2ND RESIDENTIAL BUILDING DESIGN AND CONSTRUCTION CONFERENCE

Proceedings of the 2nd Residential Building Design and Construction Conference

February 19–20, 2014
State College, PA, USA

Edited by
Ali M. Memari
Brian M. Wolfgang

PENNSTATE

PHRC

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PREFACE

Sustainability and energy efficiency of residential buildings have been the drivers for many innovations in building materials and architectural, structural, mechanical, and electrical systems in recent years. There is also increasing demand for high performance, healthy, affordable, and resilient construction. 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 Penn State University is pleased to have started a new conference series to serve the housing and residential construction industry for this purpose

The 2nd Residential Building Design and Construction Conference was held on February 19-20, 2014 in State College, PA in conjunction with the 22nd 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 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 types of residential construction including 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, manufacturers, and government and code officials to submit papers and/or make presentations on all aspects of residential buildings including the following topics:

- Alternative Energy Generating Systems
- Assisted Living and Elderly Housing
- Building Integrated Photovoltaic Systems
- Building Performance Metrics/Verification Methods and Occupant Behavior
- Building Science Aspects and Waterproofing
- Energy Efficient Building Components
- Fire Damage and Protection
- High Performance Residential Buildings
- Housing Construction Materials
- Indoor Air Quality
- Innovation in Residential Architecture and Design
- Innovations in Modular and Manufactured Housing
- Innovative Housing Construction Methods/Systems
- Innovative Wall, Floor, and Roof Systems
- Low-income and Affordable Housing
- Panelized Building Components
- Performance of Buildings under Natural Disasters

- Retrofit of Existing Buildings for Energy Efficiency
- Retrofit Methods against Natural Disasters
- Rural and American Indian Housing
- Serviceability Damage Aspects
- Smart Home Technologies
- Temporary Housing for Disaster Situations
- Whole Building Design Approach
- Zero-Net Energy Homes

The proceedings of the 2nd Residential Building Design and Construction Conference contain papers or slide sets mainly related to the following topics: Building Information Modeling, Code Requirements, Deck Design, Economic Aspects of Home Building, Energy Assessment and Audit, Energy Efficiency, Expansion of Existing Buildings, Hurricane Damage, Indoor Air Quality, Life-cycle Assessment, Litigation Issues, Multi-family Buildings, Multi-story Modular Construction, Net-zero Energy Design, Renewable Energy, Residences for Seniors, and Resiliency.

Two Keynote Speakers were invited for the conference, Tim McDonald, President, Onion Flats LLC, and Dr. David Crowe, Chief Economist, National Association of Home Builders. The conference also had two invited speakers, David Crump, Director of Legal Research, National Association of Home Builders, and Erik Churchill, Project Manager, SHoP Construction. The conference included presentations by university professors, researchers, graduate students, architects, consulting engineers, product manufacturers, and product related associations/councils. As part of this year's conference, new books related to residential construction were placed on display to introduce recent publication in the field.

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 Brian Wolfgang

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Can HOUSING save the planet?

Tim McDonald, RA, CPHC
President, Onion Flats LLC
Associate Professor of Architecture, Temple University

INTRODUCTION

“Affordable” Housing is an oxymoron. “Net-Zero-Energy” Housing is, for most, illusive and impenetrable. “Modular” Housing conjures images of cheap doublewides and trailer parks. “Housing” itself carries it’s own baggage in need of constant qualification: Subsidized Housing, Market-Rate Housing, Student Housing, Senior Housing, Co-Housing, Suburban Housing, Urban Housing…..? With such variety in scale, program, social and economic strata, what possible common denominator would allow us to discuss, if not rethink, the standards by which we envision the design and construction of “housing” in this country, and for that matter, why would we?

Given the not-quite universally accepted knowledge that climate change is real; that it’s affects are, at best, a threat, at worst, catastrophic; that it is man-made and therefore solvable; and the less commonly known fact that the making and operating of buildings account for 45% of all Green House Gas emissions in this country (Energy Information Administration 2012), it would seem a reasonable request, as a society, for buildings to take on a much more intentional role in helping to solve this real and present danger. It would also make sense that as a society we would continue to migrate back to urban centers which we all know are inherently more sustainable environments for living. Most European Union countries have approached this issue head-on by significantly increasing urban density, decreasing the value of the car in favor of more sustainable modes of transportation and, with the help of a 30 year old proven building standard initiated in Germany known as *Passive House (Passivhaus)* (Passivhaus Institute 2014), are redesigning their building codes (EPBD 2014, ECEEE 2014, Passive House US 2014) to require all new buildings to achieve “Net (or Nearly)-Zero-Energy” by 2030. Passive House is a “fabric first”, super-insulated and air-tight approach to the design and construction of buildings which is based on rigid metric standards and meant to reduce energy consumption in any type of building by 70-90% of typical construction. With such radical reduction in energy consumption, these buildings claim to be capable of readily generating the remainder of the energy they need to survive with equally reduced on-site renewable energy generation. We are much slower to act in this country because energy is still cheap, space is more plentiful and our politics are more polarized. The work of Onion Flats, a Philadelphia-based development/design/build company simply attempts to skirt these issues by asking “If it doesn’t cost more to build to this higher design and sustainability standard, why wouldn’t we?”

This paper looks at several projects completed, under construction and in development by Onion Flats. Their 15 year evolving practice and interest in the design and construction of sustainable, urban communities proposes a rigorous yet common sense approach to “affordable” housing which gets better with scale, makes more sense in cities, is inspiring to live in, might help save the planet and will leave politicians, developers, builders, architects, academics and students alike asking, “Why would we do any less?!!!!

Figure 1, Typical Onion Flats Project: Rag Flats, 2006 AN

APPROACH TO ARCHITECTURE

In 1997 my brother and I started a small development/design/build collaborative called Onion Flats. The intention of the collaborative is to integrate seamlessly the process by which our ideas about architecture, the city, and sustainable development go from interpretation to construction to habitation. In other words, we have always found it necessary to *build* the work that we designed, and in most cases, own it as well. While this has required a greater degree of liability and responsibility, it has also offered a space of freedom and opportunity to "play", to explore ideas about the city, community and high-performance building in a very direct and productive manner. Our projects have been experimental, primarily urban, focused on affordability and in the most general sense "sustainable". "Sustainable" or "green" has always been descriptive enough to capture the kind of work that we did. Our projects (e.g., Figure 1) have taken on a broad range of efforts related to sustainability such as storm water management, water conservation, indoor air quality efficient lighting/heating/cooling systems and recycled materials, waste and buildings. All of these issues remain central to the communities we design today but they're issues that are now built into our DNA and frankly require less work. Dual flush toilets, low-flow fixtures, LED lighting, no VOC paints and sealants, high-efficiency heating and cooling systems, locally sourced and recycled products, near-zero-waste recycling centers for construction materials…..these are all standard products and services that are readily available to the design and construction industry currently and are affordable. We have honed in, therefore, on a facet of housing and community development which requires the most creativity, thinking and innovation: *Energy*. Understanding how to radically reduce the amount of energy consumed by buildings, without sacrificing other architectural and urban design related commitments, has required that we re-train ourselves in good building science practices, passive solar design principles and mechanical systems engineering. We've had to also re-think the way we construct our buildings, imagining a holistic and *sustainable building system* that could be modular, significantly more efficient, higher quality and affordable. Most importantly, we've had to re-consider the *metric* by which we can gauge the performance of our buildings. "Net-Zero-Energy-Capable" housing, developed in a dense urban environment (with limited solar generation potential) and constructed at a cost equal to conventional construction, if accomplished, might help raise the standards of what is possible in any form of housing in this county. And so, our most recent work is framed by the following question: *"Can urban housing, affordably, generate all that it needs to survive?"*

Answering this question first requires a baseline metric between *energy* and *housing* that we can reference. Data on energy consumption within a typical American home, cross-referenced to the energy consumption guidelines within the residential building code provides us a baseline average metric of ***20.5 kWh/sf/year*** of "site" energy consumption per home. If we try to make sense of this number based on the above question, and we take, for purposes of discussion, a typical, urban Row home in Philadelphia, one that is 16'-0" wide x 40'-0" long, three stories tall, and therefore, a total 1920sf with an average consumption of 20.5 kWh/sf/yr, this home would consume roughly ***3245 kWh/month***. If you wanted to "zero-out" that energy consumption with photovoltaics on your roof, you would need approximately 2832 sf of roof space to have this building achieve NZE (Figure 2).

This means that an urban building, built to code, cannot possibly generate all it needs to survive on it's own site.

Figure 2, Required roof area for 20.5 kWh/sf/year consumption

Figure 3, Required roof area for 4.5 kWh/sf/year consumption

Working in reverse if you only had a 16'x40' roof, how much energy can that roof generate? 615sf of roof space can generate about 6.15kW of electricity and that would require the home to consume only ***4.5 kWh/sf/yr*** of electricity, a ***78% reduction*** in consumption. This is an important metric if one is serious in asking the difficult question of how urban housing could even begin to support a Net-Zero-Energy-Capable initiative. Curiously, this ***roof metric*** is precisely the metric which defines a *Passive House*.

Passive House is a German building standard which it's founder, Dr. Wolfgang Feist, developed in the 1980s after being inspired by the super-insulated home experiments taking place in North America in the

1970s. It is, therefore, a standard which was originally based on a heating-dominated climate, one which emphasizes super-insulation, airtight and thermal-bridge-free construction, balanced ventilation and relies on internal heat gains and passive solar radiation to provide the majority of heating needs for the home. Technically, there are really only three requirements that, if followed, make a Passive House:

- A maximum of ***4.75 kbtu/sf/yr*** for heating/cooling (about ONE TENTH of what a typical home uses).
- A virtually airtight building which must measure no more than ***.6 ACH50*** (which is about TEN times as tight as the code requires), combined with required mechanical ventilation through an ERV or an HRV.
- A maximum Specific Primary Energy Demand of ***38 kBTU/sf/yr*** of "source" energy (not site).

Total allowable consumption of ***38 kBTU/sf/yr*** of "source" energy converted to Kilowatt Hours is ***4.5kWh/sf/yr*** of "site" energy (assuming a 2.5 multiplier), perfectly aligning with the *roof metric* mentioned above. Theoretically, this means that Passive House and urban housing are ideal collaborators in an effort to explore how urban housing can generate all that it needs to survive. And so, while I know our housing projects are more than the sum of their electrons, this is the context within which I'd like to begin to introduce our work. Four projects will briefly be reviewed: FIRST: Thin Flats, a nine unit multifamily, LEED PLATINUM project in Northern Liberties; SECOND: Belfield Townhomes, a three unit, subsidized housing project, and Pennsylvania's FIRST Certified Passive House project, completed in 2012; THIRD: Stables Townhomes, a 27 unit market rate townhome project currently under construction with Phase One complete, and a pre-Certified Passive House. FOURTH: Ridge Flats, a 146 unit mixed-use project, designed to be the largest Passive House project in the country, scheduled for construction in the late Spring of 2014.

Figure 4, Thin Flats, 2008, first LEED Platinum duplexes in the USA

MEASURING UP

Thin Flats is comprised of eight duplexes and one single-family row home (Vivian 2011, Flannery 2011, Vivian 2010, Fernandex 2009). The one on the left (Figure 4) is the Row home and highlighted on the right is one lower duplex. We had a reasonably good thermal envelop with R38 walls and a .32 U value for windows, with a broad range of sustainable practices, such as an intensive green roof, solar thermal hot water, radiant heating, rainwater cisterns, pervious parking lot, etc. The blower door tests for the duplex unit measured *4.8ACH50* and the single-family home measured *2.1ACH50*, more than twice as tight as the duplex. With 24 months of measured data, and the duplex unit averaging ***9 kWh/sf/yr*** and the single family home averaging ***7 kWh/sf/yr***, the larger single family home used almost HALF the energy that it was projected to use and ONE THIRD of the energy of the Reference “Code Home”, while the duplex unit used 20% less than was projected and over 60% less than the Reference “Code Home”. By all accounts, this project was a success from a performance perspective, with what we knew at the time. We had never heard of Passive House in 2004-2006, and while the project is a resounding success from the projected performance goals of a LEED Platinum building, these units are still using 36-50% more energy than a Passive House, which also means that even if we filled the roofs with PV, this project would probably not be able to achieve Net-Zero-Energy. This is not a critique of the project or of the LEED building standard, but an important context through which to understand the rigorous performance criteria of a Passive House. And at ***$144.00/sf*** Hard construction costs, these higher-end, market-rate condos, with custom detailing, finishes and fixtures, still fit within our definition of “affordable” construction, but Thin Flats was also, in many ways a “standard” development, or more precisely, the limit of what we could do with standard approaches to design and construction. After this project, we began to look critically and intentionally for more replicable systems of construction that would increase efficiency at multiple levels, while allowing us to still maintain control of larger scaled projects.

BELFIELD TOWNHOMES

Figure 5 Belfield Townhomes: Left: Front porches with green walls; Right: Image from above

In 2010, we were approached by the Philadelphia Office of Housing and Community Development (OHCD) to determine if we could salvage an affordable housing development in the Logan section of the City that OHCD had been working unsuccessfully on for several years with a local Non-Profit CDC. Prior designs were inefficient and had come in over budget. The funding, which was earmarked for the project through the Philadelphia Redevelopment Authority (PRA) and HUD, was imminently at risk of being returned to HUD due to inaction. We were told that the project, once designed and permitted, had to be built in no more than SIX months. We were asked not simply to design the project for the CDC but to act as co-developer and take full responsibility for the logistical, financial and technical success of the project. The requirements were simple: design and build three much-needed homes for this community that would house large, formerly homeless, families, with a handicap accessible ground floor, within the budget and timeframe allotted. This project (Figure 5) would be the first new construction to take place in this community within the last 50 years. There were no "green" or "sustainable" requirements specified for the project. We reviewed the site, the former design, program requirements, budget and schedule and determined that this project, while risky, offered us the opportunity to experiment with several ideas regarding affordability, high-performance building technology and alternative construction techniques we had been developing conceptually for years. This project would be a "first" for us in several ways:

- it would be our first subsidized housing project
- it would be our first project constructed in a modular factory
- it would be our first attempt (and the State of Pennsylvania's) at the rigorous ***Passive House*** building standard, and with that, a Net-Zero-Energy-Capable prototype of "affordable", subsidized housing.

At first we didn't even tell the CDC or PRA that we would be designing the project to the Passive House standard. Since we were co-developers and being asked to be fully liable for bridge financing, design and construction of the project within the schedule and budget allowed, it was, in effect our risk to take. The budget (which averaged ***$130sf*** for Hard Construction costs) seemed reasonable, however untested. We had designed and built some of the first LEED Platinum projects in the country, become Certified Passive House Consultants several years prior and while convinced of the common sense and rigorous building science principles behind Passive House thinking and building, we would be effectively going out on multiple experimental limbs to make the project a success (Torres-Moskovitz 2013).

Figure 6, Belfield Townhomes: Kitchen/Living Area

Also, essential to the experiment, was challenging the *standards* by which architects, urban planners and Municipal Housing Authorities conceptualize "subsidized/social/affordable housing". We saw an opportunity to define "social" housing as the best rather than the cheapest, fastest and often ill-conceived forms of housing. Was it possible to narrow the gap (or maybe even eliminate it) between "market rate" and "subsidized" housing? Should there be a difference? Could subsidized housing also be inspiring, filled with light, life, high-quality, high-performance, long-lasting and healthy materials and systems? Could it equally have the ability to encourage its inhabitants to be conscious-of and care-for one's environment? Most importantly, could it all be done within the budgets that Federal and Municipal subsidies typically support? We saw the potential for this project to demonstrate not only a new standard of *performance* but also *design* of housing in general for the City if not the country. We saw the potential to demonstrate with this project, not a prototypical *building* as much as a prototypical ***system of building*** that was replicable, scalable and capable of enabling any building to radically reduce it's energy consumption and then generate the remainder of the energy that it needed to survive, particularly in urban environments. We saw the opportunity to demonstrate how one the oldest forms of urban housing, the "row house", could still remain relevant and, in fact, an essential partner in addressing issues of climate change, social inequity and urban blight (James 2012).

