household and are not suitable for domestic use (Buildings Department 2013b). Fire safety requirements on ventilation, open space, means of escape and other fire service installations of industrial buildings are different from the regulations of residential buildings and composite buildings.

The average area of an SDU per capita was about 6.3 m^2 for those staying at SDUs (Policy 21 Limited 2013). Note that for public rental housing (PRH), the actual usable floor area per person is about 13 m^2 as compiled in end-September 2013. SDU households have a much crowded living environment than the PRH households. According to the accepted standards for floor space of World Health Organization (Wikipedia 2013), the range of floor area for one person is 7 m^2 to 9 m^2.

There are many problems on indoor environment quality, structural stability and others to be addressed separately (Leung 2014). In this presentation, fire safety in SDUs will be pointed out. Note that an accident occurred in 2011 with 4 dead and 19 injured. The top 10 most serious fires happened in the last two years are listed in Table 1. As observed from the table, fires were mainly caused by electrical short-circuit and electric meter overload. Poor fire safety management in blocking escape routes is the main reason for casualties and injuries. Case 4 as listed in Table 1 is the most disastrous case with serious consequences. The fire was caused by electrical short-circuit. As reported in the news (e.g. South China Morning Post 2011), many occupants could not escape from the building because the escape routes were either blocked or altered.

Table 1. Ten fire accidents with SDUs from 2011 to 2013

Case	Date	Cause of the fire	Number of deaths	Number of injuries	Cause of the deaths or injuries
1	15 June 2011	Cigarette or incense	4	19	The floor layout changed because of building SDUs. Evacuation was difficult.
2	19 July 2011	Electrical short-circuit	0	3	• Many objects were put in the fire escape route. • Smoke door opened to spread fire and smoke fast. • Many people felt irritating after inhaling smoke.
3	3 November 2011	Circuit overload	-	-	No casualty and injury reported.
4	30 November 2011	Electrical short-circuit	9	34	Many objects were put in the fire escape route.
5	11 January 2012	Electrical short-circuit	-	-	No casualty and injury reported.
6	2 August 2012	Circuit overload	-	-	No casualty and injury reported.
7	26 August 2012	Circuit overload	0	5	The exit door was locked, people could not escape.
8	5 October 2013	Circuit overload	1	2	Many objects were put in the fire escape route and staircase.
9	1 December 2013	Electrical short-circuit	0	2	Many objects were put in the fire escape route and staircase.
10	29 December 2013	Arson	0	25	Many construction materials placed at the exit of the building, extending evacuation time.

A leaflet on fire safety regulations of SDUs was issued (Buildings Department 2013b) as shown in Appendix A. Common fire safety problems of SDUs identified from a survey carried out by the Institute of Surveyors (2011) are listed in Appendix B.

SURVEY ON SDUs

A total of 10 buildings including 8 residential buildings and 2 industrial buildings were surveyed with their potential fire hazards inspected (Leung 2014). These buildings are distributed in different districts in the downtown areas of Hong Kong, including Yau Ma Tei, Fanling, To Kwa Wan, North Point, Sham Shui Po, Mongkok, Tai Po and Hung Hom labelled as R1 to R8 for residential buildings; and labelled as I1 and I2 for industrial buildings in Kwun Tong in Tsuen Wan respectively.

The floor areas of the eight residential flats with SDUs are shown in Table 2, ranging from 3.7 m^2 to 6.5 m^2. Pictorial views of SDUs in the eight residential buildings are shown in Figure 1.

Table 2. SDUs surveyed in residential buildings

Building number	District	Room area	Combustibles	FLD (MJm^{-2})
R1	Yau Ma Tei	3.7 m^2	a single bed, clothes, small wardrobe, newspaper, carton	556
R2	To Kwa Wan	4.6 m^2	Paper, plastic wardrobe, bunker bed, television, an air conditioner, fan, clothes, table, refrigeration	949
R3	Fanling	4.2 m^2	Paper, plastic wardrobe, bunker bed, table, clothes, fan, curtain	1024
R4	North Point	5.6 m^2	bunker bed, refrigeration, paper, clothes, wardrobe	1326
R5	Sham Shui Po	3.7 m^2	bunker bed, table, clothes, paper, wardrobe, chair	1563
R6	Mong Kok	6.0 m^2	Wardrobe, television, double bed, air-conditioner, small wardrobe, clothes	767
R7	Tai Po	3.7 m^2	Single bed, fan, radio, small wardrobe, newspaper, clothes	576
R8	Hung Hom	6.5 m^2	Bunker bed, table, clothes, wardrobe, computer	787

(a) SDU in R1 at Yau Ma Tei

(b) SDU in R2 at To Kwa Wan

(c) SDU in R3 at Fanling

(d) SDU in R4 at North Point

(e) SDU in R5 at Sham Shui Po

(f) SDU in R6 at Mongkok

(g) SDU in R7 at Tai Po

(h) SDU in R8 at Hung Hom

Figure 1. Combustibles inside SDUs of residential buildings

The FLD (in MJ/m^2) at each SDU was surveyed (Fire Services Department 2012) by inspecting the total number N of different combustibles, the mass of each combustible m_i (in kg) and its calorific value E_i (in MJ/kg), and the floor area A (in m^2) of the building concerned:

$$FLD = \frac{\sum_{i=1}^{N} m_i E_i}{A} \quad (1)$$

The combustible items observed in buildings R1 to R8 are listed also in Table 2 with their FLD estimated. Values of FLD measured from 556 MJm^{-2} to 1563 MJm^{-2}. High FLD observed at each unit is found in small units.

In Hong Kong, the upper limit of FLD allowed (Fire Services Department 2012) is 1,135 MJm^{-2}. In these eight surveyed domestic buildings, 25% of those SDUs have fire loads exceeding the upper limit. For the SDUs in R2 at To Kwa Wan and R3 at Fanling, the FLDs are very close to the upper limit. The FLD of those SDUs are only estimated, based only on the dead fire load. There are many combustible objects stored in some SDUs not allowed to enter. The FLDs estimated are only minimum values. SDUs would have a much higher FLD. The percentage of those SDUs with FLD exceeding the upper limit should be more than 25%.

From the survey in eight residential buildings and SDUs, high FLD over the upper limit of the code requirement (Fire Services Department 2012) is a concern. A flat subdivided into several SDUs will have higher FLD; if a fire occurs, it will be more dangerous than a fire in a building without any SDUs. Storing large amounts of combustibles will give a big fire in the SDU with a long duration.

SDUs IN RESIDENTIAL BUILDINGS

Fire safety problems surveyed are shown in Figure 2. Basically, the problems are:

- The corridor width is less than 0.75 m.
- Many combustibles are placed in the escape route.
- Escape routes are blocked.
- Too many electric wires and electric meters are installed in the public escape staircase.
- Electric wires are not connected orderly because of addition and alteration works.

Local regulations (Buildings Department 2011) require that for a flat with less than 3 persons, the clear width of the internal corridor serving the SDUs should not be less than 0.75 m. Narrow corridor violates the regulations and would give difficulty in evacuation. However, narrow corridors are observed in the unit in R1 at Yau Ma Tei and R2 at To Kwa Wan as shown in Figure 3. Since one floor may contain several SDUs, the population density on a floor with SDUs should be much higher than the population density on a floor without SDUs. A flat with narrow internal corridors and high population density would give (Reax Fire Protection Engineering Services 2014) long evacuation time.

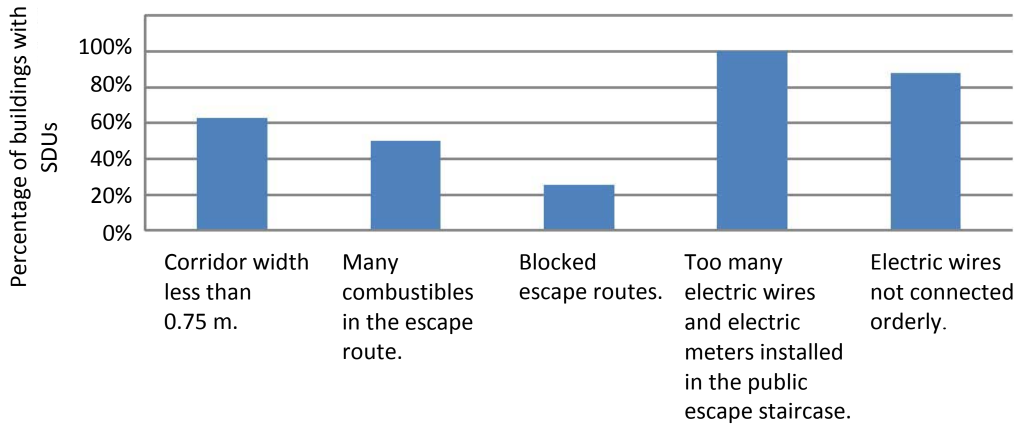
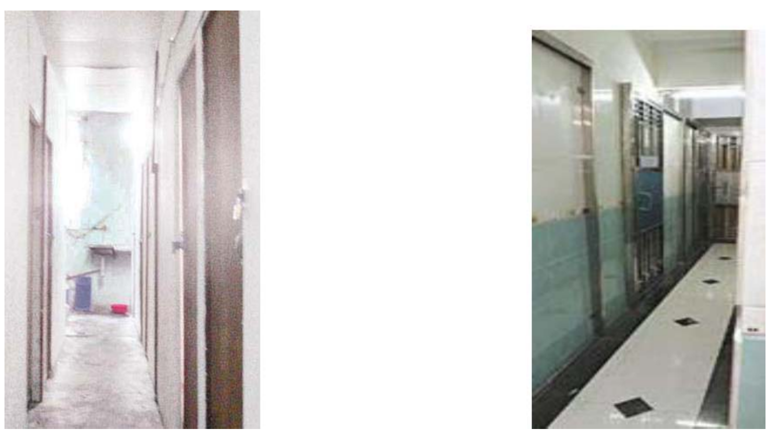


Figure 2. Observed fire safety problems in SDUs



(a) R1 (b) R2

Figure 3. Narrow corridor observed

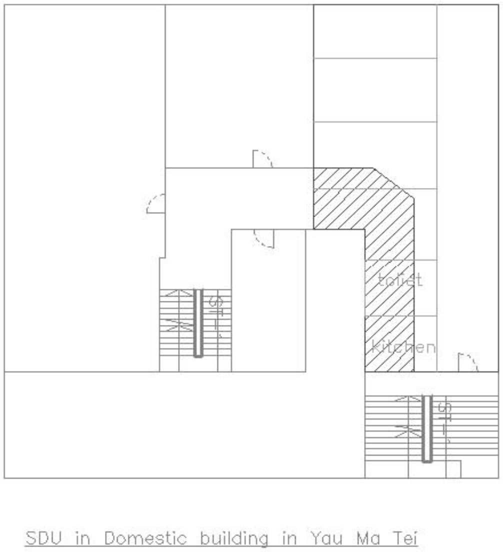
Many combustible objects are placed in the escape route as in R5 at Shum Shui Po and R4 at North Point as shown in Figure 4. Putting objects in the escape route will not only block the corridor, but it may also increase the rate of fire spread (Cheng and Hadjisophocleous 2011). Most of the objects placed on the corridors and staircases are combustible. Upon igniting those objects, the fire may spread easily and rapidly from one unit to another unit, or from one floor to another floor. Large amount of smoke will be produced to reduce the visibility (Klote and Milke 2002). People might die due to inhaling too much smoke.

Some escape routes are blocked as in R1 at Yau Ma Tei and R2 at To Kwa Wan as shown in Figure 5 on the floor layout plans. As in Figure 5a, the three SDUs can reach both staircases in the original building design. However, another SDU was built with an illegal partition wall, which blocked the escape route from the other two flats to the staircase. For the case in Figure 5b, the floor in that building was originally built with two large units. However, the two large units are subdivided into several SDUs. The escape route is blocked due to the added doors and partition walls. Although there are two staircases, occupants cannot use the nearby staircases. Blocking the escape route would give long evacuation time which might lead to fatality and injuries. Units with only one staircase are very dangerous.

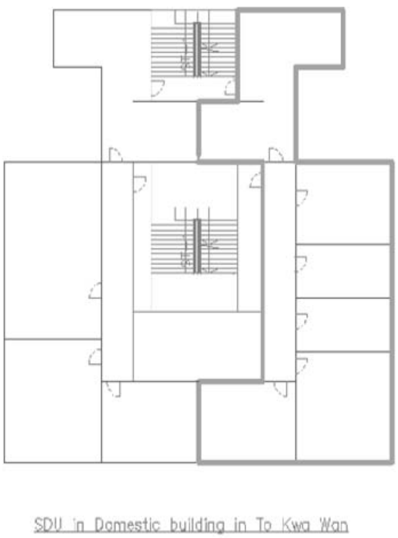

(a) R5 at Sham Shui Po


(b) R4 at North Point

Figure 4. Combustibles placed in SDUs



(a) R1 at Yau Ma Tei



(b) R2 at To Kwa Wan

Figure 5. Blocking of escape route

(a) R1 at Yau Ma Tei (b) R6 at Mong Kok

Figure 6. Electrical meters

All the eight buildings with SDUs surveyed have many electric meters and electric wires installed in the escape routes or staircases as in R1 at Yau Ma Tei and R6 at Mongkok shown in Figure 6. As observed from the figure, each SDU has its own electric meter for paying the electric bill. Those electric meters may not be installed by registered persons or companies. Further, too many users as indicated by the number of electric meters would cause overload as occupants are having many low quality electrical appliances, such as pirated cellular phones with explosion reported in the past. Note that electrical overload is the main cause of fire as reported in the past fire accidents in SDUs. It can be observed from Figure 6a that electric wires are not connected orderly. Protective coating of electric wires might be ruined to cause electricity leakage.

SDUs IN INDUSTRIAL BUILDINGS

Many SDUs are built in industrial buildings because of the relatively cheaper price. However, industrial buildings are not suitable (Buildings Department 2013b) for domestic use because the designs of the provision of ventilation and natural lighting and means of escape for industrial buildings are different from those for domestic buildings. Industrial buildings would store dangerous and inflammable goods.

It can be observed that electric wires are not connected orderly in I2 at Tsuen Wan on some floors with SDUs as in Figure 7a. The escape route in an industrial building is wider than that in a domestic building as shown in Figure 7b for I1 at Kwun Tong.

The corridor and escape route for SDUs in industrial buildings are better than those in domestic buildings. In the industrial building, the corridor of the floor with SDUs complied with the requirement of minimum clear width of the internal corridor. The width of the corridor is more than 1.5 m as shown in Figure 7b. No objects were placed in the escape route.

However, the escape route design did not satisfy the requirement (Buildings Department 2011; Fire Services Department 2012) that the length from any living unit to the escape staircase should not be longer than 18 m. As the industrial building has a large floor area, some SDUs have escape route over 18 m (Cherwell Fire Safety Limited 2011). As in Figure 8 on the SDU at Kwun Tong, the floor is separated into two parts, each with 33 SDUs. The population of the floor is high. On that floor, the escape route in some SDUs is more than 18 m. The required evacuation time will be extended for high occupant loading. Although the situation of the public corridor of the floor with SDUs in industrial building is better than that in domestic building, the escape route design failed to comply with local regulations.

(a) Electric wires in I2 at Tsuen Wan (b) Corridor of SDUs in I1at Kwun Tong

Figure 7. Industrial buildings with SDUs

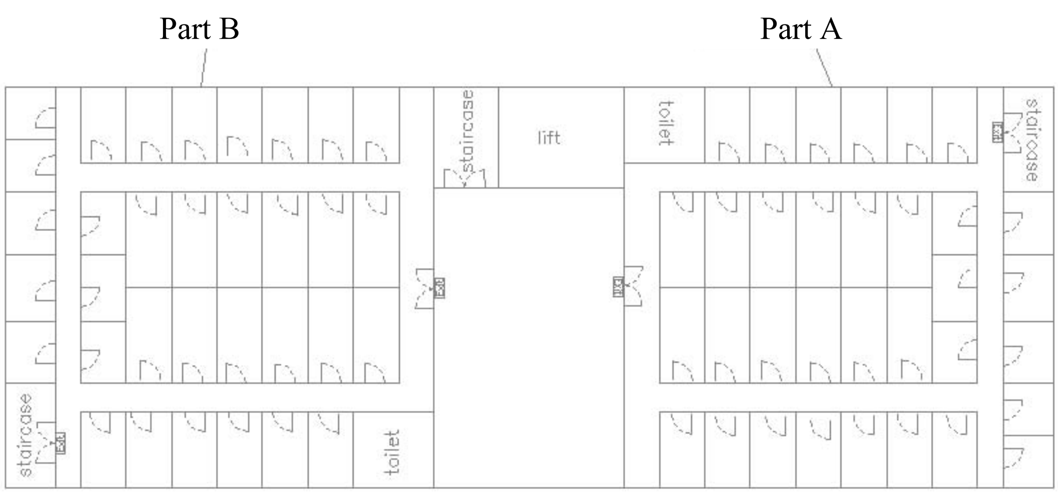


Figure 8. Layout plan of a floor with SDUs in the surveyed industrial building I1 at Kwun Tong

RECOMMENDATIONS

From the above study, recommendations are made along four areas to upgrade fire safety in buildings with SDUs. These are on fire safety auditing; upgrading the design, installation and maintenance of appropriate fire safety provisions; raising the awareness of occupants on fire safety and providing suitable training; and the establishment of a Building Fire Warden System.

- **Fire safety auditing**

Local government encourages building owners to pay more attention to the fire safety in their building, particularly in SDUs. A fire safety checklist for the general use of building owners or occupiers was devised by Fire Services Department (FSD) (2010). The purpose of the checklist is to facilitate building owners or occupiers to carry out routine inspections on fire safety provisions of their own buildings, and to rectify minor irregularities identified. After the survey visit on the ten buildings with SDUs, most of the SDU owners are not concerned with fire safety. The government should pay a more active role requesting building owners to conduct regular fire safety checks. Mandatory fire safety check is good for monitoring SDUs with a high potential fire risk. Officers must be sent to inspect fire safety regularly. Sudden inspection must be practised.

Further, monthly fire safety check by SDU owners themselves is suggested. A group can be established to take responsibility for the fire safety of the building with SDUs.

- **Fire safety provision**

Fire safety provision includes the passive construction elements such as fire escape route and fire resisting constructions; and active fire service installations (FSI) (Fire Services Department 2012). As surveyed, FSI in the ten buildings with SDUs did not comply with the local requirements (Fire Services Department 2012). The government FSD and BD have already reinforced the inspection of target buildings, and taken follow-up actions if potential fire hazards caused by obstructions to fire escapes or structural problems are identified, or if there are problems associated with FSI. However, action must be taken to control and ensure new SDUs are built with appropriate fire safety provisions.

Items of works found in SDUs are included in the Minor Works Control System (MWCS) (Buildings Department 2013c). The government should consider incorporating the fire safety provisions in the MWCS to upgrade fire safety in SDUs.

Additional FSI such as residential sprinkler should be installed as FLD in buildings with SDUs is high.

- **Fire safety awareness and training**

Occupants living in SDUs are mostly fundamental class of low educational level and low income. All the ten surveyed buildings with SDUs have a high FLD and with combustibles put on the public area staircase. Many combustibles such as newspaper and old electrical appliances are stored. In view of these, knowledge of fire safety and appropriate training must be provided to the occupants.

Occupants must be alerted to the hidden fire hazards. The fire safety awareness among the household should be strengthened. District Fire Safety Committees (Legislative Council 1999) in crowded districts with SDUs such as Yau Ma Tai, Sham Shui Po and Mongkok, should promote more on the importance of fire safety. More leaflets, pamphlets and posters should be distributed to the public, owners of the buildings with fire safety problems and people of different races.

It is difficult to alert occupants to the fire risks of SDUs. More talks must be arranged by the District Fire Safety Committees to the building owners with SDUs. The purpose of these talks is to provide training for the building owners, so that they know how to increase the fire safety awareness of the households in their buildings.

- **Building fire warden system**

Fire wardens and building households can assist the management of fire safety by reporting any issues or problems that they may identify. The government should encourage SDU owners to designate a warden responsible for fire safety in the building. Occupants in SDUs can be grouped together to take care of fire safety.

The FSD should control the fire warden system and ensure the responsible person has adequate knowledge on fire safety management, including not to build illegal structures such as partition walls.

CONCLUSIONS

Fire safety in the buildings with SDUs is reported in this paper. From the site survey, common fire safety problems in those buildings with SDUs are identified. Problems for SDUs in residential buildings are narrow corridor, combustible objects put in the escape route, blocked escape routes, and large number of electric wires and meters improperly installed in the public escape staircase. These may increase the fire risk to the inhabitants in the building with SDUs and may cause higher numbers of deaths and injuries in a fire.

The situation is better for SDUs in industrial buildings. However, the industrial building is not suitable for establishing SDUs because there are still factories operating. Dangerous and inflammable goods stored can bring fire hazards to the occupants concerned.

The FLD in SDUs is much higher than the maximum FLD requirement (Buildings Department 2011; Fire Services Department 2012) of domestic flats in Hong Kong. Therefore, the FLD of SDUs must be controlled. Based on the survey result, recommendations are made to upgrade fire safety in SDUs.

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APPENDIX A: FIRE SAFETY LEAFLET BY BUILDINGS DEPARTMENT (2013)

http://www.bd.gov.hk/english/documents/pamphlet/SFIBe.pdf

- Do not remove existing fire rated doors or replace them by doors not meeting the required fire resistance rating.
- When the original fire rated door at the entrance of the flat is maintained. The width of the corridor should not less than 0.75 m if the total number of occupants is not more than 30persons and should not less than 0.85 m if the total number of occupant is more than 30 persons and not more than 200 persons.
- When the original fire rated door at the entrance of the flat is removed or replaced by a door not meeting the requirement of the fire resistance rating, the

width of the corridor should not less than 1.05 m.

- The partition walls between the subdivided unit and corridor and the door of each subdivided unit should be fire resistance. The door should be able to close automatically and smoke-sealed.
- The exit route should have a clear headroom of not less than 2 m.
- In the enclosures of exit staircase, there should not exist any new door and ventilation opening.
- For the fire rated wall separating the unit and the means of escape, there should not exist any new opening for ventilation or for installation of air-conditioners and exhaust fans.
- If there are installed any metal gate, those should not obstruct the means of escape.
- The subdivided unit should not block or obstruct the means of escape leading to any exit staircase.

APPENDIX B: FIRE SAFETY PROBLEMS SURVEYED BY THE INSTITUTE OF SURVEYORS (2011)

http://www.legco.gov.hk/yr10-11/chinese/panels/dev/papers/dev0620cb1-25782-c.pdf

- Escape routes are often blocked or are inaccessible due to the illegal construction of partition wall, it increases the difficulty of fire escape.
- There are leak of fire resistance wall and door, it encourages the fire spread.
- There are leak of emergency lighting.
- New installed metal gate obstruct the means of escape.
- Too many electrical equipment which cause electric overload, increase the fire risk.
- Too many electric wire and electric meter installed in the public escape staircase and the electric wire is messy.
- The escape route is more than 18 m, too long escape route may over the required safety egress time, high risk to people from fire.
- The electric meter for each SDU is not installed by registered electric company or any certified people, therefore, the handling load of the electric meter may not meet the required standard.