The homes are simply and efficiently organized (Figure 6), with a handicap-accessible ground floor living, kitchen, bathroom and bedroom. The second and third floors have three more bedrooms, two bathrooms and one office. The buildings are set back from the sidewalk, to match the adjacent neighbors and create planters and a front porch for community engagement. The orientation of the building follows the urban grid in this part of the city, which is not ideally oriented for maximum southern exposure, however, shading devices on the South/West face of the buildings appropriately shade in the summer and allow for maximum heat gain in the winter. A 5Kw photovoltaic array on each home maximizes the area that each roof offers and is designed to, as defined through the Passive House energy modeling software, enable these houses to achieve Net-Zero-Energy.

SUSTAINABLE BUILDING SYSTEM

An "affordable", high-performance, building system that could be replicable at large scales drew us to modular construction (Figure 6). We had been exploring the benefits of modular construction for several years. Even though the modular industry has been primarily geared in the United States toward the single-family suburban home market, the repetitious and cellular nature of typical urban housing typologies is actually more ideally suited to a modular and manufactured system of construction. *Scale* is critical to the success of any manufacturing process, and *repetition* is key to efficiency and affordability. It's easier for a manufacturing plant to build a large volume of the repetitive cells that define a large building than it is to build a large volume of small individual buildings. Similarly, *scale* matters when designing a Passive House. It is easier to design affordable Passive *HOUSING* than it is to design an affordable Passive *HOUSE*. Large multifamily buildings have smaller surface-to-volume ratios than single-family detached homes, and therefore inherently have less opportunity for heat loss, making large buildings, purely from a building physics perspective, more efficient. After having already determined that the *roof metric* for energy *production*

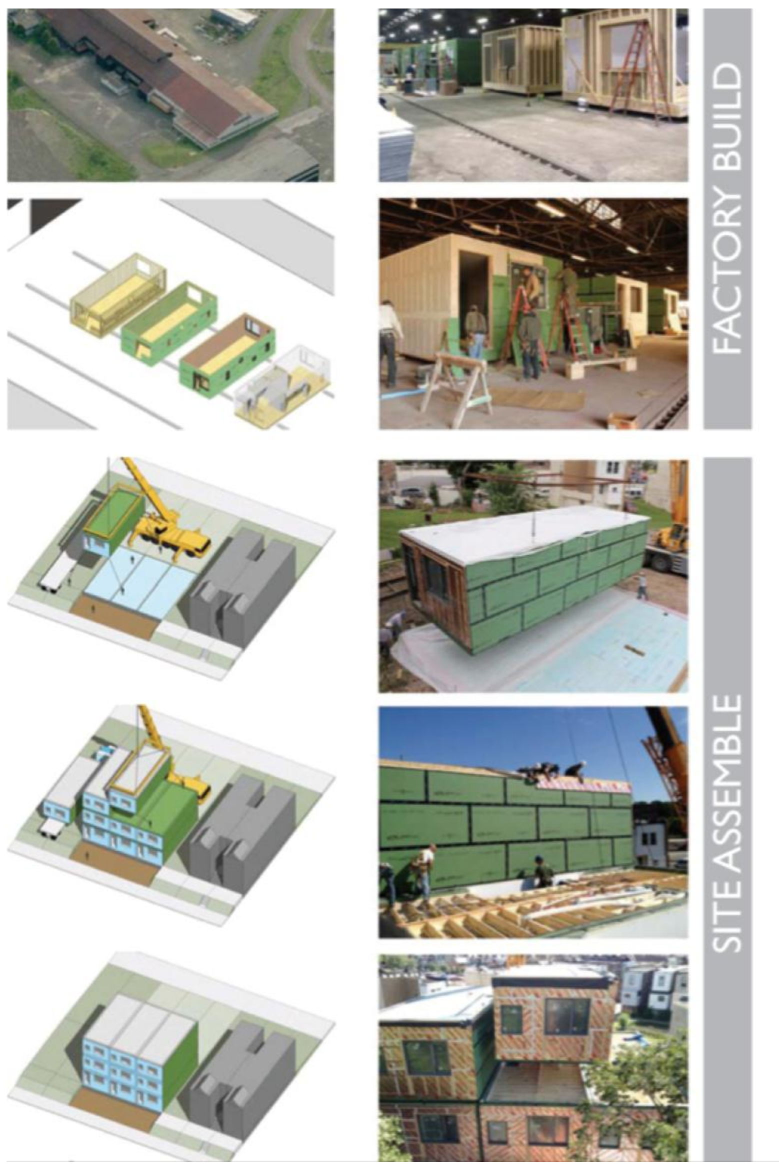

Figure 6, Process of modular from the factory to site assembly capacity with typical urban housing typologies aligns well with the Passive House *metric* for energy *consumption*, i.e. that urban housing and the Passive House standard are good bedfellows, we've come to the same conclusion about Passive House and modular construction.

In order to test this conclusion, we needed to design not simply a more efficient building but rather a more efficient building ***system***, one that was both radically unique and capable of meeting the thermal bridging, air-tightness, thermal resistance and ventilation criteria of a Passive House, but at the same time, rooted in every day modular framing techniques which could be easily transferred to each building trade on the production line.

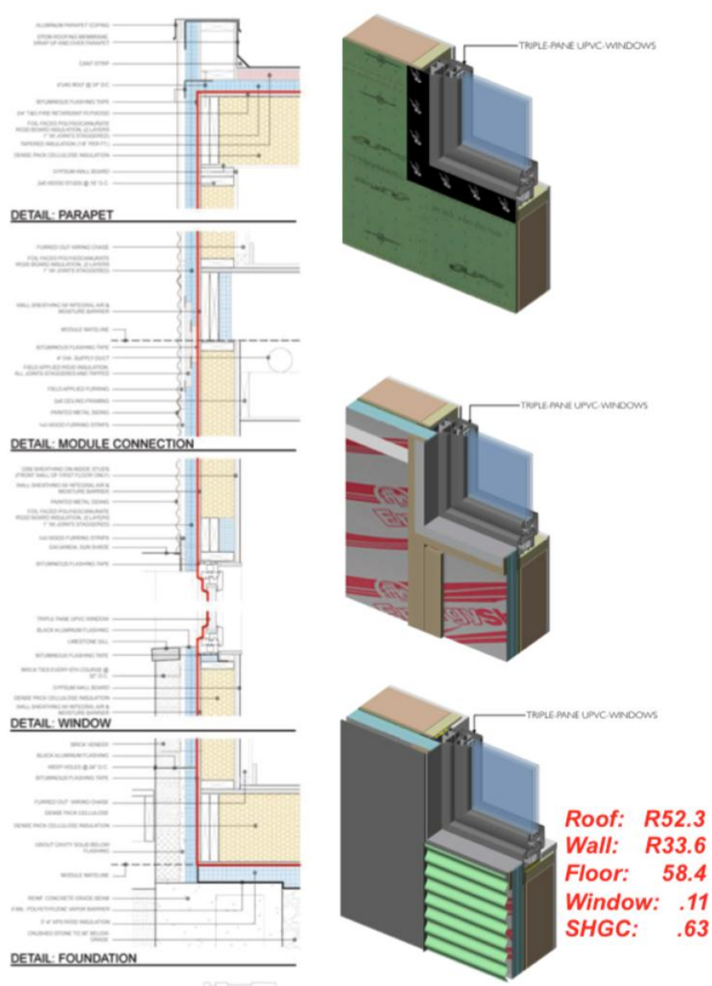

Figure 7, Composition of the Sustainable Building System thermal envelope

Typical 2x6 and 2x12 wood framing was chosen as the base structure and thermal envelop, primarily because it was what the production crew knew best (Figure 7). The materials were also inexpensive and readily available. In order to simplify the detailing of the air-barrier layer we placed it on the outside of the framing and had it double as the moisture barrier. Our triple pane windows would sit flush to the exterior air barrier making air sealing between them and the wood framing extremely simple and as "fool-proof" as possible. In order to achieve the required R-values needed in the roof, floor and walls, we filled the wall/floor cavities with dense-packed cellulose and then clad the envelop beyond the air/moisture barrier layer with two continuous layers of polyisoscianurate rigid foam board, staggering the joints between the layers to insure a tight and thermal-bridge-free skin. Beyond this exterior insulation layer on the walls, we created a vented but closed rain-screen system finished with a mix of metal panel, concrete board and brick.

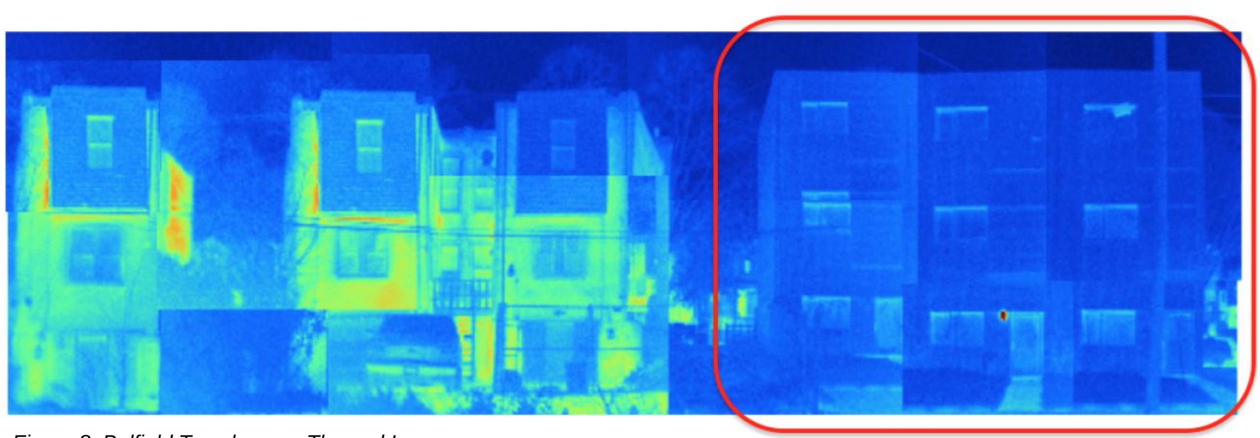

Figure 8: Belfield Townhomes: Thermal Image

There would be no opportunity to perform a pre-drywall blower door test on these houses (often preferred during the construction of a Passive House) because the air-tightness of the individual modules could not effectively be tested until they were installed, with seams sealed, on-site. We had performed several experiments during the energy modeling phase of the project in which we compared the importance of *thermal resistance* (i.e., insulation) versus *air-tightness* in the overall performance of the building's thermal envelope. While both are critical to the performance goals of a Passive House, slight reductions in air-tightness have a significantly larger impact on Specific Primary Energy Demand than similarly slight reductions in the thermal resistance values of the envelop. This is certainly one of the most important lessons learned during this project and has helped to further hone our Sustainable Building System as well as our detailing. Luckily the blower door test measured ***.4ACH50*** for each home, 30% tighter than the .6ACH50 required by the Passive House standard! Thermal imaging provides a visual representation of just how tight the homes really are (Figure 8).

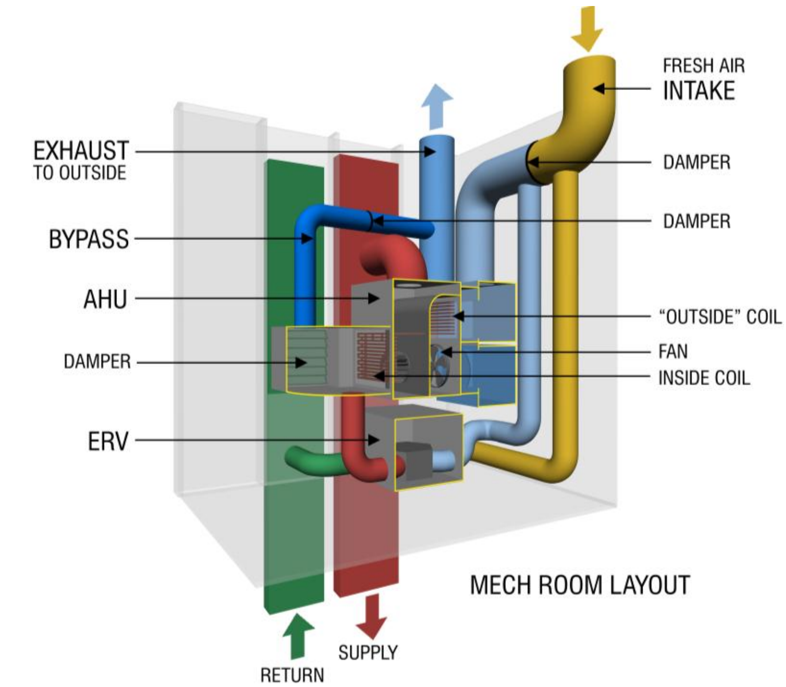

Figure 9: Left: diagram of "coupled" PTAC (AHU) and ERV; Right; as-built

MECHANICAL SYSTEMS

After exploring several options for heating/cooling/ventilation for these three story homes, we were inspired by European low-energy and composite heating/cooling/ventilation/domestic hot water systems (known as "magic boxes" (Holladay 2010), but none were available in the US. Our collaborating mechanical engineer, however, took clues from these sophisticated and inaccessible systems and designed a cost effective and "coupled" air-source heat pump/ventilation system that partially mimicked the magic box, but worked with an off-the-shelf, inexpensive yet highly efficient 9000BTU Packaged Terminal Air Conditioning (PTAC) heat pump unit and an Energy Recovery Ventilator (ERV). We located the mechanical room on the third floor (Figure 9) so that our fresh-air intake and exhaust air ducts would come through the roof. Each town home in the development has its own combined heat pump/ERV unit for heating, cooling and ventilation. We had decided early on that we would only have electric in the houses, no natural gas. Gas would have been another costly service, it would have required venting for several appliances, and therefore, more punctures in the thermal envelop and the potential of heat loss and air leakage, and gas is a non-renewable resource that can't be generated on-site. Domestic hot water is provided by a Heat Pump Water Heater (HPWH) and placed in the laundry room so that it symbiotically works to reduce heat and humidity generated by the condensing dryer and washer.

ENERGY MONITORING

A significant and robust energy, temperature, humidity and CO2 monitoring system is installed in each home within the Belfield project. Every electrical circuit is monitored for energy consumption and the production of the 5Kw PV system covering each home's roof (Figure 10). Temperature sensors are placed in each room in the house, with two CO2/humidity sensors positioned on upper and lower levels. All data is collected through a monitoring hub and managed through a website unique to each home. The monitoring is absolutely essential to understanding not simply how the home performs but how the occupants live within the homes. We realized very quickly with this project that there is no such thing as a "Net-Zero-Energy" building. There are only "Net-Zero-Energy-Capable" buildings, because as we can now clearly see with about 12 months of measured data, the occupants often have desires contrary to the lean performance goals of their homes.

The data, from three identical houses, shows widely ranging energy consumption (Figure 10). Analyzing each circuit we discovered a complicated and fascinating story of occupant behavior, property mis-management and a need for significant education.