CLC-RBDCCpaper-1d

Flashover Fires in Small Residential Units with an Open Kitchen

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ABSTRACT

The open kitchen design in small residential units where fire load density and occupant load are very high introduces additional fire risk. One big concern is that whether flash-over can occur which may trigger a big post flashover fire, resulting in severe casualties and big property damage. It is important to understand and predict the critical conditions for flashover in this kind of units. Based on a two-layer zone model, the probability of flashover is investigated by a nonlinear dynamical model. The temperature of the smoke layer is taken as the only state variable and the evolution equation is developed in the form of a simplified energy balance equation for the hot smoke layer. Flashover is considered to occur at bifurcation points. Then the influence of the floor dimensions and the radiation feedback coefficient on flashover conditions is examined. When the dimensions of the floor vary, the resulting changes in internal surface area or size of floor area both have effect on the flashover conditions. When the radiation feedback coefficient is of small value, there is no possibility of flashover. With the increase of the radiation feedback coefficient, at first it significantly affects the conditions for flashover and then moderately when it reaches a larger value. It is proved that the flashover phenomenon can be demonstrated well by nonlinear dynamical system and it helps to understand the effect of various control parameters.

NOMENCLATURE

c_p specific heat at constant pressure (J/kg.K)
C_d flow coefficient
g acceleration due to gravity (m/s^2)
G_E heat gain rate of the hot smoke layer (W)
h_c convective heat transfer coefficient (W/m^{2}K)
H height of the apartment (m)
H_{com} heat of combustion (J/kg)
H_d height of the opening (m)
H_{vap} heat of evaporation (J/kg)
L length of the apartment (m)
L_E heat loss rate of the hot smoke layer (W)

$\dot{m}_a$ mass inflow rate of ambient air (kg/s)
$\dot{m}_{out}$ mass flow rate of hot smoke out of the opening (kg/s)
$\dot{Q}$ heat release rate of the fire (W)
$\dot{Q}_0$ free burning heat release rate (W)
r stoichiometric ratio
$\dot{R}_{in}$ incident radiant heat from smoke layer to fire base (W)
t time(s)
T temperature of the hot smoke layer (K)
T_{equ} equilibrium temperature (K)
T_0 ambient temperature (K)
T_w temperature of the wall surface contact with the hot smoke (K)
U_c wall temperature parameter
W width of the apartment (m)
W_d width of the opening (m)
Z smoke layer interface height above the floor (m)
Z_N neutral plane height (m)

Greek symbols

χ combustion efficiency
χ_R radiation factor
μ radiation feedback coefficient
ρ_0 density of the ambient air (kg/m^3)
λ eigenvalue
σ Stefan-Boltzmann constant (W/m^{2}K^4)

INTRODUCTION

Due to limited land resources, more and more high-rise residential buildings have sprung up, especially in densely populated areas (Chow 2005). Over the years, due to the unique challenges in fire safety, high-rise buildings have attracted people's attention. There are various fire hazards in these tall residential buildings. With the adoption of some design features, like green building (Chow 2003) and open kitchen (Chow 2011a), new fire risks may be posed. Open kitchen design has been adopted for many small units with floor area less than 30 m^2 in tall residential buildings in places like Hong Kong (Chow 2011a, 2011b). This is because open kitchen design in small residential units can give a better space utilization.

Kitchen is an area with special fire hazards. Traditionally, it is required to be enclosed by fire resisting construction. According to the NFPA home fire report (Ahrens 2013), cooking equipment was the leading causes for home fire and injuries. It was also reported that only a small percentage of them (less than 5%) extended beyond the kitchen, but these "escaping" fire accounted for a large proportion of the deaths and damages. Fire load density in some residential buildings was reported to be extremely high, more than 1400 MJm^{-2} (Arup Hong Kong 2010). If fires originating from the open kitchen find their way to other parts of the unit a big fire will be resulted. Once flashover occurs, with the aid of wind effect, the fire may spread to the upper floors or even the adjacent buildings, making the fire damage more catastrophic. Therefore, flashover must be investigated in such types of units and precautions must be provided to prevent it from happening.

Flashover is often defined as a very rapid and sudden transition from a growing fire to a fully developed fire (Karlsson and Quintiere 2000). Because it has contributed a lot to many disastrous fires (Rasbash 1991), numerous researches have been conducted to understand and predict this dangerous phenomenon, experimentally or numerically. Thermal instability is considered to be one of the mechanisms of flashover (Thomas et al. 1980). During the process of a compartment fire, heat radiation from hot smoke and heated surfaces intensifies the burning rate of the fuel causing more energy to be released. Consequently, the smoke layer temperature becomes higher and then energy feedback is also augmented. A positive feedback loop is formed. There may be a moment that a relatively small, localized fire suddenly jumps to a big ventilation controlled fire with all the exposed combustible surfaces involved in the fire. This jump is called flashover. Therefore, flashover is considered as a nonlinear dynamical process and nonlinear dynamical theory has been applied to study flashover (Beard et al. 1992). Different dynamical models have been suggested (Beard et al. 1992, 1994; Bishop et al. 1993; Graham et al. 1995; Liang et al., 2002, 2013; Novozhilov 2010; Liu and Chow 2014). These models are based on a zone model (one-zone or two-zone) with an energy balance equation set for the hot smoke layer. The number of system state variables ranges from one to three. Assumptions and simplification are made to obtain algebraic solutions. Critical conditions for flashover derived from most of the models are based on the analysis of heat gain rate and loss rate for the smoke layer. Ignition of virgin fuels is considered as alternative critical condition for flashover in a conjugate thermal model proposed which depends on the thermal and physical property of the fuel (Novozhilov 2010).

Compared with numerical or experimental study, nonlinear dynamical models can offer a better and simple way to understand flashover. In a compartment fire system, the onset of flashover is affected by various parameters. The effect of heat release rate has been described in detail previously (Liu and Chow 2014). The effect of dimensions of the apartment and radiation feedback on the critical condition of flashover is examined here.

THE ROOM FIRE MODEL

Flashover in an example apartment with an open kitchen was examined by nonlinear dynamics. The example apartment as shown in Figure 1 has a length of L, width of W and height of H. A single rectangular vent of width W_d and height H_d is located at the center of one wall. A fire source is centered at the floor level. The process of the apartment fire is considered as a dynamical system. The state of the system is controlled by a set of parameters. Based on a two-layer zone model, the evolution equation is developed for the upper hot smoke layer. Temperature is often used to describe the development process of a compartment fire and it is an important indicator of the advent of an untenable condition. Therefore, temperature of the smoke layer T is chosen as the single state variable. Parameters such as heat release rate, dimensions of the enclosure, geometry of the opening, and height of the smoke layer serve as control parameters. When change is made to one or more control parameters, the system state responds accordingly and normally a small perturbation only causes a relatively slight variation in the state of the system. Notably, the system can experience violent change with its structure becoming qualitatively different at critical parameter values. These qualitative changes in system state are called bifurcations (Thompson and Stewart 2002). A local bifurcation occurs when parameter changes cause an equilibrium point to lose its stability. The local stability of an equilibrium point can be determined by its eigenvalues of the constant Jacobian matrix. If all eigenvalues are negative, the equilibrium point is stable. Conversely, it is unstable. When the eigenvalue is equal to zero, bifurcation occurs. In this application, when bifurcation occurs, the system jumps from the current equilibrium state to a new remote one and flashover is deemed to happen. More information about nonlinear dynamical theory can be found in references, such as Thompson and Stewart (2002).

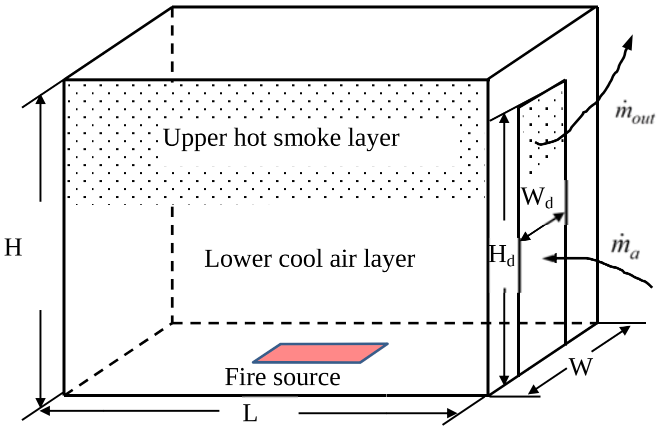


Figure 1. Schematic of the example apartment

Some assumptions are made in this nonlinear dynamical model as listed below:

- The density of the smoke layer is assumed to be constant, i.e. a value of ambient density ρ_0.
- The temperature of the lower air layer and its bounding surfaces are assumed to be kept at the initial temperature T_0.
- The fire source temperature is assumed to be the ambient value T_0 and its emissivity is taken to be 1.
- Before flashover, the fire is assumed to be quasi-steady and the height of the smoke layer interface is constant and kept at 0.5 H (Thomas et al. 1980).

- The height of the neutral plane coincides with the height of the smoke layer interface.
- In ventilation-controlled stage, the air entering into the apartment is assumed to be completely consumed.
- The surface of the wall is assumed to be black body and the emissivity of the smoke layer is assumed to be 1.

The evolution equation for this fire dynamical system is developed based on the energy conservation for the upper hot smoke layer. It takes a similar form as described in (Bishop et al. 1993; Graham et al. 1995; Liang et al., 2002, 2013; Novozhilov 2010; Liu and Chow 2014).

$$m \cdot c_p \cdot \frac{dT}{dt} = G_E - L_E \tag{1}$$

The left hand side of Equation (1) is the energy change rate of the smoke layer. m is the mass of the smoke layer; c_p is the specific heat capacity (at constant pressure); T is the average temperature of the hot smoke layer and t is time. On the right hand side, G_E and L_E are net heat gain rate and net loss rate of the hot smoke layer respectively. Both are functions of smoke layer temperature. Since time is not explicitly included in the right side of the equation, this fire compartment dynamical system is a continuous autonomous system.

$$G_E = (1 - \chi_R) \cdot \dot{Q} \tag{2}$$

The heat gain rate of the smoke layer G_E is determined by the fraction of the heat release rate of the fire $\dot{Q}$ that goes into the upper smoke layer. Part of the energy released by a fire is emitted by radiation and does not enter the smoke layer. In real fire plumes, for many common fuels, the radiant part χ_R typically accounts for 20 to 40% of the total energy released (Karlsson and Quintiere 2000).

The calculation of heat release rate is based on the availability of air supply. There are two cases: fuel-controlled fire and ventilation-controlled fire. For a fuel-controlled fire, there is enough air for combustion and the heat release rate depends on the mass of combustible gas released:

$$\dot{Q} = \dot{Q}_0 + \chi \cdot \dot{m}_f \cdot H_{com} \tag{3}$$

For a ventilation-controlled fire, excess of fuel is released and the heat release rate depends on the mass flow rate of air into the compartment:

$$\dot{Q} = \chi \cdot \frac{\dot{m}_a}{r} \cdot H_{com} \tag{4}$$

Where $\dot{Q}_0$ is the free burning heat release rate of the fire, without feedback from enclosure and smoke layer; χ is the efficiency of the combustion ; $\dot{m}_f$ is the additional rate of fuel burned due to thermal feedback from the enclosure and hot smoke; H_{com} is the heat of combustion of the fuel, $\dot{m}_a$ is the mass flow rate of ambient air into the compartment; r is the stoichiometric air to fuel mass ratio. $\dot{m}_f$ can be determined through the net incident radiant heat on the fuel surface $\dot{R}_{in}$ and the heat of evaporation or gasification of the fuel H_{vap}.

$$\dot{m}_f = \frac{\dot{R}_{in}}{H_{vap}} \tag{5}$$

In a compartment fire, the hot smoke layer and heated boundary surfaces radiate heat back to the fuel surfaces, which accelerate the gasification rate of the fuel. This radiant feedback has been recognized as playing an important role in the onset of flashover (Yuen and Chow 2004). It is affected by both the emissivity and temperature of the smoke layer and the wall surfaces, and their view factors to the fuel surface. In this model, calculation is based on a considerably simplified formulation.

$$\dot{R}_{in} = \mu \cdot \sigma \cdot (T^4 - T_0^4) L \cdot W \tag{6}$$

Where $L \cdot W$ is the area of the smoke interface; σ is the Stefan-Boltzmann constant; μ is the radiant feedback coefficient; and T_0 is the ambient temperature.