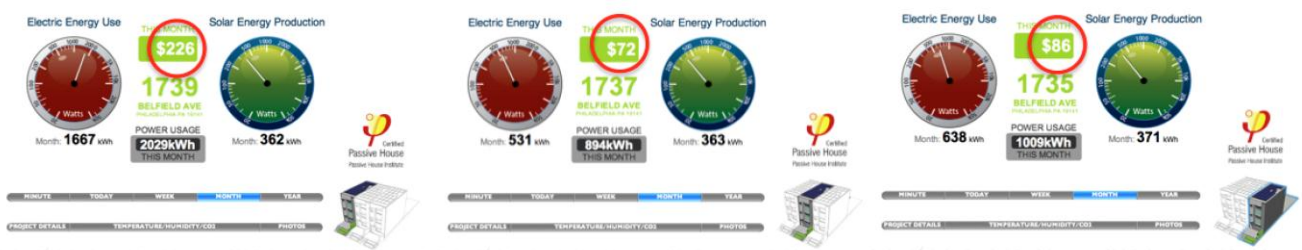

Figure 10: Website portal page of each Belfield Townhome linked to respective and more comprehensive energy monitoring sites for each home

We took a snapshot of one month's energy consumption (February, 2013) which demonstrated monthly electricity bills ranging between $72.00 and $226.00 (Figure 10). We looked at the circuits in the home consuming the most energy and noticed the "Laundry" circuit was recording an average of *104 loads of laundry in 30 days!* We then looked at the HPWH circuit and noticed that the water heater was effectively running in purely electric resistance mode, not Heat Pump mode, most of the month. The heat pump

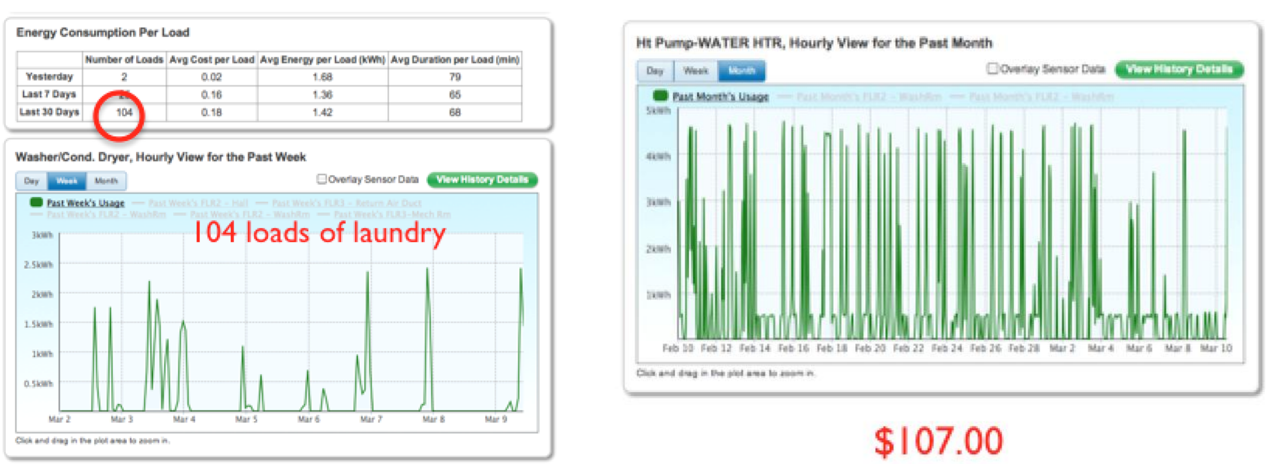

Figure 11: Left: Energy consumption graph for Laundry circuit; Right: Energy consumption graph for HPWH

inside the HPWH has a COP of 2.5, which means essentially that it is 2.5 times more energy efficient than an electric resistance water heater. It turned out that the hot water alone was accounting for *$107.00* of this home's $226.00 utility bill (Figure 10)! It also demonstrates a larger, unexpected issue. We suspect that this one home has been effectively running a small Laundromat, with friends and family coming by to clean their clothes daily. Given that Laundromats are common for most people in this neighborhood and that private washers and dryers are an unaffordable luxury, we completely missed the potential impact that this one social and economic construct would have on the energy demand of these homes. The washer and dryer in this unit running so continuously has also caused other unintended consequences such as significant heat build-up in the home. While this is not problematic in the winter, it contributes considerably to the cooling load and energy consumption in the summer.

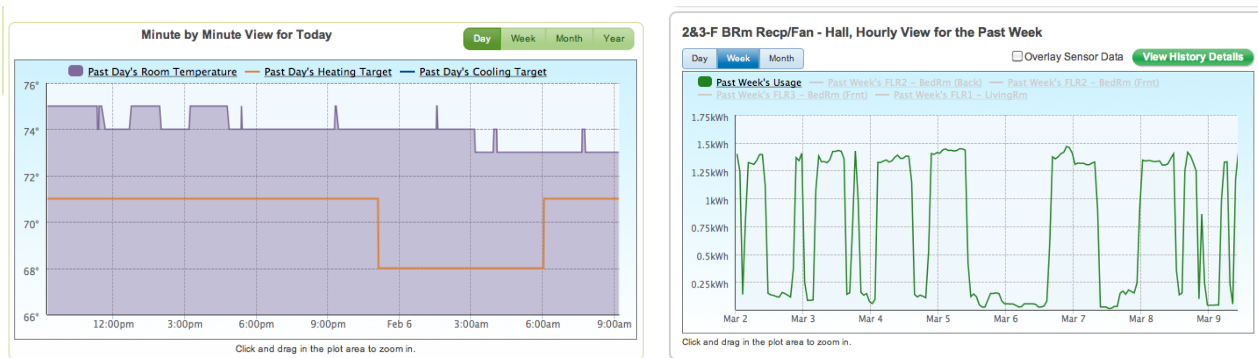

Figure 12: Left: Thermostat set temp relative to Actual room temp; Right: graph indicating significant plug load energy consumption of electric strip heaters

We discovered other significant anomalies between the homes' energy consumptions (Figure 12). In one home, during February and March, the indoor air temperature was consistently being maintained one or two degrees above the set 70 degree thermostat temperature, even though the heat pump rarely turned on. At first we were pleased, thinking that our Passive House was doing exactly what we expected, i.e., maintaining it's indoor air temperature and comfort levels with nothing more than the internal heat loads of people, lighting and appliances. Looking more closely, however, we discovered unusually high plug loads coming from several rooms, which we discovered, upon inspection, was the result of tenants plugging in electric resistance strip heaters throughout the home! This was not because the rooms were cold, but rather simply because they owned them, as they had been accustomed to using them in their prior leaky residences. On several occasions when we'd visit the homes to check on such problems that we were seeing in the monitoring data on-line, we'd arrive to homes in the middle of the winter, with windows and doors open, tenants with shorts and t-shirts on and complaints of variations in temperatures between floors and rooms.

As one might imagine, the performance of these houses has fallen short of their projections. With 12 months of data, while these houses are consuming between 25% and 66% more energy than they were designed to consume, two of the units, using roughly the same energy, ***6-7 kWh/sf/yr***, are still the lowest energy homes we've ever built and roughly 65% more efficient than a typical American home built to code. And while occupant behavior might appear to be an easy target for not meeting the Passive House projections, the primary culprit is actually much more obvious and unfortunate: the Non-profit CDC that owns and operates the properties ***does not charge its tenants for electricity*****!** As such, there is no incentive for tenants to be conscious of their energy consumption. In other words, NO VALUE is placed on energy consumption by the property owners. Even with that significant management flaw, after subtracting the energy generated by the PV on the roofs of the units, they still, on average, require only between ***$32*** and ***$93/month*** to operate all utilities. Armed with this data, we have approached both the owners and tenants of these homes in order to hopefully transform both occupant and management behavior and narrow the gap between human and building performance.

Figure 13: Site Plan of Stables Townhomes

SCALING UP

The Belfield Townhouses was an important first step in developing an affordable, high-performance, building system that could be replicable at large scales, guided by the Passive House building standard and applicable to both the subsidized and market-rate, urban, multi-family housing industry. We are currently under construction with a 27 unit market-rate townhouse development in the Northern Liberties section of Philadelphia referred to as Stables Townhomes (Figure 13). The project is comprised of three "bars" of 9 four-story, single-family townhomes. Similar to the Belfield Townhomes, we treated each "bar" in the energy modeling software as ***one*** building. The adiabatic party walls between each individual townhome are contained within the thermal envelop of each bar, eliminating the need for any heat loss calculations. For air-tightness purposes, however, again identical to the Belfield Townhomes, we air-sealed between each unit. The "bars" were designed and

Figure 14: Photo of completed Phase 1 of Stables Townhomes

oriented to capitalize on the almost-perfect Southern exposure of George Street. Floating planters and balconies on the South side of the home both capture and deflect the sun depending on the time of year. We have recently completed the first three units of the George Street "bar" and expect to have all 27 units completed by the end of 2014 (Figure 14).

Stables Townhomes is similarly designed and built in a modular factory with the exact same building system and detailing as Belfield, but simplified and improved. It has the same "coupled" hybrid heating/cooling/ventilation system, but with a slightly larger 12,000BTU heat pump within the PTAC unit to heat and cool the roughly 2400 sf of space (Figure 15). The most significant difference between Belfield and Stables is that Stables has a basement, and Belfield didn't. We chose to make the basement "technically" outside the thermal envelope and therefore had to diligently air-seal and insulate between the first floor and basement levels. All mechanical equipment is located in the basement with exhaust and supply air ducted from an outside wall on the first floor. A slightly altered ducting plan separating "exhaust" from "return" air, insures even air temperature distribution and balanced ventilation on all four floors. The same temperature, humidity, CO2 and electricity monitoring systems are installed in each home with it's own dedicated website.

Figure 15: Photo of completed mechanical system in basement

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BUILDING LEAKAGE TEST COMPARISON

Test #1
Test File: Depressurization File
Date of Test: 7/5/2012
Customer: Onion Flats, LLC
111 West Norris Street
Philadelphia, Pennsylvania 19122
Phone: 215-783-5591

Test #2
Test File: Pressurization File
Date of Test: 7/5/2012
Customer: Onion Flats

Test Results

	Test #1	Test #2	Change	Percent
1. Airflow at 50 Pascals:	293 CFM	201 CFM	-92 CFM	-31.4 %
	0.48 ACH	0.33 ACH	-0.15 ACH	-31.4 %

FINAL AIRFLOW .49 ACH 50

Figure 16: Photo of blower door test for first completed unit, with measured results

The measured airtightness of the first home came in almost identical to the Belfield homes at ***.49ACH50*** *(Figure 16)*, and once the rest of the block is constructed and tested, Stables will become the 2nd Certified Passive House project in Pennsylvania. Each home has a slightly smaller 4.5kW PV system on each roof, but has the capacity to hold 8.5 kW of PV. With only 4 months of data, currently measuring only ONE home, and with owners who are conscious, diligent and interested in their energy consumption, we project that their annual consumption will be approximately 8244 kWh or ***4.3kWh/sf/year***, which would meet the Specific Primary Energy Demand projections of a Passive House. If the owner chose to place an extra 4kW of PV on this roof, this could conceivably "zero-out" its energy consumption on-site. At a ***$147.00sf*** Hard construction cost for these "market-rate", Net-Zero-Energy-Capable homes with custom finishes, fixtures, appliances, carport and 320sf green-roof garden, we consider this "affordable" housing.

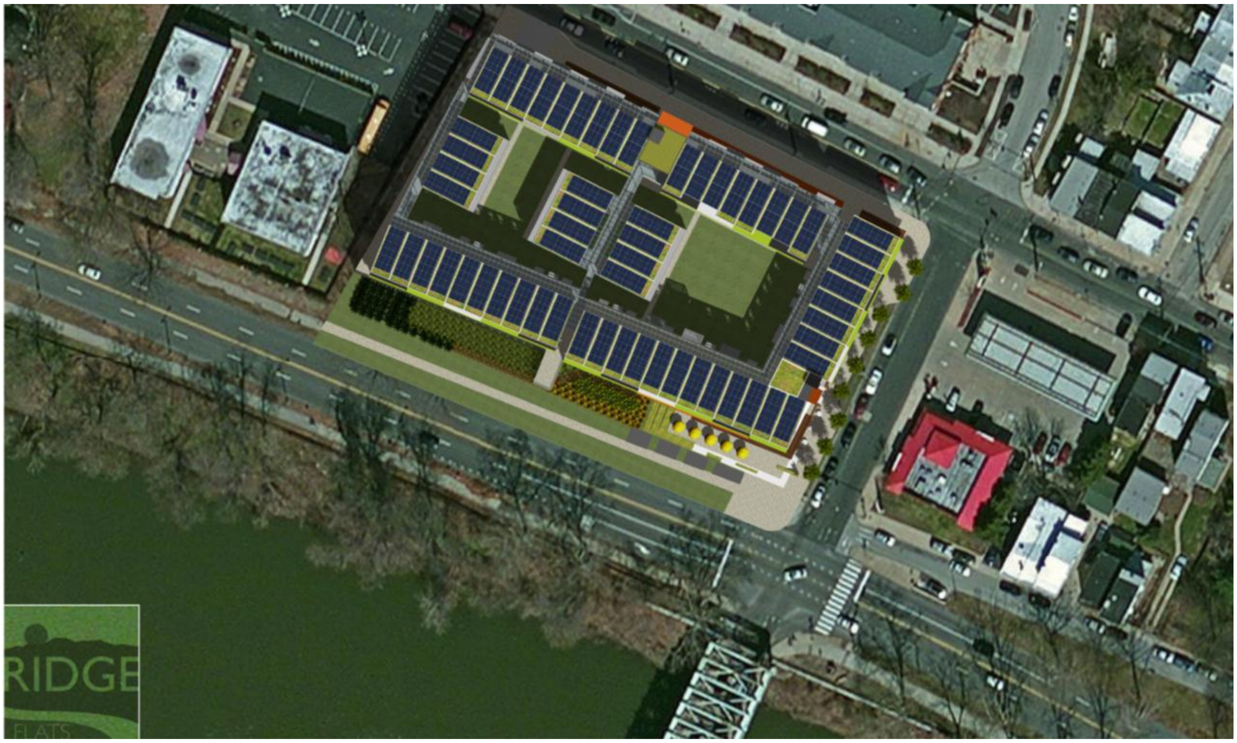

Figure 17: Site Rendering of Ridge Flats

PUMP UP THE VOLUME

While our earlier projects have been small but key experiments in the development of affordable, high-performance design and construction standards for the housing industry, with the ***idea*** of scalability in mind, Ridge Flats, our most recent project, is an experiment in SCALE itself.

Ridge Flats, a 146 unit, mixed use project situated along the Schuylkill River in the East Falls neighborhood of Philadelphia is slated to begin construction in late Spring of 2014 (Figure 17). Once completed, it will be the largest Passive House Certified project in the country. The Philadelphia Redevelopment Authority, which owns the land, put out a competitive RFP to developers for which our proposal was chosen. The neighborhood and City of Philadelphia were inspired by the design and performance goals of the project and saw the potential for it to become a model for future urban development standards. With 100,000sf of four story, wood-framed, residential construction above a one-story non-combustible parking and retail space, Ridge Flats is a model for many types of mixed-use urban housing, including student dormitories, inter-generational housing and co-housing communities (Figure 18). The residential units are 1 and 2 bedroom rentals ranging from 560sf to 937sf, open and spacious, with private outdoor balconies for each unit and a 7000sf communal garden accessed by all units at the second level. The first floor steel and concrete "podium" will be site-built. The residential units will be built in a modular factory, utilizing the same Sustainable Building System developed for our smaller Stables and Belfield projects. Modules will be delivered to the site with finished interiors and exteriors and custom "building gaskets" designed for air and water-sealing between contiguous modules. Limiting the amount of work to be done on-site is key to the affordability, coordination and quality control requirements of the project. The thermal envelope is virtually identical to our earlier projects and demonstrates the replicability of the Sustainable Building System. We are in the process of designing our own hybrid heating/cooling/ventilation/domestic hot water system, as we had done in our earlier projects, but look forward to the day when such combined systems are commercially available in the United States for low-energy multi-family applications. A 266kW photovoltaic roof-top array is designed to provide Ridge Flats with enough electricity production to make it a Net-Zero-Energy-Capable community, and one of the largest in the country (Klayko 2012, Defendorf 2012, Saffron 2011).

Figure 18: Rendering of corner of Kelly Drive and Calumet Streets, Ridge Flats

CONCLUSIONS

"Can HOUSING save the planet?" While this is an intentionally provocative, maybe somewhat naïve question with which to begin and end a paper, it is none-the-less an appropriate description, for better or for worse, of the somewhat naïve and risky work Onion Flats. "Housing", as a noun, most often needs an adjective to frame or activate it in one direction or another. Housing doesn't have to just passively *function*, it can also *perform*. I went to two $10.00 performances in the movie theatre over the last couple of weeks. One left me depressed and lifeless, the other made me laugh and inspired me to look at my environment in a more intentional way when I left the theater. I spent the same $10.00 on the two performances. So, if it doesn't cost anymore to be depressed or inspired, for our Housing to merely *function* rather than *perform*, why wouldn't we chose an inspiring performance?

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Home Building Impact

David Crowe
Chief Economist

February 20, 2014

National Association of Home Builders

WHY Reject New Homes

- Property tax is insufficient to pay for new service demands
- New homes bring traffic congestion, crowded schools, ‘different’ neighbors
- Environmental damage
- Fields and forests disappear

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LOCAL ECONOMIC IMPACT

Construction phase

- Jobs
- Materials
- Local fees, taxes, contributions

Ripple or feed-back from construction

- Wages spent in local economy

Occupancy phase

- Earnings spent in local economy

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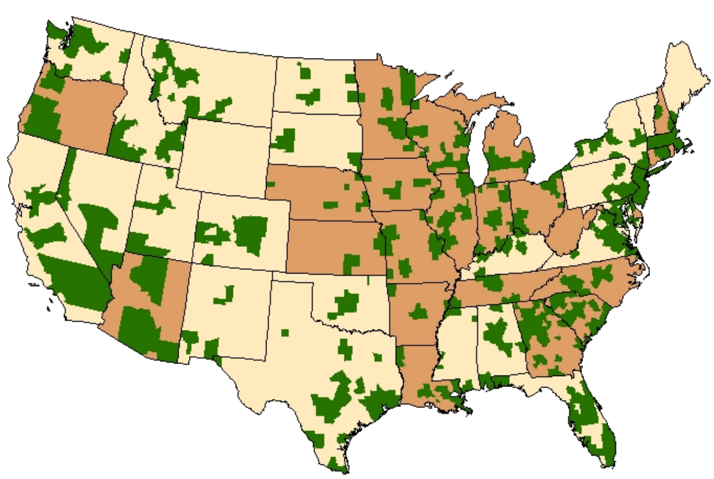
NAHB

Areas Covered by NAHB Local Impact Studies (Over 750 Done So Far)



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Assumptions of the Model

Inputs To Model	Single-family
Average house price:	$321,000
Average raw lot cost:	$40,000
Permits/Infrastructure:	$7,915
Annual property taxes:	$2,810

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FIRST YEAR IMPACT: Single-family Construction - Every 100 Homes

Local Income	Local Taxes	Local Jobs Supported
$14,233,300	$1,333,000	213

INCLUDING:

147 Jobs in Construction
32 Jobs in Wholesale and Retail Trade
17 Jobs in Business and Professional Services

* One job represents enough work to keep one worker employed full-time for a year.

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FIRST YEAR IMPACT: Single-family *Ripple*

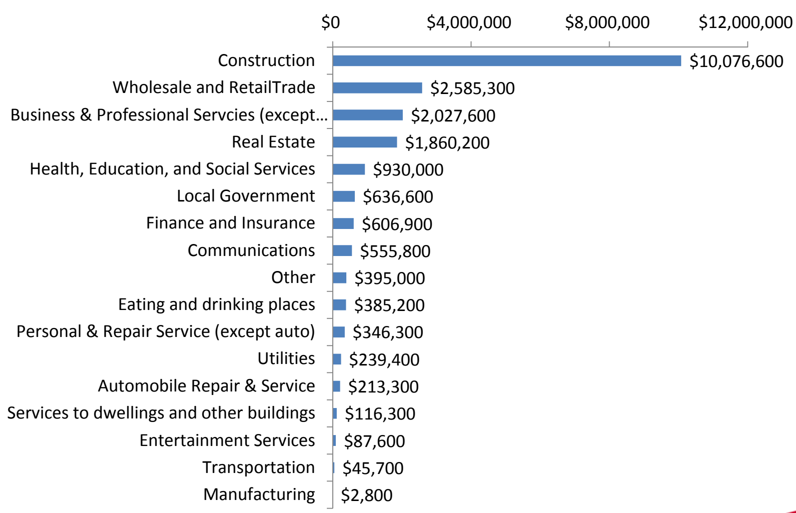
Local Income	Local Taxes	Local Jobs Supported
$6,877,300	$869,700	111

INCLUDING:

29 Jobs in Wholesale and Retail Trade
15 Jobs in Eating and Drinking Places
17 Jobs in Health, Education and Social Services
12 Jobs in Local Government

National Association of Home Builders

First Year Impact of 100 Single-family Homes Added Incomes



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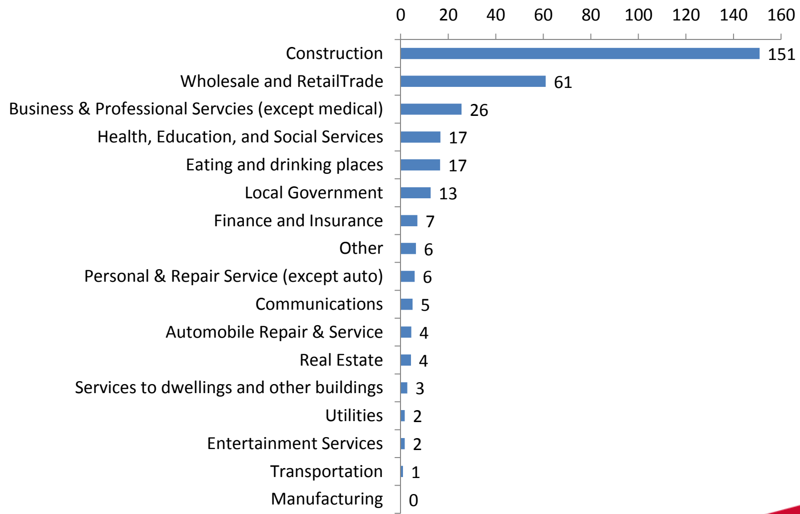
First Year Impact of 100 Single-family Homes Jobs



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ONGOING Single-family ANNUAL EFFECT

Local Income	Local Taxes	Local Jobs Supported
$3,060,900	$743,300	53

INCLUDING: → 38% from real estate tax

14 Jobs in Wholesale and Retail Trade
7 Jobs in Eating and Drinking Places
5 Jobs in Local Government
7 Jobs in Health, Education and Social Services

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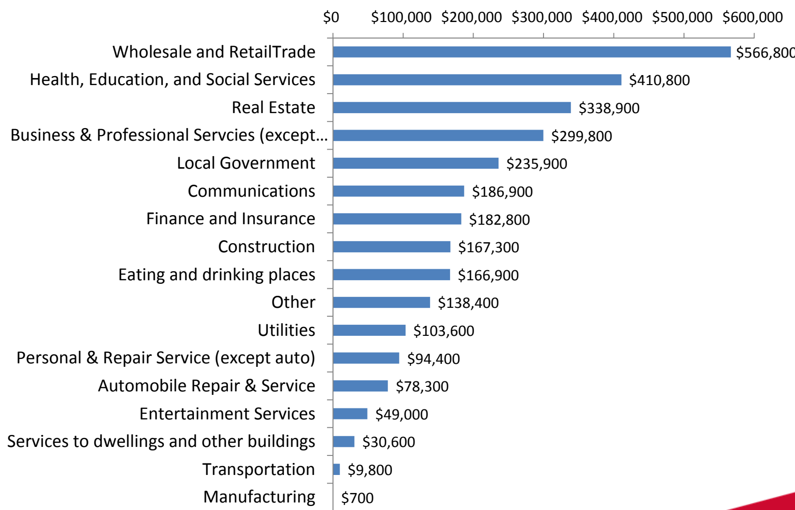
On Going Annual Impact of 100 Single-family Homes Incomes



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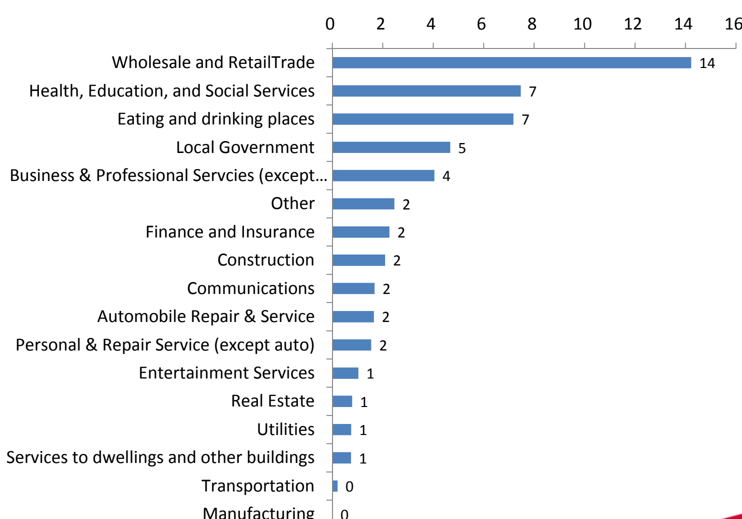
On Going Annual Impact of 100 Single-family Homes Jobs



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NEW HOMES REQUIRE:

INFRASTRUCTURE

- Fire and police protection
- Garbage collection
- Parks and recreational opportunities
- Roads
- Correctional facilities
- Primary and secondary education
- Etc.

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Where's Data/Facts?

- Local government budgets
- Federal government surveys
- Model estimating relationships

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Required Current Expenses per Unit

	Single-family
Education	$1,697
Police Protection	$534
Fire Protection	$245
Corrections	$172
Streets and Highw ays	$66
Water Supply	$185
Sew erage	$102
Health Services	$226
Recreation and Culture	$254
Other Government	$835
Utilities	$216
Total	$4,530

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Required Capital per Unit

Function	Single-family
Schools	$9,120
Hospitals	$990
Other Buildings	$2,889
Highw ays and Streets	$1,816
Conservation & Development	$61
Sew er Systems	$2,273
Water Supply	$2,990
Other Structures	$2,663
Equipment	$232
Total	$23,035

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Now that we know:

The benefits of construction

&

The costs of construction

Does new construction pay for itself?

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Flow of Expenses and Revenues

Year	Current Expenses	Revenue	Operating Surplus	Capital Investment	Debt at End of Year	Interest on Debt	Net Revenue
1	226,700	2,574,300	2,347,600	2,303,400	57,169	101,369	(57,169)
2	453,400	743,300	289,900			2,516	287,384
3	453,400	743,300	289,900				289,900
4	453,400	743,300	289,900				289,900
5	453,400	743,300	289,900				289,900
6	453,400	743,300	289,900				289,900
7	453,400	743,300	289,900				289,900
8	453,400	743,300	289,900				289,900
9	453,400	743,300	289,900				289,900
10	453,400	743,300	289,900				289,900
11	453,400	743,300	289,900	23,200			266,700
12	453,400	743,300	289,900				289,900
13	453,400	743,300	289,900				289,900
14	453,400	743,300	289,900				289,900
15	453,400	743,300	289,900				289,900

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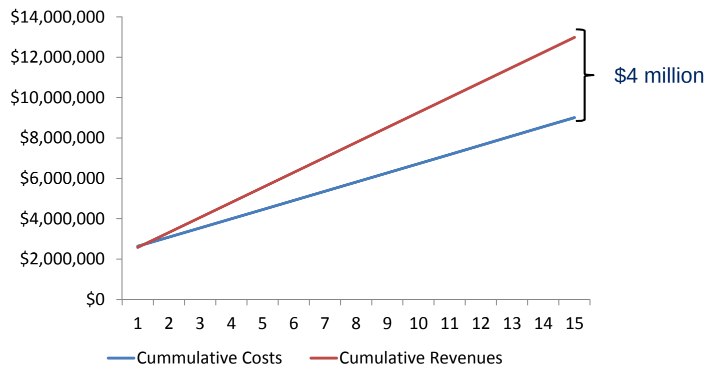
Yes it does!

For **each** single-family unit --
• By the end of the 2nd year economic impacts offset fiscal costs.
• By the end of the 2nd the debt is fully paid off
• By the 3rd year, net is $289,900 thereafter



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SUNLIGHT REFLECTED FROM DOUBLE-PANED LOW-E WINDOWS, AND DAMAGE TO VINYL SIDING AND OTHER MATERIALS

David N. Crump, Jr.
National Association of Home Builders

OVERVIEW

Direct sunlight has the capability of heating the surface of materials through absorption well above the ambient air temperature. Even so, the heat from direct sunlight does not generally result in significant damage to building materials, beyond effects associated with fading and weathering. Reflected sunlight from modern windows is another matter. Glass in double paned windows may on occasion slightly warp or deflect due to a difference in the barometric pressure between the interior of the glass panes and the outside air pressure. This can create a concavity in the glass. Such a concavity is a normal response to pressure differences, does not affect the performance of the window, and does not constitute a defective window condition. However, the concavity may focus sunlight reflected from the window in a fashion similar to the effect seen when light passes through a magnifying glass. This focused light may land on adjacent building surfaces, and appear as a brilliant star-shaped spot. The concentrated heat generated by the focused reflected sunlight results in surface temperatures well above that encountered from direct sunlight, and has the capability of causing damage to exposed materials, especially those which are plastic based.

VINYL SIDING

According to the U.S. Census Bureau, vinyl siding has been the most commonly used exterior cladding on new single family homes every year since 1994. Homeowners appreciate its durability (under most conditions), and its low maintenance qualities - no painting. But, vinyl siding is a plastic based product, and as such is susceptible to the heat effects caused by focused reflected sunlight. The Vinyl Siding Institute (VSI) states that temperature ranges beginning at 160-165 degrees Fahrenheit can soften normal grades of vinyl siding. Darker colors absorb more heat, and will soften before lighter colors of siding. There have been reports of reflected sunlight heat damage to materials other than vinyl siding, such as wood and paint discoloration, and damage to other plastic based products, such as automobile components, lawn furniture, decking, window lineals, and trim.

LOW-E WINDOWS - REFLECTED SUNLIGHT EFFECT

The use of double-paned low-e windows are now generally mandated by modern building and energy codes for new home construction. Low-e window glass is coated with a thin layer of metal or metallic oxide. Visible light passes through low-e windows without difficulty, but the metallic layer blocks the passage of heat inducing ultraviolet light into the home, reflecting that light outward. This keeps the home cooler in summer. In winter the effect is reversed, with interior heat blocked from passing outward. In this way low-e windows reduce energy costs.