In a ventilation-controlled fire, the gas temperature is most often very high and the smoke gas is roughly mixed evenly. A simplified expression can be used to obtain the mass flow rate of air into the compartment through openings (Karlsson and Quintiere 2000):

$$\dot{m}_a = 0.5 \cdot W_d \cdot H_d^{1.5} \tag{7}$$

Where W_d and H_d are the width and height of the opening respectively. The product of W_d and $H_d^{1.5}$ is the well-known ventilation factor.

The total energy lost from the hot smoke layer L_E is caused by mass flow through the opening, conduction loss to the compartment boundary and radiation loss to the opening.

$$\begin{aligned} L_E &= \sigma(T^4 - T_0^4)[LW + W_d(H_d - Z)] \\ &+ \sigma(T^4 - T_w^4)[LW + (2L + 2W)(H - Z) - (H_d - Z)W_d] \\ &+ h_c(T - T_w)[LW + (2L + 2W)(H - Z) - (H_d - Z)W_d] \\ &+ \mathrm{c}_p \dot{m}_{out}(T - T_0) \end{aligned}$$

(8)

Here, T_w is the surface temperature of the upper parts of the walls bounding the hot smoke gas; Z is the height of the smoke layer interface from the floor level; and h_c is a convective heat transfer coefficient. In Equation (8), there are four items on the right hand side. The first item is the radiative heat loss from the smoke layer to the lower part of the compartment and vent; the second item and the third item are the radiative and convective heat loss to ceilings and the upper part of the walls, respectively; the forth item is the enthalpy flowing out through the vent.

For simplicity, the surface temperature of the heated walls T_w is approximated as a fraction of the smoke layer temperature (Bishop et al. 1993):

$$T_w = U_c(T - T_0) + T_0 \tag{9}$$

Where U_c is a wall temperature parameter ranging from 0 to 1, which depends on the thermal inertia properties of wall materials.

In compartment fires, the hot smoke flows out through the portion of openings above the neutral plane and fresh air enters the compartment from below. The outflow driven by buoyancy through the vent can be estimated (Rockett 1976):

$$\dot{m}_{out} = \frac{2}{3} C_d \cdot \rho_0 \cdot W_d \cdot H_d^{\frac{3}{2}} \sqrt{2 \cdot g (1 - \frac{Z_N}{H_d}) \frac{T_0}{T} (1 - \frac{T_0}{T})} (1 \text{-} \frac{Z_N}{H_d}) \tag{10}$$

C_d is the flow coefficient; Z_N denotes the height of neutral plane from floor; g is the acceleration due to gravity; Z is the height of smoke layer interface from floor. For simplicity, Z_N was assumed to be coincided with Z, then Equation (10) can be rewritten as

$$\dot{m}_{out} = \frac{2}{3} C_d \cdot \rho_0 \cdot W_d \cdot (H_d - Z)^{\frac{3}{2}} \sqrt{2 \cdot g \frac{T_0}{T} (1 - \frac{T_0}{T})} \tag{11}$$

According to the dynamical theory, the critical conditions for flashover are:

$$\frac{dT}{dt} = 0 \tag{12}$$

$$\lambda = \frac{\partial}{\partial T}\frac{dT}{dt}\bigg|_{T=T_{equ}} = 0 \qquad (13)$$

T_{equ} represents the equilibrium points of the system and λ denotes the eigenvalues.

Based on the model developed above, the effect of varying floor dimensions and different radiation feedback coefficient on the critical condition for flashover was examined.

The selected values of control parameters and constants used are listed below. Referring to DiNenno (2008), the combustion heat of food oils are about 40 MJ/kg, so a value of 42 MJ/kg is given to H_{com}, but the vaporization heat for miscellaneous materials is difficult to determine. Some of the values in Table 1 refer to (Quintiere et al. 1979).

Table 1. Selected values for parameters

Parameters	Values	Parameters	Values
σ	$5.67{\cdot}10^{-8}$ $Wm^{-2}K^{-4}$	r	30
c_p	1003.2 J/kg K	T_0	300K
C_d	0.7	U_c	0.7
g	9.81 m s^{-2}	W_d	1 m
h_c	7 W m^{-2} K^{-1}W/m^2K	Z	1.5 m
H	3 m	χ	1
H_{com}	$4.2{\cdot}10^7$ J /kg	χ_R	1/3
H_{vap}	$1.008{\cdot}10^6$J/kg	ρ_0	1.18 kg·m^{-3}

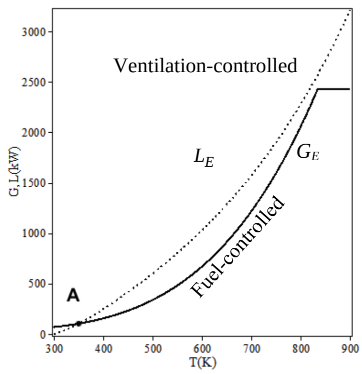
EFFECT OF THE APARTMENT GEOMETRY

Many of the small units with open kitchens are less than 30 m^2 in area in tall residential buildings in Southeast Asia including Hong Kong (DiNenno 2008). Units with floor dimensions of 6 m × 3.5 m, 7 m × 3 m, 5 m × 6 m, 5 m × 5 m, 7.5 m × 4 m are chosen to study the effect of floor dimensions on the critical condition for flashover. In these scenarios, the radiation feedback coefficient μ keeps a constant value of 0.15 and the other parameters are set as listed in Table 1.

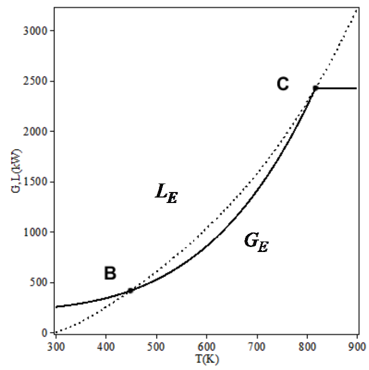
First, the critical condition for flashover in an apartment with a floor area of 6 m × 3.5 m was examined. The curves of energy gain rate G_E and energy loss rate L_E were plotted respectively as a function of temperature under different $\dot{Q}_0$ value to find their intersections (equilibrium points), as shown in Figure 2. The G_E curves consist of a fuel-controlled stage and a ventilation-controlled stage. The heat release rate in the latter stage is constant and thus corresponds to a horizontal line. Figure 2 shows there may be one, two or three possible intersections of the G_E and L_E curves. From a temperature perturbation analysis, it is easy to find that equilibrium points A, B and D are stable, which can be also seen from Figure 3. When a fire progresses to equilibrium points like A, B or D, the temperature of the smoke layer will stabilize at a relatively low temperature.

The equilibrium state at points C, E and G are unstable. At point C (ventilation-controlled equilibrium point), if there is a small decrease in temperature, the fire would drop sharply to point B and stabilize there. The more dangerous situation is point G which we have interest in. If there is a small increase in temperature at point G, the fire will jump rapidly from an equilibrium state to a new stable state.

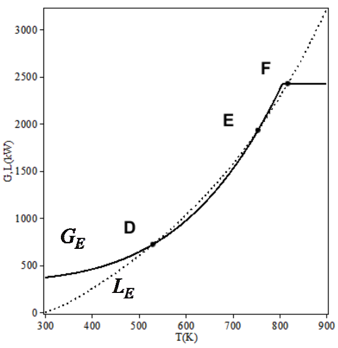
Figure 3 demonstrates how a bifurcation occurs in the fire system. From Figure 4, it can be observed that the corresponding eigenvalues of branch ABDG are negative, so they are stable. Branch GEC are unstable because their eigenvalues are positive. Point G is the critical point whose eigenvalue is zero.



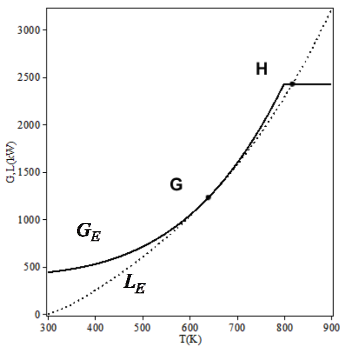
(a) $\dot{Q}_0$ = 100 kW



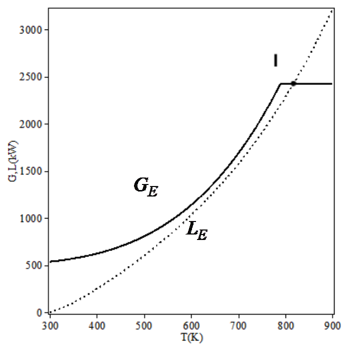
(b) $\dot{Q}_0$ = 374 kW



(c) $\dot{Q}_0$ = 550 kW



(d) $\dot{Q}_0$ = 656 kW



(e) $\dot{Q}_0$ = 800 kW

Figure 2. Curves of heat gain and loss rate for the smoke layer

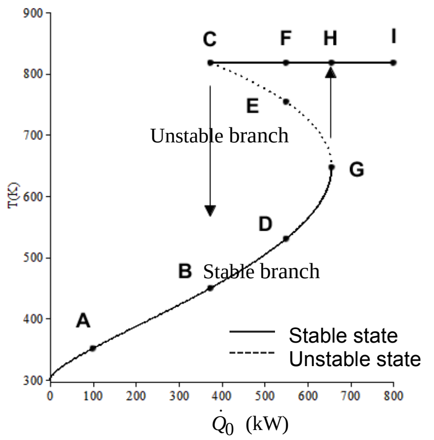


Figure 3. Schematic of bifurcation

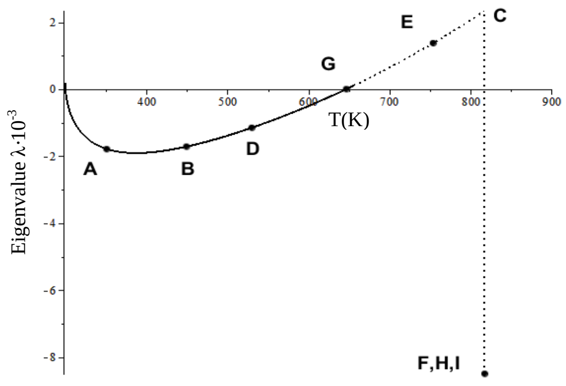


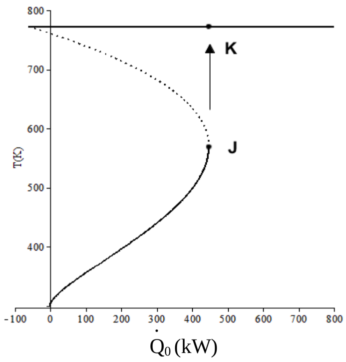
Figure 4. Eigenvalues for equilibria

When a small fire starts on branch ABDG, as the free burning heat release rate of the fire increases, the fire will eventually reach G, the intersection of stable branch with unstable branch, a fold catastrophe occurs. At point G, the system state rapidly jumps from a fuel-controlled equilibrium point to a new remote ventilation-controlled equilibrium state denoted by point H with a sharp increase in temperature. Flashover occurs at the bifurcation point. At point G, the heat release rate is about 1270 kW and the smoke layer temperature is 646 K. The new state H has a temperature of 818 K.

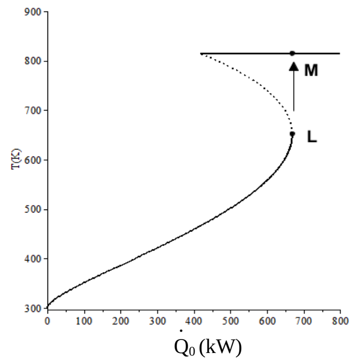
The critical flashover conditions for apartments with floor dimensions of 7.5 m × 4 m, 7 m × 3 m, 5 m × 5 m, 6 m × 5 m were examined similarly. Figures 5(a) to 5(d) show the bifurcation points and the new equilibrium states for each case. The values for critical temperature, critical heat release rate and equilibrium temperature after flashover are presented in Table 2.

Table 2. Summary

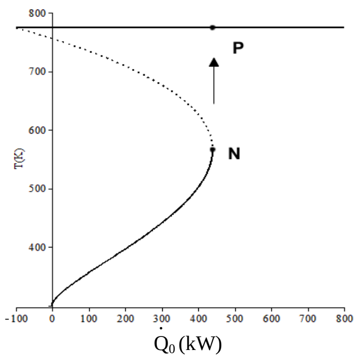
Scenario number	1	2	3	4	5
Floor dimensions (m.m)	6×3.5	7×3	5×5	6×5	7.5×4
Internal surface area (m^2)	57	60	60	66	69
Critical temperature (K)	647	652	604	566	569
Critical $\dot{Q}_0$ (kW)	656	669	542	439	447
Corresponding $\dot{Q}$ (kW)	1898	1953	1694	1444	1475
New stable Temperature (K)	818	814	772	774	772



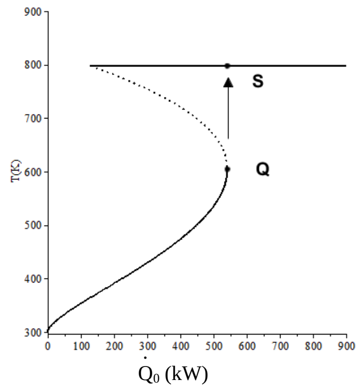
(a) Floor of 7.5 m × 4 m



(b) Floor of 7 m × 3 m



(c) Floor of 6 m × 5 m



(d) Floor of 5 m × 5 m

Figure 5. Critical conditions for flashover with different floor geometry

The flashover criteria (Karlsson and Quintiere 2000) include smoke layer temperature below the ceiling reaching 500 to 600°C, heat flux to the floor more than 20 kW/m^2 or flames coming out the openings. As shown in Table 2, the temperatures after bifurcation in Cases 1 to 5 coincide with the temperature criterion. In Case 1 and Case 2, the floor areas are equal but with different length to width ratio which give rise to difference in the internal surface area. Case 4 and Case 5 hold the same situation. For cases with the same floor area, the values of critical temperature and critical heat release rate for an apartment with a smaller internal surface area are lower when compared with the one with a bigger internal surface area. When the internal surface area of an apartment is small, less heat is conducted away from the enclosure boundary, allowing more energy to be stored in the apartment. Therefore, it requires a smaller heat release rate to initiate flashover and when flashover occurs, a higher compartment temperature appears. Three floor area values 21 m^2, 25 m^2 and 30 m^2 were investigated. It can be summarized that compartments with larger floor area needs a small critical heat release rate for flashover. In the fire dynamical model developed, the thermal radiation feedback is closely related with the smoke layer interface area, i.e. the floor area. If the other conditions are the same, as the floor area increases, the fire base receives more energy feedback from the upper part of the compartment. But for a large compartment, it may take a longer time to reach a higher temperature. When the effect of compartment geometry on flashover condition is examined, the radiation feedback coefficient is kept constant. Actually, it varies with the geometry of the compartment and it varies in the process of the fire even in the same compartment. However, it is difficult to tell how it changes quantitatively. Therefore its effect is specifically studied in the next section.

EFFECT OF RADIATION FEEDBACK

In compartment fires, heat released from the fire is the source term of the energy obtained by the smoke layer. In the thermal instability theory for flashover, the radiation feedback to the fire source is of great importance. The heat feedback process is very complicated with many factors involved. It relates with the geometry of the enclosure, temperature and emissivity of the wall surface, the concentration and distribution of the participating media such as carbon monoxide and soot, the thickness and temperature of the smoke layer, the size, temperature, emissivity of the fire source and its position in the compartment. In the model employed, the heat radiated to the fuel is significantly simplified. The parameter μ, radiation feedback coefficient, implicitly incorporates the effect from emissivity, view factor. And except radiation from smoke layer, there is radiation from the hot surfaces and ceilings which should not be ignored when they are at an elevated temperature. In fact, the parameter μ varies with the change in compartment geometry, smoke layer emissivity, fire area and so on. While, it is taken as a constant when the effect of other parameters is addressed which may result in errors.

The effect of radiation feedback coefficient μ on the onset of flashover was evaluated in an apartment with dimensions of 6 m in length, 3.5 m in width and 3 m in height. The other parameters are set as in Table 1. Figure 6 shows the critical heat release rate and critical temperature for flashover with a varying μ, respectively.

As demonstrated in Figure 6, when the value of μ is small, little thermal energy is radiated back to the fire source, so that flashover does not occur. When the radiation feedback coefficient μ increases gradually, the critical heat release rate drops sharply at first, then more gently. When μ is 0.1, the critical heat release rate and critical temperature are 14.88 MW and 1273 K respectively. By contrast, when μ is 0.25, the minimum energy required for flashover is about 0.8 MW and the corresponding critical temperature is 484 K. This is because due to a strong radiation feedback, the fire grows very quickly, flashover can take place earlier.

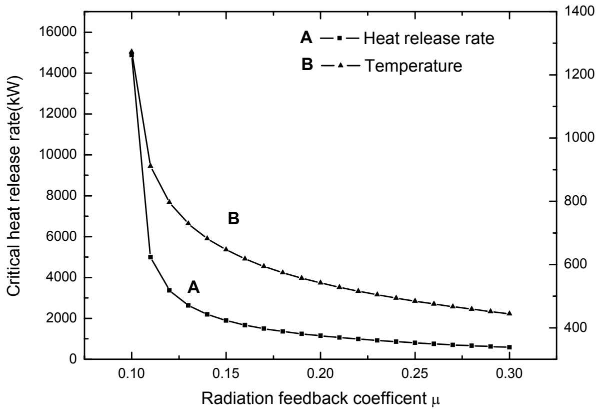


Figure 6. Critical heat release rate and critical temperature against varying radiation feedback coefficient for the case with a floor of 6 m × 3.5 m

CONCLUSIONS

The open kitchen design makes the fire risk increase in these high-rise residential buildings with a high fire load density. The ignition probability and the probability that the fire can spread out from the kitchen are necessary to assess the fire risk, however they are difficult to obtain. The critical flashover conditions were examined by a single variable nonlinear dynamical model. The smoke layer temperature was taken as the single state variable. The effects of apartment dimensions and radiation feedback on flashover conditions were examined with selective parameter values. The internal compartment surface or the floor aspect ratio may change with the variation of the unit floor area. Consequently, they will have effect on the heat transfer process and then affect the critical condition for flashover. The thermal radiation feedback coefficient is an important parameter which is changing in the fire process and it is difficult to determine the exact value for it. It was proved that flashover can be demonstrated by the model developed in terms of thermal instability. The complicated heat transfer process in fire scenario is represented by a simplified model which results in errors. A more accurate model addressing the heat radiation feedback to the fire source is needed to achieve more reasonable prediction.

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Changing paradigms of Affordable Housing in Independent India

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ABSTRACT

Housing policies in India evolved with country's transformation since Independence. These policies shaped the vision of quality living and devised tools to resolve the housing need. Recently launched housing policy Pradhan Mantri Awas Yojna (PMAY-2015) attempts to accommodate development dynamics and aspiration of the country at present. The article would outline following objectives:

a) Paradigm shifts in housing policies
b) Land and Finance mechanisms in Affordable Housing (AH)
c) Opportune moments to integrate sustainability: Sustainable Total Living Environment for Affordable Housing (S_{US}TLE-AH) model

Scope for discussion in the paper is evolution of housing and AH policy, the PMAY and the SUSTLE-AH model. Review of Indian housing policy brings out broad attitudinal changes in Government's role from direct provider with social welfare approach, to facilitator. Land and finance mechanisms, earlier failed to help lower income groups to access housing due to flawed policy and its implementation. The PMAY's target to provide housing for all in 500 class I cities by 2022, is a colossal task; this requires careful treading to ensure the mission enables millions of targeted beneficiaries to possess housing. Land and finance are two biggest constraints in AH. To acquire larger parcel of land, government has devised models like Joint venture (JV), Land reform, Indirect intervention. This paper explores emerging means to access housing finance for affordable housing through PMAY.

AH through PMAY presents an opportune moment for the country to provide quality living to large number of population. The SUSTLE-AH model experiments with such alternatives which duly recognize extreme variety in socio-cultural and climatic contexts in different parts of the country. The paper concludes with an overview on land, finance and sustainable concept integration in housing through PMAY.

INTRODUCTION

Housing is a basic social aspiration and indicator of living quality. Affordable Housing (AH) is socio-political agenda in any democratic country which ensures every family has a shelter to reckon with. India intensified its search for alternate options to AH as around 1.77 million people live without a roof over their heads (Jha, 2013) and around 10 million of the houses are dilapidated state while around 7 million are living unliveable conditions (MHA, 2011).

To overcome this giant gap, the Government of India (GoI) has come up with an ambitious plan of providing permanent shelter through the mission 'Pradhan Mantri Awas Yojana' (PMAY 2015)- Housing for All by 2022, with significant deviations from previous schemes. Policies are instrumental to realize socio-economic development goals set by any government which they propose in their election manifesto. Housing policy includes agenda-setting and creating procedural tools for policy application and appraisal. Implementation tools are fundamental to policy design and they device modification in the way services are provided to public or the approach of implementation of processes. Land and Finance mechanisms have evolved further in PMAY in comparison to other previous programs launched after independence of the country in 1947.

Review on policy changes and its impact on house ownership by economically weaker section (EWS) and low income group (LIG) people will be first deliverable of the article. Deliberations on strength and opportunity created by the PMAY will follow next. Lastly, the Sustainable Total Living Environment for Affordable Housing (SUSTLE-AH) model, a policy implementation tool, will be discussed. The SUSTLE-AH accommodates the concept of sustainable integration of design and planning of housing with appropriate technologies and materials, Eco-services' system network and disaster risk reduction. The model is developed as a road map to sustainable alternative for AH.

TEMPORAL SHIFT IN HOUSING POLICIES IN INDIA

After six decades of housing policy design and implementation for EWS and LIG housing in India, significance and limitation of these policies are being critically reviewed (Hingorani, 2011). After Independence, the young nation was reeling with burden of migrated people. Policies evolved with time to address changing socio-economic context. Initially, housing policies considered house to be a provision to be made available by the government, and no participation was expected from the target beneficiaries. A comprehensive list of policy initiatives are presented in Table 1. The quality of the housing provided was not good. Readily available housing could not evoke any sentimental attachments. People from lower income group could not retained ownership of the same for long. Market economy played role in change of ownership from the beneficiaries to higher income group which was in contrary to original intention. Rent control act led poor maintenance of rental housing stock leading to worse living conditions for tenants and loss of capital and income for landlords.