The use of double paned low-e windows will not necessarily result in any damaging reflected sunlight incident. A combination of contributing factors must be present before the effect occurs or causes damage to any nearby materials, including vinyl siding. The presence of the concavity in the double glass panes and the focusing of the reflected light beam appear to be the primary cause of damaging heat generation, more so than the mere increased reflectivity of the low-e window. According to Mark LaFrance, a spokesperson for the U.S. Department of Energy (DOE), clear glass will reflect 10% of the sunlight's energy, while low-e windows reflect 30-50%. So while any double-paned window may generate a focused beam of reflected sunlight, the greater reflectivity of low-e glass exacerbates the effects of the focused reflected beam by generating more heat. The heat from double paned low-e window reflected sunlight has been measured in excess of 200 degrees Fahrenheit at its point of focus, more than sufficient to soften and distort any normal grade or color of vinyl siding.

Other conditions may have an influence. The angle of the sun is a factor. A low angle of sunlight (such as might occur in late fall, winter, or early spring) is more likely project the reflected sunlight beam outward, away from the ground and onto the surface of nearby buildings. Proximity to a neighboring structure is a factor. An NAHB Builders' Survey conducted in 2011 indicated that most vinyl siding damage occurs when the distance between the window and the siding is 30 feet or less. However, distances of up to 100 feet between window and vinyl siding have been reported. Other factors such as wind speed, air temperature, and the presence of buffering foliage all appear to have an impact on whether the reflected sunlight results in damage.

RANGE and EXTENT of OBSERVED EFFECT

Distortion to vinyl siding from reflected sunlight has been reported in all geographic regions where vinyl siding is used. First reported in the late 1990's, observed incidents have risen proportionally with the increase in the use of low-e windows in residential construction. Exact numbers of reflected sunlight damage incidents are unknown, but an informal poll of major builders disclosed approximately 2000 incidents over a 10 year period. The NAHB Builders' Survey received 152 reported incidents. Reflected sunlight damage to vinyl siding has been observed everywhere vinyl siding is used, primarily in more northern states, but also in Virginia, and North and South Carolina. There are fewer reports of reflected sunlight damage in areas such as Florida and Texas where vinyl siding is less frequently used, and much fewer reports from states west of the Mississippi River where there is a manufacturing requirement for the installation of capillary tubes in double paned window construction. There are also fewer incident reports from areas where fresh air ventilation is more common than air conditioning, apparently due to the diffusing presence of window screens.

ARGON LOW-E WINDOWS

There are different types of low-e windows available in specific climate zones. Low-e windows with high solar heat gain coefficients and low conductivity are preferred for northern climates where passive solar heating is advantageous in winter months. In order to retain the passive solar heat in the home, a dense, low conductivity gas, commonly argon, fills the area between the sealed glass panes. However, argon low-e windows have a greater incidence of glass deflection, resulting in those sunlight focusing concavities. This seems to be because the argon atom is smaller than natural air molecules. Over time the argon gas will escape through the window seal, but since the air molecules are too big to enter and replace the argon, there will be a barometric pressure difference between the interior of the panes and the outside air that can cause glass deflection. So, the prevalent, often mandated use of argon low-e windows in northern states appears to be a factor in the greater incidence of reflected sunlight vinyl siding damage in these areas.

REMEDIATION EFFORTS

Since the factors and conditions that produce the reflected sunlight damage effect can reoccur, just replacing damaged vinyl siding is not a permanent solution. Placing an exterior screen over the offending window has been shown to mitigate the damage effect by diffusing the reflected light and reducing its focus. Or, hanging an awning over the window will prevent the reflection from reaching an adjoining home. But, these solutions generally require the cooperation of the neighbor who owns the reflecting window. At times these neighbors are cooperative, but some are not, and then other remedies must be explored. Blocking the reflected sunlight will eliminate the damage. This can be achieved by planting intervening trees and shrubs, or installing any barrier sufficient to block the reflected light. Some homeowners have experimented with installing an ivied trellis over the vinyl siding to intercept the reflected beam. Also, replacement of damaged vinyl siding with another non-plastic based exterior cladding that can withstand the reflected heat is a solution, but expense becomes a factor with this course of action, and mismatched cladding on the affected side can pose aesthetic objections as well. Replacing low-e windows with less-reflecting clear glass windows is a possible remedy, but depending on the jurisdiction, low-e coated windows could be mandated by the local building code (making the use of clear glass illegal).

CAPILLARY TUBES - Another suggestion for avoiding the reflected sunlight damage effect involves the use of double paned windows equipped with capillary tubes installed during the window manufacturing process. The capillary tube connects the interior space between the window panes to the outside air, permitting a gradual equalization of barometric pressure, and thereby lessening the possibility that a concavity will develop in the glass. Without the concavity in the glass, reflected sunlight is unfocused, its intensity is diminished, less heat is generated, so there is less likelihood that nearby vinyl siding will become distorted.

In the higher altitude Western States, capillary tubes in double paned windows are mandated by manufacturing protocols for homes located at greater than 5000 feet in altitude. The tubes are needed because the reduced outside air pressure found at altitude can result in distorted or cracked window glass. The regional presence of capillary tubes in low-e windows appears to be the reason why there are so few reports of reflected sunlight damage to vinyl siding in the Western States. As evidence, there was a reported incident of vinyl siding distortion damage in the Tacoma, Washington area (elevation below 5000 feet). The builder replaced the original double paned windows (not equipped with capillary tubes) with windows that were equipped with capillary tubes. After replacement, there was no reported reoccurrence of vinyl distortion from reflected sunlight.

Low-e windows supplied east of the Mississippi do not as a practice come equipped with capillary tubes, but builders can request tube equipped windows from the manufacturer. The additional cost of tube equipped windows is said to be nominal, from $0 to $1.00 per window. Many production builders in the east have reported their decision to only use capillary tube installed low-e windows in future construction in hopes of avoiding incidents of vinyl siding damage from reflected sunlight in their developments.

Capillary tubes are not always the answer, however. These tubes cannot be used in argon filled low-e windows. The presence of a capillary tube would allow the argon gas to immediately escape, thereby making that beneficial feature useless. So, if the building code requires an argon gas filled low-e window, the use of a capillary tube is not an option.

DOUBLE STRENGTH GLASS

Double paned windows are normally manufactured with single strength glass 3/32" thick. Double strength glass 1/8" thick is also commonly produced by glass manufacturers, but not routinely used for windows. Double strength glass keeps a flatter surface, and is less subject to deflection. That would lessen the possibility that a concavity will occur in the glass panes, and lessen the chance that reflected sunlight will be focused and cause damage to nearby vinyl siding. Reportedly, there is very little cost difference involved in manufacturing windows with the thicker glass, but to date there has been little manufacturing of windows with double strength glass.

HEAT RESISTANT VINYL SIDING

The Lubrizol Corporation and the Kaneka Texas Corporation each manufactures a CPVC product for use in vinyl siding. CPVC siding is said to withstand heat ranges of 185 to 220 degrees Fahrenheit (normal grade vinyl siding begins to distort at 160 – 165 degrees). The cost of CPVC siding is currently several times that of regular siding, making it non-cost effective compared to other exterior cladding materials. Also, the product is reportedly more difficult to extrude and to mold into siding.

The Vinyl Siding Institute reports that other chemical companies and vinyl siding manufacturers are actively exploring formulation of heat resistant vinyl siding products, but these are undeveloped and not in production.

LIABILITY AND WARRANTIES

To date, there has been no reported litigation concerning damage caused to vinyl siding by sunlight reflected off low-e or other double paned windows. Some attorneys have made demands on behalf of vinyl damaged clients against the owners of offending windows based on public nuisance grounds. At least one homeowner indicated an intent to file a complaint with the Consumer Product Safety Commission based on fire safety concerns. However, there have been no reported instances of fires, and the temperature readings for focused reflected sunlight (less than 250 degrees F.) are well below the combustion temperature of wood – 451 degrees Fahrenheit. The possibility that reflected sunlight poses a fire hazard has been investigated in several states, including Massachusetts and North Carolina, but ultimately discounted. In the future, as the phenomenon of damage to vinyl siding from low-e window reflection becomes more well-known, it may be expected that lawsuits could be filed against architects and builders based on theories of negligent design or construction for failing to anticipate the problem and for failure to make an effort to prevent or avoid this situation.

Home owners with distorted vinyl siding routinely make warranty claims against their builders, the siding supplier, and the manufacturer. For more than a dozen years, vinyl siding manufacturers have included this standard exclusion in their warranties… "This warranty does not apply to siding products… which have been distorted or melted due to an external heat source, including but not limited to a barbecue grill, fire, or reflection from windows, doors, or other objects." Despite the warranty exclusion, if pressed, vinyl siding manufacturers will sometimes offer to furnish replacement siding on a one-time basis, labor not included.

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Pennsylvania Housing Research Center (PHRC)
2nd Residential Building Design and Construction Conference
Penn State University
20 February 2014

TITLE: "*New Methods of Delivery: Prefabrication Strategies in Residential Construction*"

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PRESENTATION ABSTRACT:

Founded in 1998, SHoP has continually sought to improve the design and quality of residential construction by examining methods of delivery and exploring new approaches and technologies. As architects, construction managers, and developers, SHoP has operated in various contractual positions and utilized different scales of prefabrication. Our approach is that prefabrication is not an architectural philosophy, nor defines a style—it is a construction technology, and that when married with the right project team and process, is another tool that can be employed to deliver the highest value to all stakeholders. It is not simply about doing more with less, it is about expanding the opportunities for design. By integrating design, engineering, fabrication, and on-site construction, SHoP works across the entire delivery model to realize the best opportunities for prefabrication. A Virtual Design and Construction process is designed and managed for each project that creates feedback loops between designers and fabricators to help identify and unlock the most value. The additional value can be seen in reduced costs, reduced onsite duration with less impact to the community, higher quality for the tenants, and lower embodied energy. Case study examples of SHoP's use of prefabricated construction solutions include The Porter House, Manhattan, NY; 290 Mulberry, Manhattan, NY; B2 Bklyn Modular, Brooklyn, NY; and a modular brownstone in Redhook, NY.

SECTION 1:

Energy Efficiency, Design, and Retrofit

Adoption Patterns of Energy Efficient Housing Technologies 2000-2010: Builders as Innovators?

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Abstract
The U.S. housing industry is often considered an innovation laggard. Whether because of endogenous or exogenous risks, homebuilding firms have traditionally resisted innovation. However, recent evidence suggests builders' material selections have been growing more innovative—more specifically, these selections have been growing greener. Though little empirical work exists that measures and analyzes such phenomena, the paper will report on a national study[2] of "green building" innovation in residential construction from 2000-2010. This paper asks two research questions: 1) to what extent are builders, if any, adopting higher efficient building products over their traditional economic substitutes? And 2) what are the market, demographic, and regulatory factors associated with homebuilders' green and energy efficient technology selections? The authors analyze data from the National Association of Homebuilders' Builders' Practices Survey (BPS) from 2000 to 2010, estimating a series of logit models focusing on builders' choices to install high performance building technologies including PEX piping, custom sized-HVAC systems, programmable thermostats, and high efficiency insulation. This research builds both methodologically and substantively upon the foundation laid by Koebel et al (2013) and McCoy et al's (2013) work examining builders' choices to adopt high efficient windows and Sanderford et al (2013) paper examining factors associated with the diffusion patterns of Energy Star certification in new homes.

Introduction
Innovation is often noted as a key ingredient in the recipe for creating competitive advantage and distinction among firms as well as for generating new markets for products and processes (Chesbrough et al. 2006; Christensen et al. 2004; Von Hippel 2005). The literature focusing on the diffusion of innovations is rich and covers a diverse range of topics including building science and construction (for a sample of literature see Beal and Bohlen 1957; Beal and Rogers 1957; Bose 1964; Downs and Mohr 1976; Li and Sui 2011; Shields and Manseau 2005; Watts and Dodds 2007).

Over the last twenty years, building science scholars have studied innovation in building construction, predominantly focusing on commercial and large-scale facility creation (Slaughter 1993; Slaughter 1993; Slaughter 1998; Tatum 1987). In fact, a journal (*Construction Innovation)* has been created to continue this scholarship. However, much like previous research, the recent literature in this and other related journals has largely retained a commercial focus (e.g., Habets et al. 2011; Morledge 2011; Wong et al. 2011) or focused on firm size as a predictor of adoption of innovation (Abbot et al. 2006; Hardie and Newell 2011).

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[2] This research is supported by US Department of Housing and Urban Development Grant # 10814146, *Impact of Market Behavior on the Adoption and Diffusion of Innovative Green Building Technologies*. All opinions are those of the authors and not HUD.

A growing portion of the construction innovation literature has cropped up around residential construction and housing technologies. Supported, in part, by programs such as the Partnership to Advance Technology in Housing (PATH), a joint effort between the Department of Housing and Urban Development and the National Association of Homebuilders, the segment of the literature has helped provide insight into how innovation blooms and can best be supported in housing and homebuilding (Blackley and Shepard III 1996; Bradshaw II 2011; Koebel 1999; Koebel 2008; Koebel and McCoy 2006; Koebel et al. 2004; Manseau and Shields 2005; McCoy et al. 2010; McCoy et al. 2008; Toole 1998).

Historically, in the construction innovation literature, the homebuilding industry (and by extension the builder) has been considered an innovation laggard—or the last of Rogers' classifications of adopters to take up new ideas and products (Gann and Salter 2000; Rogers 1995; Woudhuysen and Abley 2004). Based on the homogeneity of homes, volumetric production, assembly risks, and the fact that most innovations are hidden behind walls, this attribution is not unfounded or regularly inaccurate. The builder essentially plays the role of the assembler, stitching together various housing components. They bear a significant amount of risk, as they are required to assemble these technologies according to building code and manufacturer specifications. They must also intermediate the needs and preferences of the end user—all while earning a return sufficient enough to continue playing their part in this (somewhat) theater of absurd expectations. However, as innovation has been observed to play a role in creating competitive advantage for firms, homebuilders may adopt innovations that allow them to earn a superior return as compared to their less innovative counterparts.[3] At present there is a limited understanding of the market, policy, firm, climate, product, and industry characteristics that are associated with a builder's choice to adopt innovative technologies in housing.

This paper is part of a larger research project by a team of researchers at Virginia Tech. The goal of the project is to develop a deeper understanding of the factors that help explain the geographic and temporal variation in adoption and diffusion rates for various green housing technologies. For a description of the larger project and a detailed literature review, see (McCoy et al. 2013). Papers by team members have reported on national studies of the diffusion of innovation among home builders and production home builders respectively (Koebel 2008; Koebel and McCoy 2006); the diffusion of high efficiency insulation products (Sanderford et al. 2013); the commercialization of innovation in residential construction (McCoy et al. 2010); the diffusion of green certification (Energy Star) in new housing (Sanderford et al. 2013); the role and importance of high efficiency performance in green certification standards (Nikhoo et al. 2012); the impact of valuation models on the Moore's Chasm challenge for green building (Sanderford et al. 2013; Sanderford and Pearce 2013) and the application of Agent Based Modeling to develop diffusion scenarios (Rahmandad et al. 2013) based on the empirical results reported herein.