TABLE 1: List of Housing Policy Initiatives in India since Independence

Period	Settings	Initiatives	Outcome
1950s and 1960s	During this period government was the Primary policy driver. Housing was considered more a welfare job than economic growth contributor. Private sector intervention was limited to HIG housing section. There was lack of coordination among different programs due to absence of strong housing policy. Development funds were majorly coming from central government subsidies. In the latter part state governments shared responsibilities other than funding. Construction of institutional buildings and affordable housing for poor were considered as government's responsibility. Major emphasis was on cost reduction, whereas there were shortcoming in master planning and land assembly for the poor	1952: Subsidised Housing Scheme for Industrial Workers and Economically Weaker Sections 1954: Low Income Housing Scheme 1956: Subsidised Housing Scheme for Plantation Workers 1956: Slum Clearance and Improvement Scheme 1959: Middle Income Group (MIG) Housing Scheme 1959: Rental Housing for State Government Employees 1959: Village Housing Projects Scheme 1959: Land Acquisition and development by State government 1961: Rent control Act	Due to lack of funds, targets were not achieved, on the contrary existing housing stock was reduced in the process of dismantling of depleted units, meant to reconstruct/ relocate. Public housing was out of reach both in terms of economic affordability and physical location from workplace. This resulted in the growth of informal illegal private housing, which was affordable and well- connected, but of low quality built environment. State governments were failed to assemble land for housing for urban poor. Growth in HIG/MIG housing stock was appreciable in proportion to demand.
1970s and 1980s	Housing in this period was considered more than just a shelter. High subsidies were replaced by cross-subsidization and cost recovery. In-situ slum upgrading and site and services programs were introduced instead of shifting of slum- dwellers. Formal housing finance organizations like HUDCO, HDFC, NHB were formed. State governments started sharing more finical responsibility. Central Government's role was changed to facilitator to state government and private sector instead of direct actor. Importance of community participation was	1970: Housing and Urban Development Corporation (HUDCO) established 1971: Provision of House Sites of Houseless Workers in Rural Areas 1972: Environmental Improvement of Urban Slums 1977: Housing Development Finance Corporation (HDFC) established 1980: Sites and Services Scheme 1981: Scheme of Urban Low-Cost Sanitation for Liberation of Scavengers 1980: Sites and Services Scheme 1981 & 89: Scheme of Urban Low-Cost Sanitation for Liberation of Scavengers	HIG/ MIG benefited most from housing finance organizations. Government employees were the main beneficiaries of public housing schemes. Despite efforts, there were slag in community participation and growth was slow in weaker sections' housing. Rapid changes to institutional frameworks of programs and their structure slowed the process further.

	encouraged. Housing stock in urban sector had better growth in-comparison to rural section	1985: Indira Awas Yojana 1986: Urban Basic Services Scheme (UBS) 1987: National Housing Bank (NHB) established 1988: National Housing Policy (NHP)	
1990s and 2000s	Urban Local Bodies came to the driving seat with more powers and responsibilities with 74th Constitutional Amendment Act. Central government's role was that of an enabler and participation from private sector was encouraged. Still it was the MIG and HIG group who took maximum advantage of housing finance institutes. Focus was given on research of building material and affordable construction technology. Housing was integrated with urban services and public transportation under JnNURM.	1990: Building Materials and Technology Promotion Council (BMTPC) replaces NBO 1990: Night Shelter Scheme for Pavement Dwellers 1990: Nehru Rozgar Yojana's Scheme of Housing and Shelter Upgradation (SHASHU) 1990-01: Urban Basic Services for the Poor (UBSP) 1996: National Slum Development Program (NSDP) 1998: 2 Million Housing Program 2001: Valmiki Ambedkar Aawas Yojana 2005: Jawaharlal Nehru National Urban Renewal Mission, JnNURM 2007: National Urban Housing and Habitat Policy (NUHHP)	Shortage of housing continued in LIG/ EWS sectors. Land assembling was still an issue. UBLs were seem to lack in capacity to cope up with the targets. Community participation and Policy approach under JNNURM had limitations and thus resulted in inappropriate usages of funds.
2010 onwards	The shortage of housing units meant for LIG/ EWS is the target to reduce; contribution from government, private sector and beneficiaries are identified.	2013: Rajiv Awas Yojana 2015:PMAY- Housing for all	Private participation in affordable housing was encouraged under RAY Private sector Investment increased in AH, as is considered as Infrastructure projects.

Based on Hingorani, 2011

In 1970s and 80s, systematic effort to integrate poverty alleviation agenda to housing was initiated. Attention shifted to public-private partnership. Government's role was shifting as enabler than provider of housing; emphasis on efficient land and finance mechanisms, building materials and appropriate technology was laid. Through schemes like 'sites and services' or 'slum upgradation', clear shift towards participatory development was visible; beneficiaries were expected to contribute partly. Despite significant shift in paradigm, it failed to address the housing need of weaker sections and well-off section of the society continued to consolidate housing as asset.

In 1990s, after 73rd and 74th amendment of the Indian Constitution, Local Bodies (LBs) were entrusted with resource management. Implementation relied profoundly on capability of individual LB; planning and implementation capacity building become a major challenge for success. Incentives for private real estate sector and loan availability from housing finance industry brought positive change to MIG and HIG housing significantly. Later on, it eventually led to speculative housing stocks lying vacant. In the year of 2005, the Jawaharlal Nehru National Urban Renewal Mission (JnNURM) (MoUD, 2005) was instituted. This was meant for 64 cities at initial stage and is one of the largest investment allocated by any government globally. This has a component of Basic Services for Urban Poor (BSUP) to improve quality of built environment and services for weaker sections. The Mission offered options of in-situ renewal, redevelopment or new housing in different location. Efficient LBs could take advantage. This entire mission could bring a new perspective into capacity building of LBs. But success was limited to only those LBs who are equipped with professional project management. The Sardar Patel Urban housing Mission was discussed widely in the year of 2014 which was laden with new ideas like Foreign Direct Investment, Infrastructure project, high rise dense neighborhood etc. The GoI introduced the PMAY-2015 which is being analyzed in following sections.

PMAY-2015

In the year of 2014, the GoI planned to provide roof to every urban homeless family with a dwelling unit under Sardar Patel Urban housing Mission. Later the mission was discussed further and the ''Pradhan Mantri Awas Yojana – 2015: Housing for all" is launched. The Mission identified scope to address the housing requirements of the Urban Poor (including slums) in four verticals (MoHUPA, 2015):

- Slum rehabilitation of Slum Dwellers with participation of private developers using land as a resource
- Promotion of Affordable Housing for weaker section through credit linked subsidy
- Affordable Housing in Partnership with Public and Private sectors
- Subsidy for beneficiary-led individual house construction

This is meant to cover all statutory towns as per Census 2011 and priority will be 500 Class I cities. These 500 Class I cities will be covered in three phases: Initial phase will end by 2017 with focus on 100 cities and then 200 each for 2nd and 3rd phase planned to finish by 2019 and 2022 respectively.

Slum Dwellers, Urban poor living in non-slum area, Prospective Migrants and Homeless and Destitute are in focus of the Mission. The recognized policies are: In-situ development/ upgrading for slum dwellers; affordable housing in partnership for urban poor; Temporary rental housing/ affordable house with interest subvention for migrants and government sponsored rental housing/ night shelter for homeless.

The Mission is expected to support construction of houses upto 30 m^2 carpet area with basic civic infrastructure. The States/UTs have the flexibility to determine the size of the house and other facilities at state level with consultation with the GoI but the central financial assistance not to be enhanced. Target of developing ten million dwelling units has been set under this scheme. It is the state government who will select the cities, deal with private investors, and decide upon building norms / guidelines like allowable built area, density etc. as per regional requirements, framed in consultation with experts from regional technical institutes.

"In-situ" Slum Redevelopment using land as Resource. This is an important tool for providing houses to eligible slum dwellers. This approach aims to leverage the locked potential of land under slums to provide houses to the eligible slum dwellers bringing them into the formal urban settlement (MoHUPA, 2015). Private Partner would be selected through Open Bidding System.

The government has a provision of doing the resettlement by self or by the help of private partners. The land of the slum would be under Central Government. Table 2 tabulates the process flow and role of stakeholders involved under this vertical. The larger portion of the land will be used for redevelopment of slum. But a small proportion of the land can be used for generating revenue by cross–subsidization and other tools.

Credit Linked Subsidy Scheme. (MoHUPA, 2015) This scheme is meant for the beneficiaries of EWS and LIG sector, seeking loans from Financial Institutions. The eligible beneficiaries will get the loans for an interest subsidy at the rate of 6.5 % for a tenure of 15 years or during tenure of loan whichever is lower. The subsidized rate would be applicable for loan amount of Rs. 6 lakhs only, for the Dwelling Unit with Carpet Area 30 m^2 and 60 m^2 for EWS and LIG sections respectively.

Affordable Housing in Partnership (AHP). AHP is the only scheme in the policy with a supply side intervention. For any AH project (as defined by PMAY), the Central Government will provide an assistance of Rs. 1.5 Lakhs per EWS dwelling unit to the developer. Benefits and credentials, definition of EWS etc. can be changed by State Governments with consultation of Ministry of GoI.

Beneficiary led individual house construction or enhancement. The beneficiary, living in or outside the slum, will get central assistance of Rs. 1.5 lakh for construction of new houses under the mission. The 4^{th} vertical recommends that the beneficiary of this scheme should not be taking advantage over any other schemes of the policy (MoHUPA, 2015).

TABLE 2: Process Flow, Role and Responsibility of stakeholders under "In-situ" Slum Redevelopment

Serial no	Strategy	Responsible Authority
1.	Beneficiary de-notification	Central government
2.	Additional FAR/FSI	State government
3.	Grant (Rs. 1Lakh/house)	Central government
4.	Upper Ceiling Cost	MoHUPA
5.	Privately owned land	Incentivised by state government
6.	Eligibility of slum dweller	State Government
7.	Beneficiary contribution	State Government
8.	Ownership rights or renewable /mortgage & inheritable leasehold rights	State Government
9.	2 components: - "slum rehabilitation component" - "free sale component"	
10.	Area of slum under private developers	Implementing authorities
11.	Slum dwellers can participate by association or other suitable means	
12.	Developers - open transparent bidding Eligibility under State Government	

Based on MoHUPA, 2015

CHANGING DIMENSIONS OF LAND MARKETS FOR MASS HOUSING

In India, land use has been identified as a state (provincial) subject matter. Whereas any public authority can acquire land for 'public purpose' as defined in Land Acquisition Act, 1894. Traditionally compulsory acquisition of land has been a major source of land assembly by the public agency for all categories of housing and infrastructure development. In 70's, almost all the state governments came up with Town and Country Planning Acts in order to control over use of land for a sustainable development and significant numbers of such planning authorities were framed accordingly. However in 90s, control over use of urban land was further percolated to the urban local bodies (ULBs or municipalities). On the other hand, in order to maintain an equitable distribution, the land ownership under any individual has been restricted for decades. As a result until 2000, bigger land parcels were scarce, especially in urban areas for large housing and other projects. Realizing these, governments started exploring various models (see Table 3 below) for mobilizing large land for mass housing.

Therefore the land management in India has been flown into two directions. Firstly the control over use of land has been decentralized up to the ULB level and secondly the extent of ownership of land has faced multiple restrictions with single ownership, causing scarcity of large land parcels in urban areas. Through various reforms and interventions as discussed above which government attempted to deregulate the land and to make it more market friendly to enable developers to develop large housing projects. In the recently launched PMAY, government is encouraging similar approach in JV models through the sub-scheme called Affordable Housing in Partnership (AHP). However through the state level housing policies, other approaches like reforms and indirect interventions are applicable for housing.

TABLE 3: Land assembly models related to housing in India (after 2000)

Sl no.	***Model***	***Description of Model***	***Result***
1	Joint Venture (JV) Model	Cross subsidy based approach started in the state of West Bengal in the year 2000 and later adopted in the scheme named Affordable Housing in Partnership under JNNURM and PMAY. This model encourages private companies to form JV with public agencies like municipal authorities, housing boards and development authorities. Land is acquired by government partner and development right is given to private partner for developing housing with 50:50 sharing of profit.	Many housing projects came up through these model in spite of limitation of land laws.
2	Land Reform Model	Various legal and policy initiatives taken by government of India towards making land available from the market avoiding any legal and institutional barriers by doing • Repeal of Urban Land Ceiling and Regulation Act (making large land parcels available) • Amendment of Land Acquisition Act (making the process simple, shorter, inclusive and effective)	Following these there are many housing projects coming up in the country which are market based and servicing the affordable groups
3	Indirect intervention Model	Various tools like Transferable of Development Right (TDR), Variable Floor Area Ratio, and Reservation for affordable housing and rental housing has been attempted to increase the total supply of homes in piece of land. Rental housing has been indentified in PMAY as a preventive mechanism for the slum formation.	Due to these indirect influences of land market, the proportional share of affordable housing in mainstream housing market has increased manifold.