Differentiating itself from previous literature and its broader research project, this paper asks two research questions: 1) to what extent are builders, if any, adopting higher efficient building

[3] Architectural historian Bar Faree once remarked that, "a *building* must pay, or there will be no *investor* ready with money to meet its cost." While he was talking about the decision to build taller skyscrapers with fewer rentable floors, his logic carries for builders and housing. Builders constantly must assess what types of units they know they can sell. Where an innovation creates a risk relative to the potential sale-ability of a home, it must be scrutinized carefully. In the US, the appraisal process tends to be based on a comparable sales analysis. Where there is sufficient data about a home and others with similar attributes, the appraiser can easily distinguish the contributory value of the attribute to the estimated market value of a home. However, as there often is limited data available in the housing data about the presence of various innovations, appraisals can be confounded—reinforcing innovation weary behavior of builders.

products over their traditional economic substitutes? And 2) what are the market, demographic, and regulatory factors associated with homebuilders' green and energy efficient technology selections? The authors analyze data from the National Association of Homebuilders' Builders' Practices Survey (BPS) from 2000 to 2010, estimating a series of logit models focusing on builders' choices to install high performance building technologies including PEX piping, custom sized-HVAC systems, programmable thermostats, and high efficiency insulation. This research builds both methodologically and substantively upon the foundation laid by Koebel et al's (2013) work examining builders' choices to adopt high efficient windows. Based on Koebel's findings this paper also makes some observations on the long-held view that builders are innovation laggards.

Literature Review

Detailed reviews of the housing innovation and green housing technology diffusion literature can be found in (McCoy et al. 2013; Sanderford et al. 2013). This short review focuses on the literature conducted around three themes in housing innovation: energy efficiency, eco-labels or green building certifications, and high performance housing technologies. We focus on these themes, as they are some of the key building blocks of innovation that drive increased environmental performance and are connected to increases in housing value.[4] The authors noted when diagramming this paper that there were blunt parallels between our work and the stories of first generation Blackberry and iPhone consumers buying the devices with the sole intention of smashing them open to examine its unique arrangement of components. While the metaphor has limited utility, the notion that technologies are the building blocks of increased performance was rather useful in this paper's development.

Germane to the broadest of the three themes, energy efficiency, the literature offers a wide range of highlights. Scholars have shown that there are health benefits that can be generated through the use of various types of building insulation that also increase the operational efficiency of the home (Chapman et al. 2009; Howden-Chapman et al. 2007). Additionally, research indicates that the internal temperature and relative humidity of a home are key metrics that can help frame a builder's or occupant's decision to upgrade housing technologies to their more energy efficient economic substitutes (Milne and Boardman 2000). Further, understanding the needs and preferences of the occupant are central to matching innovative technologies and market opportunities (Crosbie and Baker 2010). In a Swiss study of more than one hundred fifty apartments, owners of these housing units showed a strong and significant preference for upgrading to energy efficient technology options (Banfi et al. 2008). Koebel et al (2013) suggest that builders in larger markets with higher incomes, larger networks of builders, and supportive public policy are more likely to choose energy efficient window options over less efficient options (Koebel et al. 2013). Devine and Bond (2013) confirm Koebel's results showing that with respect to green homes, communities with supportive public policy have stronger associations with new green home construction (Devine and Bond 2013).

The housing markets appear to have recognized the value of innovative energy efficient housing technology choices. In California, homes with solar panels commanded a price premium over similar homes without them (Dastrup et al. 2012). Similarly, based on sample of home sales in Texas, homebuyers paid a premium for homes with more energy efficient windows (Aroul and

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[4] Primarily, the authors assume that green and energy efficient building technologies qualify as innovations as they meet many of the definitions offered across the literature. See Sanderford, Koebel, and McCoy (2013), a working paper, for a more in-depth discussion of the alignment of the definition of innovation and green building technologies.

Hansz 2011). Buyers also appear willing to pay more in some markets for homes with eco-labels such as Energy Star or Green Point (Bloom et al. 2011; Kok and Khan 2012). However, as energy literacy has been observed to be rather low (Brounen et al. 2011), more scholarship focused on the interaction of people, markets, and energy efficiency is needed. Sanderford and Pearce (2013) confirmed this need via a survey of residential real estate appraisers with green home valuation training. Across this elite group, there was not a standard method of valuation for energy efficient homes (Sanderford and Pearce 2013).

Researchers have also turned their focus towards the diffusion of green building certifications into property markets. Simons et al (2009) and Kok et al (2011) both examined the spatial and temporal diffusion patterns of green building certifications in the commercial office market (Kok et al. 2011; Simons et al. 2009). Both papers suggested that, vis-à-vis office buildings, climate, and public policy are critical factors associated with the diffusion of Leadership in Energy and Environmental Design (LEED) and Energy Star certifications. Kok et al. also provided clear evidence that market and industry characteristics also played a significant role in the diffusion of these certifications (Kok et al. 2011). Sanderford et al. (2013) analyzed the same problem in the housing markets by exploring the factors associated with the choice to certify new homes via the Energy Star program (Sanderford et al. 2013). This paper showed that many of the same factors that explain the diffusion of eco-labels in the office market have analogs in the housing market. Kontokosta (2011), Simcoe & Toffel (2011), and Choi (2009) each examined the diffusion of green building public policies into property markets (Choi 2009; Kontokosta 2011; Simcoe and Toffel 2011). Simcoe & Toffel's work suggested a very interesting finding; that when using a coarsened exact pairs matching protocol, communities with green public procurement policies tend to see positive spillover effects (higher concentrations of green office space) than a city with similar demographic characteristics (Simcoe and Toffel 2011).

Recent research indicates that the number of patents for renewable energy technologies has grown substantially (Altwies and Nemet 2012; Johnstone et al. 2010; Johnstone et al. 2012). Similarly, an exploratory paper presented last year at this conference showed that builders' use of green and energy efficient technologies is growing (Nikhoo et al. 2012). Building from that initial work, McCoy et al. (2013) framed a general model to analyze the diffusion of high performance housing technologies in the homebuilding industry (McCoy et al. 2013). This paper specified a binary model based on builders' choices to use or not use a high performance technology as well as the factors potentially associated with that choice. Koebel et al. (2013) operationalized and refined that model specification relative to highly efficient window options (Koebel et al. 2013). The paper showed strong associations between builders' choices to adopt the high efficiency window option and the presence of green focused public policy, climate, market characteristics, and firm characteristics. The paper presented here distinguishes itself from the two streams of research described above in that it extends the investigation started by Koebel et al. (2013) into other high performance housing technologies (e.g., insulation, piping, and climate control).

Data and Methods of Analysis
To answer the proposed research questions, the authors used a very similar dataset based on the same set used by Koebel et al. (2013) in their analysis of windows. Using the majority of the same dataset used by Koebel and his colleagues, we appended a few additional variables (described below). We analyzed a large national data set covering nearly 29,000 builders from the Builders' Practices Survey (BPS), an annual survey conducted by the National Association of Homebuilders Research Center (NAHB RC). The BPS is designed to capture builders' usage patterns of new residential construction projects across nearly 1,100 product types and over 40 clusters of products. McCoy et al. (2013) discuss the development of the dataset for analyzing

builders' use of innovative green construction products from 2000 to 2010 incorporating local, state, and regional level data for industry characteristics, local market characteristics, and public policies. The BPS data are collected through an annual mailed survey to builder members of the NAHB. Respondents reporting zero homes built in a year were dropped from the analysis dataset, as were respondents from Alaska, Hawaii, and US territories. The respondents cannot be considered a random sample of the universe of homebuilders. However, the respondents reflect the state-by-state distribution of builders reasonably well. A comparison between BPS respondents and the number of homebuilders reported in County Business Patterns in randomly selected years of the analysis window had an average coefficient of determination of .7 indicating sufficient similarity between the distributions (McCoy 2013, Koebel 2013).

The BPS includes product use within the housing types of Single-Family Detached (SFD), Single-Family Attached (SFA), and Multi-Family (MF) at the unit of analysis of the builder firm (typically an individual survey respondent). The BPS data do not contain any information about the characteristics of the firms beyond the city and county of the respondents' addresses and summary measures of the number, size, building type, and price of the housing units built during the previous year. The data are non-longitudinal since respondents cannot be linked over time. The data set is the largest of its kind and unique in its integration of industry, market, and public policy measures (Koebel et al. 2013).

As this paper is part of a larger research effort to investigate the diffusion of innovative technologies into the homebuilding industry, we borrow heavily from previous working papers published by members of the research team. To help select the high performance technologies investigated in the models below, the team leaned on the clusters of high performance housing technologies identified by Nikhoo et al. (2013) and McCoy et al. (2013). Where as Koebel et al. (2013) analyzed the diffusion of high performance windows, this paper investigates the diffusion trajectories and factors associated with those trajectories for high performance water distribution piping, heating systems, cooling systems, insulation, and programmable thermostats.

These previous papers also created six categories of characteristics influencing high performance product adoption by builders: Market Area (categorized at the Core Based Statistical Area or CBSA level), Product, Industry, Firm, Public Policy, and Time. Firm characteristics reported in the literature include size; organizational capacity and human resources; R&D investment; and presence of technology champions.

In place of the traditional S-Curve models used to estimate the parameters for the diffusion trajectory, the authors opted for a dichotomous choice model where time is modeled as a potential factor influencing adoption. The dependent variable for each of the products evaluated in this paper is specified in binary form—reflecting whether or not a builder respondent in the BPS indicated use of a high performance product.

To analyze how external parameters surrounding this change support a general shift towards environmental performance as a central component of diffusion in the homebuilding industry, we fit a logistic regression model for the dependent variable representing the choice by a builder to use or not use a high efficient window option. The dependent variable is specified so that 0 describes use of the alternative cluster of products and 1 describes the use of a product in the high-efficiency product cluster (e.g., PEX piping). The generic logistic regression used for the base of this analysis is:

$$ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k$$

where p indicates probability of technology usage, β_0 denotes the y intercept, and x_i and β_i represent ith predictor variable and regression coefficient, respectively for $= 1, \ldots, k$. Logistic regression is a popular technique to predict binary outcomes (such as use/non-use) as a function of multiple variables, because the resulting usage percentages are correctly constrained between 0 and 100%. For more details, see Agresti (2002).

The modeling approach taken in this paper is similar to Koebel et al. (2013) where both the dependent variables and independent variables are similarly functionally specified and analyzed.

Based on the generic logistic regression function above, the functionally reduced form of the general model presented here is:[5]

$$Use\ of\ High\ Perf\ Product_n \left(\frac{P_n}{1-P_n}\right) = \mu + \beta_1 + \beta_2 + \cdots + \beta_7$$

where n = one of the five high performance products, μ is the y-intercept, and β_x are:

1. Time
2. Firm Characteristics
3. Market Area Characteristics
4. Product Characteristics
5. Industry & Labor Supply Chain Characteristics
6. Public Policy
7. Climate

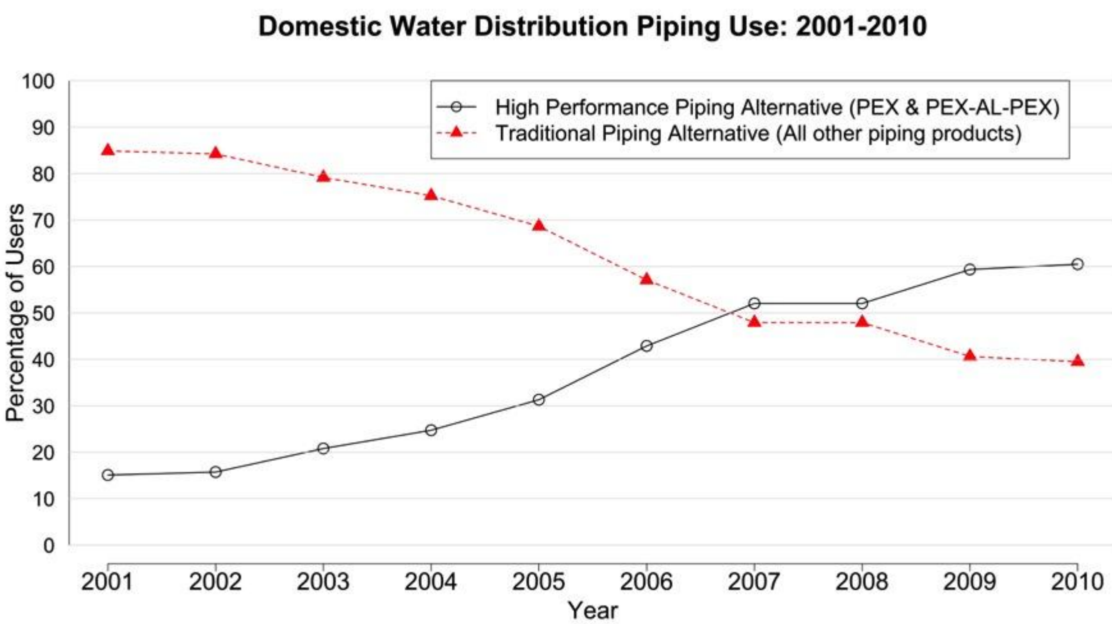
The dependent variable for each of the five models included in this paper represents choices by respondent builders in the BPS indicating use of a particular high performance technology in a particular year. Where the models are all dichotomous choice analyses, when a respondent indicated use of a high performance technology, their response was coded as a one. All responses that indicated use of other technologies in the same year were coded as a zero. Framing the dependent variable in this manner allows for comparison of economic substitutes. For example, we intend to analyze a builder's choice to use high efficient HVAC components and in one model use the decision rule that the efficient product is a 13 SEER or higher cooling unit versus the other choices of 12.9 and lower SEER units. Similar distinctions were made amongst economic substitute products in the BPS for each of the other dependent variables.

The authors gathered the independent variables at the geography of the CBSA or State and merged to the BPS data based on a cross walk file based on the U.S. County identified by the BPS respondent. For example, if the respondent indicated their primary area of business as Albemarle County, Virginia, independent variable data not drawn directly from the BPS was assigned based on the Charlottesville CBSA that includes the independent City of Charlottesville along with Albemarle, Fluvanna, Greene, and Nelson counties. Where CBSA boundaries crossed state lines, any state level was merged based on the state of the primary city/county of the CBSA. The models tested a similar set of independent variables used in Koebel et al. (2013) and Sanderford (2013), two papers where high performance windows and housing certifications were analyzed.

[5] This general model is deployed for each of the high performance technologies to be analyzed. Each technology is analyzed in the context of its economic substitutes and not among its economic complements as part of a cumulative choice to use model.

Reflecting the precedent set in Koebel et al. (2013) and Sanderford et al. (2013) and the broader econometrics literature, this paper analyzed time as both a continuous variable and as a dummy variable. Both specifications of time are examined to make certain that any effects are adequately described. This approach is substantively different from the most recent similar paper (Kok et al. (2011)) where time was modeled as part of the dependent variable—the change in the ratio of eco-labeled buildings from year to year.

From within the BPS, the team gathered the Firm characteristics. These characteristics included firm size (using number of houses built annually as a proxy), and organizational capacity based on diversity of operations spanning residential building types that include multi-family housing. Product characteristics include the per unit price of the high performance technology, a ratio of the cost of the high performance technology to the cost of the less efficient substitute.[6] Additionally, Firm characteristics include measures of the firm's average housing unit size and average sales price.

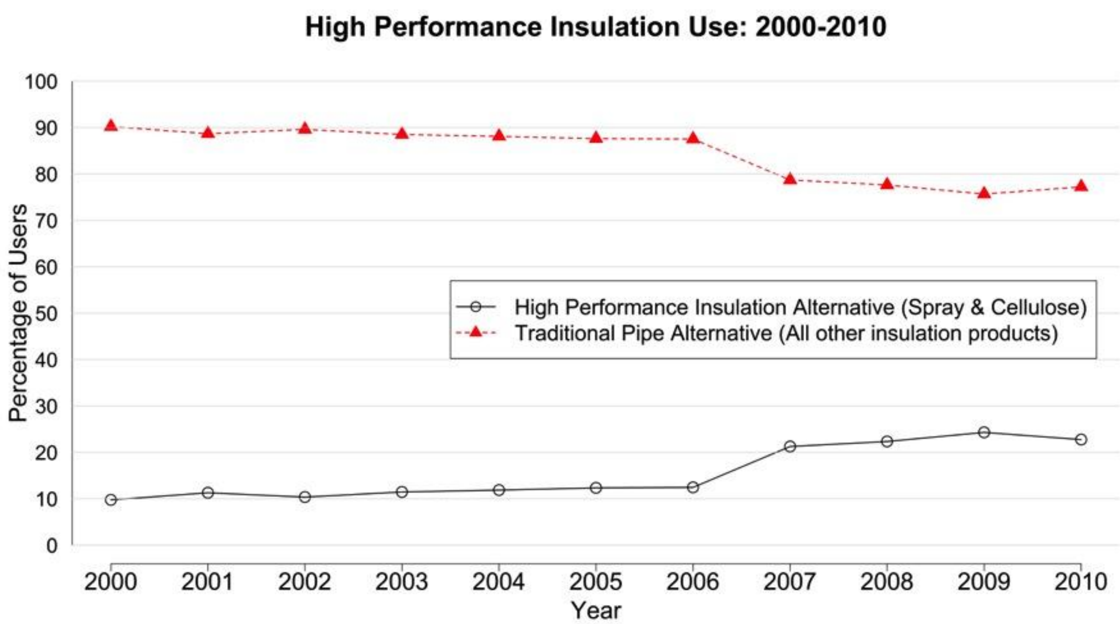


Based on the Census' County Business Patterns data for 2002, 2006, and 2010, the team included Industry characteristics noted in the residential construction literature such as concentration, supply chain, subcontractor networks, and efficiency. Based on the dependent variable, the authors substitute different sub-contractor specialties. For example, Siding and Framing Contractors were used in Koebel's windows model. Relative to the Piping model here, the authors will replace the Siding Contractors with Plumbing Contractors (and use the appropriate sub-contractor for each of the remaining technologies). To ensure appropriate alignment of the sub-contractor specialty with the dependent variable, we crosschecked the North American Industry Classification System (NAICS) codes with the tasks performed under each code.

[6] This ratio variable should be considered a relative advantage of cost indicator. A value of 1 would indicate price parity between the high performance and less efficient options. A value greater than 1 would indicate that the high performance product is more expensive than its substitute.

Drawn from the US Census' Summary Files, market area characteristics include CBSA level measures for population size, income and wealth (median income and median house value), density of housing units per square mile, and location within a network of market areas as an indicator of the potential for contagion effects—a distance decay function described in McCoy et al. (2013). Public policy measures captured the funds expended through the American Reinvestment and Recovery Act (state level), green building certifications, utility rebates, state grants, and a variety of other state and local incentives for energy efficiency. Based on the broader housing and taxation literature, the models in this paper also include state sales tax and other related business costs (e.g., workman's compensation premium rates). Additionally, the models contain a variable that measures the average cost of construction by CBSA.

Climate is modeled in this paper as the thirty-year average of the respondents' state heating and cooling degree-days both independently and also as an interaction. Across most of the energy efficiency and building performance literature (e.g., Kok et al. 2011), climate is a substantial factor that helps explain the geographic variation in the diffusion of green building rating systems and building technologies.



Anticipated Results

Based on the findings from the papers used to guide the formation of these models, the team anticipates the following associations between predictor and response variables. The expectation is that each of the models will present coefficients with similar signs to those found in Koebel et al. (2013). Where noted in a separate color, we expect the coefficient signs to align more closely with Sanderford et al. (2013). With respect to the GDP variable, we expect that the adoption patterns of these technologies will more closely track the broader green real estate and construction literature that tends to show positive associations between economic output factors and green durable goods.

Table 1: Expected Coefficient Signs by Technology Specific Models + Reference Models

Variable Description	PEX Piping	Insulation	Heating: High Efficiency	Cooling: High SEER	Programmable Thermostats
YEAR	+	+	+	+	+
Price of HP Technology	+	+	+	+	+
Total # of Homes Built	-	-	-	-	-
Respondent Also Built Multi-family units	-	-	-	-	-
Weighted Avg Square Footage	+	+	+	+	+
Total Population in 2010 by CBSA	-	-	-	-	-
Weighted Avg Price of Homes	+	+	+	+	+
ARRA Funds Per Capita	+	+	+	+	+
Gravity Index-Network Effects	+	+	+	+	+
Total # of Construction Wholesalers in 2010 by CBSA	+	+	+	+	+
Median Home Value in 2010 by CBSA	+	+	+	+	+
Median Household Income in 2010 by CBSA	+	+	+	+	+
GDP Per Capita in 2010 by CBSA	+	+	+	+	+
Heating Degree Days 30Year Avg	+	+	+	+	+
Cooling Degree Days 30 Year Avg	+	+	+	+	+
HDD x CDD	+	+	+	+	+
Total Number of Tech Specific Sub-Contractor in 2010 by CBSA	-	-	-	-	-
Total Construction Cost in 2010 by CBSA	-	-	-	-	-
Weighted Average of State Workers Comp Premiums in 2010	+	+	+	+	+
Insurance Premiums by Work Division in 2010	+	+	+	+	+
State Sales Tax in 2010	+	+	+	+	+
DSIRE: Total # of Rebates From Utilities	+	+	+	+	+
DSIRE: Total # of Grants by State & Local Govt	+	+	+	+	+
DSIRE: Total # of Other Energy Incentives	+	+	+	+	+
Avg Price of KWH: 2006-2011 by State	+	+	+	+	+
Median Year Structure Built in 2010 by CBSA	+	+	+	+	+
Percentage of CBSA Population with College Education in 2010	+	+	+	+	+
Percentage of Owner-Occupied Homes in 2010 by CBSA	-	-	-	-	-
Dwelling Unit Density in 2010 by CBSA	-	-	-	-	-

Denotes expected difference from Koebel et al (2013) findings

With respect to the climate interaction variable, the expectation is that as the climate in a State is more diverse and variable, the more likely a builder is to adopt any of these technologies. There is the complicating factor of whether or not the interaction will be significant or not. Where it was in Sanderford et al. (2013), it required the authors to discard the main effects of the individual variables.

Builders As Innovators

Based on research produced over the last ten years, it appears that the idea of the builder lagging behind others in the housing creation chain is losing its luster. Instead of considering builders as innovation laggards, researchers are able to 1) use increasingly more robust data to analyze around the decisions builders make about the choice to adopt innovative technologies, 2) deploy best data management practices and analytical methods in processing this data, and 3) see more clearly the continuous innovations that have been made in individual products assembled by the builder. So, where scholars can ask new questions of new data, it appears that they are finding that builders are not necessarily innovation laggards—especially with respect to green and energy efficient technologies. Instead, one theme that appears to have emerged from building construction innovation is the builder as a selective risk taker. As the builder is an assembler of various components, they are a rather different agent than typically analyzed in information technology or other areas of innovation research. The builder as the assembler is not responsible for creating the innovations but rather identifying and safely combining innovations that work together in systems to meet the needs of the occupant/buyer. These are influenced by market conditions, the availability of credit, qualified appraisers, climate, and a number of other complicating risk factors. Where innovations such as green certifications have been shown to reduce some of the market and performance risks in housing, we see builders moving towards these innovations. So, the builder as an innovation laggard may, at one time, have been a useful paradigm for the construction industry. However, where this paradigm often paints all builders with a broad brush, we find evidence that in some cases, builders are using more innovative products than traditional products (Koebel et al. 2013). In fact, as building science scholars adapt best research practices from their counterparts in information technology (e.g., patent analysis—see (Altwies and Nemet 2012; Johnstone et al. 2010; Johnstone et al. 2012), the prevailing notion of the builder as laggard may begin to crumble.

Next Steps and Limitations of Approach

The next steps for this project are to conduct the logistic regressions described above and to interpret the results. Differences between the model findings will be of significant interest as will differences between the model findings and those from Koebel et al. (2013). These differences will be of significant interest as the general model used here was adopted based on the model selection outcome from Koebel et al. (2013) where seven candidate models were pitted against one another using a 'least absolute shrinkage and selection operator' (LASSO) protocol. LASSO is an analytical technique that shrinks some coefficients in a regression model and sets others to zero in an attempt to retain the good features of both subset selection and ridge regression (Tibshirani 1996). Koebel et al. used the LASSO technique as part of their cross validation strategy and to select the most competitive diffusion model. In lieu of replicating the cross validation and LASSO processes, we have adopted Koebel's model specification here as it represents the most advanced model within the extant literature. While we have no reason to suspect that this model specification is incomplete as it has been rigorously tested and aligns with Rogers' classic diffusion indicators, we remain cognizant that the Koebel's model was specified on high performance window data. To the extent that the products analyzed in this paper are different with respect to adoption and diffusion, these differences could create the possibility for mis- or under-specification.

Two additional limitations of the approach taken here are 1) the embedded researcher bias in selecting the green and energy efficient technologies and 2) the degree of subjectivity about which products do and do not meet a definition of high performance. With respect to the first limitation, we selected the technologies analyzed here based on a review of the frequency and reliability of their response patterns. Further, each of these technologies was selected because of its growth in adoption over time. For example, we did not include a model analyzing the factors associated with Structural Insulated Panels (SIPS) on account of that product's flat adoption trajectory (growth from 0-3% and sustained use at the upper end of that range over the study period). Each of the technologies analyzed here exhibited an adoption trajectory that moved from a small initial value to a significantly larger value by the end of the study period. Further research will examine innovative products that have market trajectories akin to SIPS. However, for the sake of brevity we will address that analysis in a separate paper. With respect to the second limitation, we relied on previous methodologies and subject area expertise from the building scientist on our research team to help attenuate risk. The most recent methodology for selecting technologies based on the traditional-high performance distinction, we adapted Koebel et al.'s model focused on windows where the window's ability to moderate the tightness of the building envelope and reduce heat transfer were the characteristics of most importance. Where we could select technologies based on their ability to reduce air infiltration or reduce heat transfer we chose products with the most advanced scores, ratings, and characteristics. Where we couldn't, the decision focused on the upper end of a performance range. For example, air-conditioning units with a 13 or higher Seasonal Energy Efficiency Ratio (SEER) rating as high performance while all SEER ratings 12.9 and below were considered to be traditional alternative.

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An Effort to Refine Regional Energy Assessment Methods in Support of Energy Auditors to Increase Assessment Accuracy and Consumer Confidence

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ABSTRACT

More than 60% of occupied homes in the U.S. were constructed before 1980, often wasting up to 60% of the consumed energy due to building envelope and systems deficits. Homeowners spend billions of dollars annually on energy bills, and there is a potential to dramatically reduce this expenditure. This return can be achieved through energy retrofit solutions applied to homes. Decisions to pursue a retrofit action in a home are commonly based upon energy assessments provided by auditors, who utilize a mix of diagnostic tools, inspection strategies, evaluation practices such as the blower door test, and energy modeling simulations. Although a variety of energy assessment methods are available today to help identify the most promising retrofit opportunities, many barriers and issues still exist for homeowners to take action. One significant factor contributing to a lack of retrofit decision-making by homeowners is the reduced confidence based on the accuracy of energy assessments, which often miss the actual energy consumption by far. This study investigated the current energy assessment methods used by energy auditors in Southwest Virginia in order to reveal insights into their strengths and struggles when conducting assessments and reporting results to homeowners. Energy auditors from four companies who conduct energy assessments were shadowed on routine audits and subsequently interviewed. As a result, common strengths and struggles were identified regarding the processes of individual auditors, the larger local energy assessment community, and the national energy assessment industry in general. The findings identify opportunities for refinement on a regional basis, and areas for additional research towards improving energy assessment accuracy, increasing stakeholder confidence, and promoting more active retrofit decision-making. This study is an initial local effort to potentially create compatible solutions on a nationwide scale.

INTRODUCTION

According to United States (U.S.) Census data, approximately 61% of homes in the U.S. were constructed before 1980. Of these homes, 60% of the energy used by them for heating and cooling is lost due to leaky ducts, inefficient equipment, poor insulation and air leaks (ETO 2008). The U.S. Department of Energy reports that only 20% of the homes built before 1980 are well insulated (DOE 2011). The issues concerning the current energy performance in many older existing homes are emptying homeowner's pockets, spending a reported 118.86 billion dollars annually on energy (EIA 2005). As new technologies and consumption items continue to enter the market and are then subsequently found in homes, residential housing energy consumption is inevitably expected to continue to increase in the future.

The high number of homes built before 1980, which would benefit most from residential retrofitting, provides an opportunity not only for the homeowner, but also for other involved stakeholders in spurring small businesses such as auditors, contractors, and home builders/retrofitters. In a report prepared by the White House Council on Environmental Quality (CEQ) identifying the key barriers to the home energy retrofit market, it was proposed that home energy efficiency retrofits have the potential to reduce home energy bills by 21 billion dollars annually, ultimately paying for themselves over time (CEQ 2009). The potential business gained by auditors, contractors, and builders through retrofitting can grow similarly as the demand for retrofits increases.

New technologies and strategies are being developed and refined that can reduce the energy consumption of homes while also aiming to reduce their impact on the environment. Homes use approximately one fifth of the total energy consumed in the U.S., and this figure has been increasing steadily since 1985 (USGBC 2011). This shift in consumption could be due to other sectors being more proactive in saving energy, or an increased growth in housing compared to other sectors, such as transportation. The total energy consumed by homes in the U.S. as stated above does not yet take into account the energy used for transportation, production, and other associated processes with manufacturing of materials and equipment that is used in the residential construction industry, which would raise that fraction significantly. The various technologies, products, incentives and techniques being developed and used in today's residential energy efficiency market can reduce energy consumption by means of insulation, increased efficiency of heating and cooling systems, appliances and household plug-loads, and many other ways, all of which can lead to substantial monetary savings due to improved energy performance. With all these available resources and incentives, why are many homeowners not taking advantage of home retrofits and reaping the rewards? One possible problem could be the step prior to retrofitting the actual spaces, the diagnosis. This problem refers to the assessment results a homeowner receives from an energy audit of their home, which identifies deficiencies and areas for improvement in their homes energy performance. For example, if these assessed and/or simulated results differ significantly from the homeowner's actual energy consumption, the confidence in any retrofit suggestions and associated savings proposed by a tool or auditor may be very low. In other instances, where a discrepancy is not identified, a homeowner might draw wrong conclusions and invest in less profitable scenarios, and subsequently portray energy efficiency measurements as unreliable to a broader public as shown in numerous blogs and comments provided on sites such as GreenBuildingAdvisor.com.

Residential energy assessments face various issues, which in turn has contributed to homeowners reduced confidence in energy assessments and a lack of retrofit decision-making. These problems range from inefficient and inaccurate auditing practices and tools, differing opinions and perceptions from auditors, and auditors that are not properly trained (DOE 2011). Current methods in home energy assessments can lead to failures such as lower-than-expected savings, no savings at all, and in some cases even higher energy use (Shapiro 2011). Previous studies have investigated energy auditing practices and identified some common issues that contribute to inaccurate assessment results and failed retrofits (EAI and CSG 2009, Shapiro 2011). This includes factors such as a misuse or lack of appropriate tools, complicated housing characteristics, limited budgets, time-consuming assessment activities, and communication issues with homeowners.