Apart from the above model based on partnership, the PMAY mentioned in-situ development of slum in central government land, by using it as a resource for providing houses to slum dwellers. In case of relocation, a land should either be provided by the agency or the agency may collaborate with the States/UTs for obtaining land from

State/UT/City. Central Government agencies should not charge land costs for the land used for the purpose of housing the eligible slum dwellers. Central govt. agencies undertaking slum development in partnership with private developers would be eligible for slum rehabilitation grant of Rs. 100,000/- per house on an average for all slums on their land being taken up for redevelopment with private partners.

Mandatory Conditions for State/UTs were given under PMAY like

- Make suitable changes in the procedure and rules for obviating the need for separate Non Agricultural (NA) Permission if land already falls in the residential zone earmarked in Master Plan of city or area.
- Prepare/amend their Master Plans earmarking land for Affordable Housing.
- A System should be put in place to ensure single-window, time bound clearance for layout approval and building permissions at ULB level.
- Adopt the approach of deemed building permission and layout approval on the basis of pre-approved lay outs and building plans for EWS/LIG housing or exempt approval for houses below certain built up area or plot area.
- Legislate or amend existing rental laws on the lines of model Tenancy Act being prepared by Ministry.
- Provide additional FAR/FSI/TDR and relaxed density norms.

FINANCE MECHANISM FOR AH

Housing finance is relatively recent phenomenon. It became more popular in developed economies after 1993. Recently developing economies are also experiencing growth of different magnitude in housing finance. Traditional two major financial mechanisms for housing are, debt and residential mortgage[1]. In developed economies housing loan is very significant, whereas developing economies like India, housing loan constituents for 5% of GDP. Financial liberalization after 1991 and access to capital market have significantly changed housing and real estate scenario in India. Control of state run housing finance institution shrank significantly, at least in open market. But housing for economically weaker section still remains a challenge in housing finance. Even for open market housing finance has become critical after global financial meltdown and Eurozone crisis. Now states are cautious to reduce risk of its banks and limiting bad loans. Following the financial crisis bad loans and non-performing assets (NPAs) in Indian banks stood very high. NPA for Indian banks varies from 3% to 4.25%, with state run banks perform poorer than private banks. Private Banks focus more on retail lending, unlike state run banks which have more exposure in housing and infrastructure. Even for state controlled banks, it is difficult to lend for mass housing or housing for economically weaker section, fearing loan recovery woes. In this increasingly complicated financial environment state run banks also need to compete with privately

[1] There is recognition of other relevant forms of housing finance, such as developer finance, rental finance, or microfinance applied to housing. Developer finance is often in the form of unregulated advance payments by buyers, and developers sometimes provide long-term finance to buyers through installment sales when mortgage markets are not accessible. Microfinance for housing is typically used for home improvement or progressive housing purposes. Loans are typically granted without pledging properties. Although the overall impact of microfinance in housing remains limited, this activity can represent an important source of funding for those in the informal sector (Chiquier, et al., 2009).

operated bank for profit and efficient services. Otherwise capital market with some control of the state might collapse. Sustainable housing finance system is built over a certain period with effective regulations and innovative financial policy. But financing affordable housing needs a different financial strategy than in free market. This paper will explore some emerging means to facilitate access to housing finance for affordable housing and its relevance in PMAY-2015.

Mortgage has been very common tool utilize in housing finance but is less explored in affordable housing. EWS and LIG households are unable to access mortgage loan due to their below par credit worthiness. They do not have any asset or ability to contribute for initial down payment or repayment in installments. States are constrained in extending credit due to the fear of market collapse. And lenders are not very keen for financing due to credit credibility of borrowers, liquidity and high interest rates. In this context, government security can be beneficial for lenders to gain confidence in aggressive promoting of housing finance. Mortgage bonds were first introduced in Europe in the late 18th century and are a major component of housing finance today (EMF, 2001). Mortgage Pass-Through securities were introduced in the United States in the early 1970s and along with more complex structured finance instruments now fund more than 50 percent of outstanding debt in that country. Today, mortgage-related securities have been issued in almost all European and many Asian and Latin American countries (Chiquier, et al., 2009). Once security is confirmed, many lenders feel confident in financing through mortgage. It attracts investment within the country or from foreign investors, increase competition among lenders, increase efficiency in fund flow in housing market. Institutional investors like pension and insurance authorities are effective buyers of mortgage securities. These institutions have enough liquidity and long term liability which is advantageous than short term lenders. Mortgage insurance is another instrument which protects investors and buyers from default in repayment by the borrower. Borrower's credibility and asset are calculated through loan to value (LTV) ratio, which divulges information like loan default probability. But it depends on individual state and its risk-taking ability to support with insurance.

Microfinance is also getting popularity to fund small housing and housing repair. Microfinance can be useful for low income household which often finds it hard to approach capital market due to collateral shortages. Often government policies in developing country revolve around direct subsidization or cross subsidization. But cross subsidization has other social equity issues which hinders its novelty as a financial mechanism.

Developing economies have basic structural problem. It has unusual high percentage of informal economy, maximum cash transaction and high levels of inflation. Combination of all three implies underpayment and decrease in their savings. A large percentage of population is outside the purview of government benefits like provident fund, medical insurance and pension schemes. But countries with more structured economies adopt housing provident funds (HPFs) as a measure to tackle housing finance. HPFs function as long term saving schemes that operate through mandatory equal contributions from the government and the employee. Beneficiary can withdraw funds from their accrued savings or take long term loan only for housing. HPFs have been created in many emerging economies, including Mexico, Nigeria, Brazil, Jamaica, Philippines, and China (Chiquier, et al., 2009).

INSTITUTIONAL FRAMEWORK FOR HOUSING FINANCE FOR AH

Housing finance is coordinated by the central bank or a bank under direct supervision of the country's central bank. State run housing banks are very common in developing countries to finance mass housing projects. But these banks have limitations in inhibiting deep impact in housing. India has set up National Housing Bank (NHB) in 1987. This is wholly owned by Reserve Bank of India, which contributes the entire paid-up capital for its functioning. Thus nature of functioning of the NHB is different from direct banking.

TABLE 4: NHBs policy activities from 2000-01

2000-01	First Residential Mortgaged Backed Securitization (RMBS) issue in the country; Refinance scheme for reconstruction of dwelling units in Gujarat earthquake affected areas
2001-02	Credit enhancement of bonds floated by HFCs
2002-03	Liberalized refinance scheme for housing loans
2004-05	Corporate Guarantee for RMBS is provided New window of lending to Micro Finance Institutions
2005-06	Fraud management cell set up to disseminate information on frauds on housing loans
2006-07	NHB RESIDEX was launched (first official residential housing price index) Reverse mortgage loan for Senior Citizens Productive Housing in Rural Areas (PHIRA) Refinance for top-up loan for Indira Awas Yojana beneficiaries Equity participation in New Rural Housing Finance Companies
2007-08	Rural housing fund was created with INR 10 Billion (USD 155 million) allocation Rural housing microfinance was launched Home loan counselling: Diploma programme put in place (IIBF)

The NHB regulates the activities of housing finance companies based on regulatory and supervisory authority derived under the National Housing Bank Act, 1987. It also create corpus fund facilitating liquidity in financial market for housing finance companies (HFCs) or micro finance companies to borrow capital and disburse retail loan to the customers. In the past decade and half NHB has introduced many policies and ideas to make housing finance more affordable (Table 4).

The NHB has taken three pronged initiatives: firstly, to oversee capital infusion in housing finance through HFCs; secondly, to enable retail borrower regulative back up to enhance their borrowing capacity; and thirdly, to safeguard borrower from fraudulent risks. The NHB is particularly focused on financing rural housing and housing for low and moderate income households through various schemes. Acceleration of funding in rural housing is supported through policies like USD 155 million pool fund, equity participation, and top up loan for Indira Awas Yojana (IAY) and micro financing. Enabling borrower with borrowing capacity is envisaged through residential mortgage, reverse mortgage, reverse mortgage of senior citizens, and corporate guarantee for reverse mortgage. The NHB is also focusing in popularizing home loan schemes with human resource development program and safeguard borrower from risks by setting up official residential housing price index to validate real house price and avoid fraud transaction by setting up fraud management cells.

RECENT POLICY TRENDS IN HOUSING FINANCE FOR AH

After identifying the emerging financial mechanism to fund affordable housing, the following sections will analyze PMAY 2015 to comprehend the scope and opportunity of financing affordable housing in India. The policy underlined four financial strategies to implement affordable housing. These are;

i. In situ slum redevelopment through private participation. In exchange incentive for private participation would be TDR and extra FSI/FAR.
ii. Affordable housing through credit linked subsidy, by interest subvention subsidy for EWS and LIG for new housing or to build incremental housing.
iii. Affordable housing in partnership with private sector or public sector including parastatal agencies.
iv. Subsidy for beneficiary led individual house construction.

Housing finance and alternative strategies that facilitates deprived people to acquire shelter has almost remained the same in India over the past many decades. The policy rightfully seeks private participation to solve an estimated 18.78 million housing shortages in India. But TDR and FSI/FAR is yet to prove very strong intensive for private participation in venturing into affordable housing. Financing slum redevelopment is a major challenge than to provide affordable housing to EWS or LIG. There needs to be a comprehensive financial strategy to enhance capability of slum dwellers to access housing finance. It may be a strategy implementation proven elsewhere in the globe or a completely new strategy. It’s not only an economic but social issue. Economic participation from slum dwellers enables belongingness to their shelter and more attention to transform it into habitat from housing only.

Second strategy targeted towards EWS and LIG is to only subsidize the interest payable by the borrower. The strategy is very effective for the borrower as they have to pay less for their loan. But with limited government resource the number of beneficiary is restricted every year. With an estimated housing shortage of 18.78 million, this strategy will not affect significantly in reducing the number rapidly. The major concern is that subsidy in interest will reduce profit of state run financial institutions and its ability to fund any such project independently in future.

Affordable housing in partnership seeks partnership with public and private enterprises. In case of 35% of total constructed houses are of EWS category, the GoI would finance part of the project. The ratio of finance is not mentioned and hence might be decided on case basis. Here the strategy depends on direct financial assistance and cross subsidy from the project sell. This strategy is limited to government's fiscal capacity and the non-subsidized housing market. The final strategy is to extend subsidy to individual house owner in building her/his own house. The government appointed to nodal agencies to disburse fund through state to individual beneficiary.

SUSTAINABLE INTERVENTION

Affordable Housing under PMAY has the opportune moment to go beyond regular concept of low-cost housing. Central theme shall evolve around sustainability concept of quality living through socially responsive community interaction, livelihood options and optimum resource utilization. Elderly and children friendly, hazard resistant, comfortable and functional built and open spaces can be designed and planned in such a way so that beneficiaries can associate themselves with their shelter from conceptual stages. It shall meet their future aspirations and don't feel to sell their property. The Sustainable Total Living Environment for Affordable Housing (SUSTLE-AH) model is proposed as a viable intervention for this.

SUSTLE-AH MODEL

The SUSTLE-AH model (Mukherjee, 2015) recognizes 4 stages of a built-environment's lifecycle: pre-design, design, construction and post-construction; and the Design stage builds its premise for discussion in this article. Implementability review i.e. the Pre-design exercise which takes care of land and finance considerations, Construction and Post-construction operation and maintenance (O&M) are outside the scope for discussion at present. Design stage allows innovative exploration of sustainable options in the SUSTLE-AH model and includes principles of Design and Planning, Technology and Materials, Eco-services' System Network and Risk Reduction.

DESIGN AND PLANNING

Climate and local context play vital role in any housing design. These prime motives often wither away in the process of delving balance between maximum constructed floor space and profit. Social sustainability through designed built- and open spaces, natural light and air for comfort, introduction of green infrastructure as resource conservation measures, and provision of livelihood opportunities are contextual challenges for building design and site planning. Good connectivity to public transportation and selection of brown site over green site are appreciable generator of the SUSTLE-AH.

Space Design Layout at Site and Block Level. Underlying sustainable strategy for site planning is minimum intervention in the natural setup. Housing in warm-humid climate may have well-spaced staggered arrangement so as prevailing air may pass through and provide thermal comfort. Cold and hot-dry zones should have compact planning so they may provide mutual shading and protection from freezing/ hot winds. In Composite climate, blocks may be placed near to each other for mutual shading and reducing solar gains but should also be well ventilated. Preferably the longer axis of a block in such climatic zone should be along east- west axis. A tilt upto 15^{o} towards south will allow south-east rising sun inside but will obstruct south- west harsh sun. Retention of site feature like water bodies can be used as green infrastructure, as natural reservoir for rainwater and be a source of water in case of fire breakout. It can act as part of waste water treatment and for pisciculture.

Box I. Belapur Housing case study

Belapur housing is one of the early planned settlement in Navi Mumbai by Charles Correa and his team to ease pressure on Mumbai. The project was commissioned by CIDCO in 1983, and it took three years to get ready. Its prime aim was to achieve high density with low rise housing. Each dwelling unit was planned on its own plot with an idea of incremental growth. To maintain social-economic integration, different plot sizes (with 5 types range from 45m to 75m) were worked out to facilitate different economic sections of society. Incremental construction accommodated the growing aspect of family size and economic potential.

Hierarchy of open, semi-open and covered spaces was maintained from whole to part i.e. from site to an individual house. Housing cluster were grouped around an court of size varying from 8X8m to 12X12m, which further are accommodated around a community space of 20X20m. Construction material and techniques were both local, which has resulted in self-help during construction, alteration and maintenance. Facilities like toilets are provided adjacent to each other for saving on plumbing, and sanitation. So the project not only focused for providing high-density low rise housing but also considered on other key factors like economic status, social interaction, neighbourhood watch, self-help, cost cutting and future incremental option determined as per once growing capacity and need. Project-learning is relevant till date.

Source: The Architectural Review, 2015.

Clustering of the low rise buildings is a proven efficient way of facilitating affordable LIG and EWS housing sustainability. As the urban land is very scarce resource, medium to high rise building blocks become natural option in Metro and tier I to III cities to take care of higher density requirements. Hierarchy of open spaces play a significant role in public interaction and need attention while designing high-rise housing. Mix of income groups can be facilitated in different stages of design to do away with social segregation. Possibility of being seen by the neighbors while entering into any flat increases safety of vulnerable residents. Creation of the experience of a miniature street in various levels of high rise buildings can enhance ‘Knowing Your Neighbor’ thus improving safety and security of residents.

In a densely packed city, there is very less open space for social interaction, playing and other community activities. Instead of providing water-intensive sprawling lawns, community orchards and kitchen gardens will be preferred alternatives for residents, as growing their own vegetables can fetch them some economic comfort. Playgrounds will facilitate physical activity among the youngsters and will help to keep modern-day lifestyle diseases away. The design shall advocate for healthy resident population by facilitating walking, jogging, sports etc. A runners' track around the field will help all residents. Strategic placement of children's play lot alongside with Elderly Park can maintain visual control on both. Basic safety and security and utmost care for vulnerable groups like kids and elderly are key ingredients of this design proposal.

Common spaces and services. Shared spaces and services directly impact on cost saving, shared O&M expenditure and social bonding. It can be a playground or a lobby or drainage system. During design process, wet areas like toilets and kitchen may be planned adjutant to each other for sharing service pipes. Common wall not only contribute in reducing material consumption but also protect from harsher weather. Elevators for this economic group will require some unique strategy like stop on alternate floors to reduce energy consumption and maintenance cost.

Educational space for kindergarten, crèche, vocational and continuing education center, digital literacy, must be given utmost importance. Hierarchy of vertical open spaces can augment interaction among the neighboring families sharing the same lobby. The common space helps the dwellers to know their neighbors better and the same space can be used as a small court for various purposes like toddlers play area, afternoon "Adda" space for the adults and the elderly.

Provision of urban farming induces the residents into physical activities with healthy produce. Scope of income generation from rentable commercial spaces, urban agriculture and produce selling etc. shall be integrated from the very inception stage of design. Access to formal loan can help to grow these initiatives.

TECHNOLOGY AND MATERIALS

Building envelope shall response to local climate optimally. Where thermal mass is preferred in cold areas to transfer daytime-absorbed solar heat inside, surface shading is required in hot-dry zone. Brick or stone lattice may provide visual and thermal comfort in composite, hot-dry and even warm-humid zone.

Prefabrication and industrial construction is the only logical means to solve the huge task within targeted time. Modular coordination, compatibility between elements and systems are the only choice left and more intense attention shall be placed in this sector. Locally available material be preferred except for special requirements. Such materials are generally responsive to local climate and consume less embodied energy. Selection of material shall be based on its properties like conductance, colour, texture, mass, modularity, acceptability etc. Material either with good insulation properties or construction technique like cavity wall/ rat-trap bond may be preferred where there is recognizable difference between inside and outside temperature. Sometimes affordability is misunderstood as low cost construction and materials which are cheap but not long lasting. This should be avoided at any cost; the material and construction shall require minimum maintenance to keep the monthly maintenance expenditure low.

Daylight harvesting is another integral strategy of the SUSTLE-AH as it provides visual comfort and reduces energy consumption for most of the seasons. Window to wall ratio shall be provided in accordance to available daylight, surrounding built mass and illumination level required in different parts of building interiors. Otherwise, habitable spaces may lack in desired illumination quality or will have excess of thermal gain.

Energy consumption and utilization. One of the major aspect of affordability is the reduction in energy bill amount and utilization of renewable energy resources. The above mentioned strategies contribute in energy saving largely. On an average energy consumption load for EWS and LIG households are expected to be 1.5 kW and 3 kW. Energy for public facilities like street lighting, should preferably come from renewable energy source like solar photovoltaic cell. Hot water supply for laundry, kitchen, bathing etc. may come from solar water heater. India being rich in solar radiation resource, it shall be utilized to their best.

ECO-SERVICES' SYSTEM NETWORK

Systems and services play a vital role in community's life to flourish. The SUSTLE-AH takes cognizance to this fact and emphasizes the role of nature in introducing eco-services' system as integral part of design proposal. Waste becomes resource in nature and that's the principal optimization principle in this model. This reduces resource consumption, waste generation and O&M cost. So both for construction manager and facility manager of EWS and LIG housing, integrated Service system design becomes immensely important for success. Some design insights are listed below.

Road and pavements. Layout of roads shall not cut through any large open space with designated usage, as much as possible. Pedestrian walkways and jogging tracks' cover be permeable pavers as this ensures better groundwater percolation and reduces the storm-water drainage flow. Effort shall be made to keep hard-surface minimum. Waters collected after due purification shall be made accountable for future use.

Managing open spaces through provision of playground (separate for grown-ups and kids), community orchards, landscaped permeable surfaces and walkways, rainwater harvesting through rooftop collection, waste water treatment and recycling, introducing water body as resource management sink etc. are examples of various interlinking subsystems to create stronger Eco-services' system network.

Solid waste and sewage disposal. Landfill being hailed as worst form of solid waste management, community level decentralized bio-degradable waste management systems are good options. Door to door collection of solid waste may help in generating employment too. Segregation of biodegradable waste such as kitchen waste, paper, grass, cow-dung and dry leaves and feeding them into Biogas plants will deliver nutrient-rich manures and fuel gases used for domestic purposes or in vehicles. Bhabha Atomic Research Centre's (BARC) NISARG-RUNA plant for solid waste management is a good example for Zero garbage- Zero effluent waste management.

Sewage disposal system like Decentralized Wastewater Treatment (DEWATS) may be used. After primary treatment which may also generate biogas, the disposals may be used for irrigating urban vegetables/flora farming. If the housing has access to city-sewerage and storm water drainage system, it eliminates necessity of on-site treatment of sewer and solid waste, and thus saves the space and cost of installation.

Rainwater Management: Regular withdrawal and increase in impermeable surfaces expediting storm water runoff would lead to shortage of ground water. The solution should be planned in response to local requirements. Terrace runoff may be collected in underground tanks after early flush off and after screening and treatment, may be used for fire protection tanks, landscaping, urban farming, washing etc. Areas with low water table may plan for rain water harvesting and strategies must be integrated in site development proposal. Cost of filtration treatment required for rainwater to convert into potable water needs consideration. Excess rainwater from the roads, pathways and open spaces may be directed to the existing natural water body in and around the site; this helps to reduce the peak flow rate in the city sewer immediately after the rain. Locations having naturally occurring ponds with high water table may go for business like fish culture.

RISK REDUCTION

Safety and security provided through strong social bonding within neighborhood has incomparable strength. From the inception of the design, interaction between people and spaces should be the design target as this brings resiliency to neighborhood. Coherence and connection between different spaces can be created by physical or visual connections depending on appropriateness and characteristics of the spaces. Considering the present day context, where the interaction between neighbors is on a diminishing note, the design should have the capability within itself to facilitate more interaction.

Though there are lot of controversies regarding the wider social aspects of gated communities, it is widely practiced in India and successful too. The complex should be secured by external compound wall, preferably tall vegetated wall with punctures at required intervals for visual connectivity. This can ensure a sense of security and protection automatically prevailing in the residents' psychology. This helps to cut down the SPM (suspended particles) of air and noise (appx. by 10dB) pollution significantly. Thoroughfare of vehicular traffic must be restricted.

Fire safety guidelines as per the National Building Code (SP7) (NBC, 2005) shall be followed during designing. Maximum travel distance from any corner of the building to the staircase does not exceed 22.5m. The staircase should be separated by a fire rated door of 1800 mm width which opens on a direction of the flight of the staircase. Hose reel should be connected with the down-comer in each floor. Sprinkler system should be avoided due to its high installation and maintenance cost. Refuge decks should be provided as per the existing building norms.

Natural hazards like Earthquake, Urban flood, heat-waves etc. are quite frequent incidents happening to Indian cities. Resiliency through adaptation and mitigation measures are now necessity to consider integrally. Many of the Eco-services will help to non-structurally control the problem both at site level and also with larger impact footprint. Elderly, women and children-centric design shall be a norm than an exception. The design development through its form, structure, use of good materials and proper workmanship can bring better resiliency to communities.

CONCLUSION

Review of Indian housing policy brings out broad attitudinal changes in Government's role from direct provider with social welfare approach, to facilitator of housing through land and finance mechanisms. These mechanisms helped Middle and Higher Income group to consolidate their asset; but failed to cater lower income groups due to lack of access to land and finance.

The strategies outlined in PMAY 2015 are hugely dependent on the government and its fiscal capacity to finance projects. Although the vision statement of the policy emphasizes on private participation but the strategies to uphold this vision is insufficient. Attaining 18.78 million housing shortage is extremely difficult with direct assistance from the government. Alternative land and financing mechanism discussed prior might hold the key for remedy towards India's housing woes if applied innovatively.

Enhancement of financial capability of borrower will significantly improve the status of housing market in India. But it is also difficult for housing policy makers to address all these issues alone. Many relevant policies needs significant restructuring of India's economic and financial configuration. Large part of India's legal, economic and financial structure is still undeveloped. Unless the improvement is envisages in sectors like taxation, financial laws, recent housing finance strategies; it is difficult to improve housing finance and housing tenureship in India.

One another major challenge to accomplish this challenge of 'housing for all', is to device affordable construction techniques, availability of building materials, phase of construction, quality workmanship through skilled labor and many more in cohesive to established and migrated socio-cultural lifestyle through a sustainable environmental approach.

The central idea of sustainable affordable urban housing like the SUSTLE-AH is to develop a habitat which fulfils basic human needs in coherence with nature and society, is economically viable and creates opportunity to accomplish future generations' aspirations. This results both in economic as well as social learning. Social Cross-subsidy concept i.e. interaction between children and elders living in the same compound shall be objectives to achieve to keep the *parampara* alive.

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