With various difficulties being experienced by auditors and the prevalence of problematic assessment tools and practices, this leads to a lack of reliability in retrofitting and its promise of energy and monetary savings in return. The time and money spent on auditing homes also serves as a hindrance towards retrofitting, with many homeowners not wanting to invest in a process that could potentially lead to no earned value. Therefore, in order to solve these problems, one must investigate what energy assessment methods are most effective, and what can be improved that will benefit residential retrofitting processes and all involved stakeholders. Homeowners should be saving money and lowering their energy consumption. They look at their large energy bills but do not know what to do first to achieve savings. In hope of finding answers homeowners then turn to auditors. The auditor's task to accurately assess the current consumption of a home is made especially difficult due to the vast selection of assessment methods to select from, many of which being identified, or speculated, as unreliable. Reassurance and refinement in residential energy assessments is a must.

BACKGROUND

Residential Energy Audit Tools and Practices. Typically, an energy audit scenario starts with a homeowner reaching out to an auditor to assess their home's energy performance. The auditor then asks the homeowner to gather information about their home, such as various home characteristics, occupant energy use patterns, existing problems, and in some cases, annual utility bills. The auditor will use this information in assessing the home using various physical and/or a combination of virtual energy assessment tools (energy modeling tools) and practices. Some of the most common in-field tools used by auditors are Blower Door Tests, Thermal Imaging (using infrared cameras), and PerFlurocarbon Tracer Air Filtration Measurements (DOE 2011). These tools are used to detect air leaks, measure pressure differences and airtightness, and also detect areas where heat loss is occurring throughout a home.

Auditors also conduct exterior and interior inspections of a home to identify key features required when making energy assessment calculations. These features can include items such appliance models, lighting types, windows and doors types and orientations, and foundation type.

The three main groups of parameters that are to be measured during an energy audit using the previously mentioned tools and practices, include parameters involving the heat exchange through the building envelope, which includes the floors, walls, ceilings, and windows and doors; parameters involving the internal heat produced by occupant activities, lighting, and appliances; and parameters dealing with the energy supply for thermal comfort and building services, which includes HVAC systems and hot water generation/storage systems (Chen 2010). Infiltration, which is uncontrolled air leakage through the building envelope, is assessed by Blower Door Tests, and is an important influence parameter for evaluating the building envelope system performance. It affects the air exchange rates in a space, and through related heat gains and losses it directly influences heating and cooling requirements. On the other hand, the required amount of ventilation (controlled/conditioned air-exchange) that a space needs to achieve indoor air quality also impacts the heating and cooling demand in a home.

Typically, an energy audit is conducted on a home often with only limited knowledge of what the main issues are in respect to energy performance. Building characteristics, influence parameters, and occasionally some knowledge about the cost and consumption patterns of energy use by the occupants are provided to the auditors and are consequently used to assess the energy performance and deficiencies of the home. This is done under the constraints of limited time, resources, and budget. The results of the audit are subsequently communicated to the homeowner, who will use that information, to decide whether or not to retrofit certain elements of their home. The cost to perform an energy audit varies as it depends on a number of factors, including the tools and practices used, the size of the dwelling, and the overall time spent conducting the audit. In some areas around the country funding is available to support energy audits through government and local energy programs and incentives.

Energy Simulation (Modeling). Several simulation models and tools have been developed and are currently in use that aim to assess an entire home's energy performance, and some also provide recommendations for retrofit improvements in a more or less uniform way. The accuracy of the recommendations can vary based on several factors such as the inputs included and parameters evaluated.

Computer based energy modeling audit tools are commonly used off-site in conjunction with on-site tests performed. These tools are intended to help with the decision making process when it comes to improving a home's energy efficiency. Two important aspects that these calculators must take into account when providing assessments for retrofit decision-making are the homes physical characteristics and occupant use patterns. Capturing this information within these tools can be complex, and can in turn contribute to unreliable results. Occupant use patterns are more important for user specific decision-making, and can perhaps be omitted for performance based, or purely asset based, ratings and evaluations. It has been concluded from various studies that including occupant use behavior in a simulation tool, and energy assessments in general, can significantly increase the accuracy of an assessment, as well as increase the motivation for homeowners to seek an energy assessment on their home (Clevenger and Haymaker 2006); (Ingle, Moezzi et al. 2012); (Durak 2011). Asset based modeling tools such as EPS Score, a modeling tool currently piloted in energy block programs in Southwest VA, or assessments that include a minimal amount of occupant use behavior data, can cause key assessment criteria to be overlooked or distorted. This is an important consideration when selecting assessment tools to make sure a misuse is avoided, specifically when asset based modeling tools are utilized to make user specific retrofit decisions. In a report prepared for the DOE, common traits and factors that appear to influence the success of home energy retrofit decisions based on energy assessment results were investigated. One of the conclusions made from the study was that current energy assessment tools and practices are not designed to detect behavioral patterns (Lancaster, Lutzenhiser et al. 2012).

Other recent studies have investigated and debated the accuracy of various energy modeling tools such as Home Energy Saver, REM/Rate, and TREAT (SENTECH 2010, Parker, Mills et al. 2012). It was concluded that many energy modeling tools do not accurately capture data important to producing accurate assessment results.

Increasing the accuracy of energy assessments while also reducing and/or eliminating many of the common problems with energy assessments is the research task that needs to be addressed. Investigating what is available, what works, and possible solutions for improvements are the first necessary steps in this process.

STUDY GOALS & OBJECTIVES

The purpose of this study was to investigate current energy assessment tools and practices being used prevalently today, with a regional focus on Southwest VA to exclude climate diversity issues. The goal was to identify ways in which energy assessments in this region can be improved and become more effective and can lead to increased retrofit decision-making. A literature analysis has identified a need for improved accuracy in energy assessment tools and practices to communicate more reliable results and recommendations to homeowners and retrofitters. There are an abundance of available tools and practices that can be used for home energy assessments, and many others being developed, but very few have proven to provide utmost confidence in their accuracy leading to retrofit actions.

This study involved two main objectives: first, to identify key issues in current industry energy assessment methods, and second, to identify the strengths and struggles experienced with various energy assessment tools and practices used by local energy auditors. The objectives combined the use of three methodologies, which included an initial literature analysis, followed by shadowing energy auditors on routine energy assessments, and finally conducting semi-structured interviews with the same auditors thereafter.

METHODOLOGY

Literature Analysis. A literature analysis has been conducted to compile a comprehensive list of research studies representing the status quo on issues around assessment tools and practices.

Shadowing. Shadowing is an observational technique used to collect qualitative data. It involves following and observing a subject performing particular tasks and/or their day-to-day activities to gather data for research analysis. Data collection techniques associated with shadowing can also involve note-taking, informal questions and answers, as well as in-depth informal observation. Informal observation is an observational approach that is less structured, allowing the observer considerable freedom in what information they choose to gather from informants and how they wish to proceed with it (Robson 2002).

Shadowing can help the researcher to gain a sense of what actually happens rather than what should happen (Gill 2011). It is a useful data collection technique, specifically towards institutional ethnography, which is an exploration of people's social relations that structure their everyday lives and can be used to help increase efficiency and productivity (Quinlan 2011). Quinlan also discussed the Hawthorne effect, that is, by virtue of being observed, what is being observed changes. In shadowing, disruption of the normal flow of activities is how the Hawthorne effect is most commonly experienced. Because of this, keeping the right distance, ensuring participants are comfortable with the observer's presence, and being careful not to disrupt the process will allow for collecting the most useful data.

The shadowing results of different audit sessions were then comparatively analyzed and evaluated to identify prevalent issues of current auditing practices.

Semi-Structured Interviews. A series of interviews took place as part of this research study. The style of interviewing that was used was a semi-structured modus. A semi-structured interview involves having predetermined questions and topics, although the interviewer has no formal structure or outline for asking these questions. Other unplanned questions may be asked if the conversation leads into a direction that deems appropriate for the study. When interviewing participants about their personal experiences and emotive topics, "providing a non-judgmental and confidential environment, where participants can talk about their experiences in an open and unhurried manner with someone who is genuinely interested in what they have to say, can be of mutual benefit to both researchers and participants" (Lowes and Paul 2006).

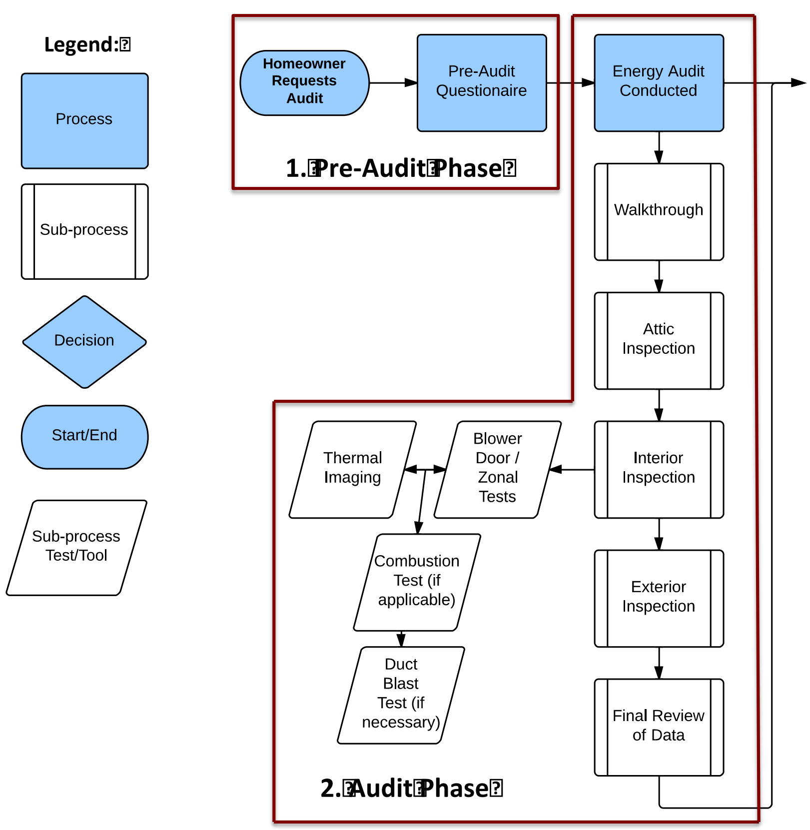
This particular style of interviewing was used for this study in an effort to gain more insightful and honest responses from interviewees due to the unrestricted nature of the interview process and conversation. The style of interview was communicated to the interviewee before the interview began, letting them know of the nature of the conversation and the freedom to stray from specific questions and topics as appropriate. Institutional Review Board (IRB) approval of questions for this study was obtained before interviews began to ensure all questions were ethically correct.

RESULTS

The results produced by both, the shadowing and the interviews were comparatively analyzed and then synthesized to produce a list of core issues of energy auditing practices. Participants of the shadowing and interview phases were then presented with the results and validated for the core findings.

Study Participants. A total of four local companies, who primarily conduct energy audits, or some select energy auditing services, were identified as potential participants for this study. Three of these four candidates were invited to participate and agreed to be shadowed and interviewed for this study. Of these three, two were energy audit companies (Company A and Company C), and one was a home inspection company (Company B). The companies were chosen based on proximity and the different perspectives they could provide based on company sizes, and services they perform.

Results of the Shadowing. Each participating company was first shadowed on a typical energy audit as performed by their auditors. This process also allowed for experiencing an unbiased view of what actually occurs during an audit. Detailed process maps of each company's typical audit process were created based on the observed activities during shadowing. An example of a process map is shown in Figure 1.



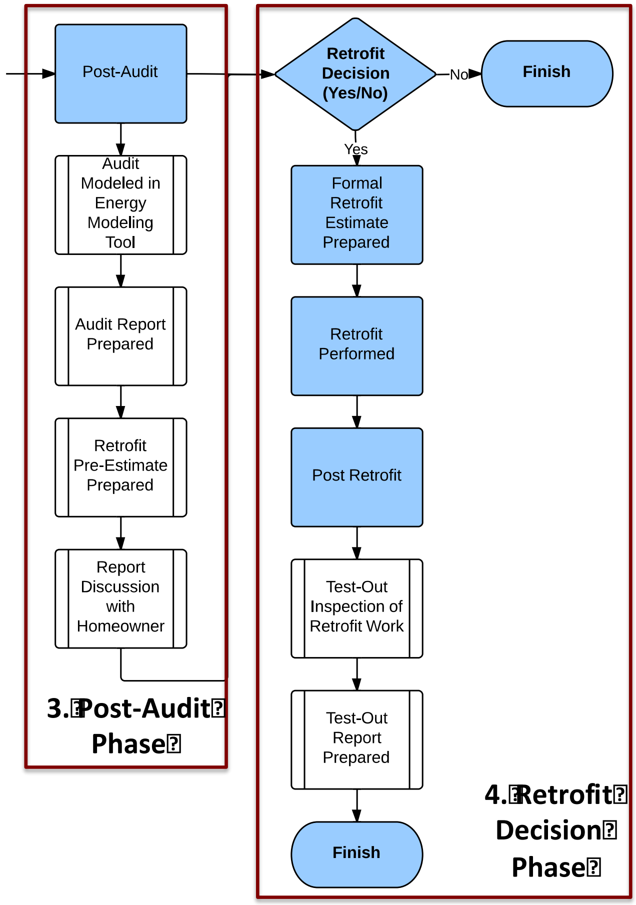


Figure 1. Example of an energy audit process map created for Company A based on shadowing activity – depicts the four different phases experienced.

The process maps provided an overview of the typical tools and tests used and performed when conducting and audit, as well as the processes they underwent pre and post audit. Four main phases were identified for each energy auditing company, which consisted of the Pre-Audit Phase, the Audit Phase, Post-Audit Phase, and the Retrofit Decision Phase. Some typical tools utilized during the majority of the shadowing observations included a blower door, infrared camera, fan flow, moisture meter, temperature sensors, gas leak detectors, and carbon monoxide detectors. EPS Score was one of the energy modeling tools used by Companies A and C as required by a local, government funded incentive program. The companies use this tool in addition to other modeling tools, for which they have obtained licenses and routinely utilize for their assessments.

Results of the Interviews. Once the shadowing phase was completed and the processes of each company were observed and documented, questions were asked to each of the participating energy auditors in the form of a semi- structured interview. Two auditors were interviewed from Company A as well as the company owner, and two auditors were interviewed from Company C. The home inspector from Company

B was not available for a follow-up interview within the allotted time frame of this study. The interview questions addressed topics such as their personal views, opinions, difficulties, and strengths when performing audits. Questions were also posed towards their opinions of their company's processes, the local energy auditing community, and the energy auditing industry in general. A total of four energy auditors were interviewed, and one of the company owners was also interviewed. Interviews were conducted privately in one-on-one sessions, which lasted between 30 minutes to one hour. As the format for the interview sessions was semi-structured, some questions that were not on the original interview guideline were asked as the conversation lead in a way that was appropriate for the study. Common perceptions were synthesized from all interviews and shadowing events to identify the main strengths and struggles faced in the local energy auditing industry, and will be discussed below.

DISCUSSION

Some general similarities gathered in the analysis process include the certifications held by each auditor interviewed, in which all of the auditors hold at least one certification, with the exception of one of the company owners, who does not hold any certifications. A certification held by all the auditors is the Building Performance Institute (BPI) Certified Professional certification. All interviewed auditors have been conducting energy audits for between one and two years, with the exception of one auditor who has been conducting energy audits for five years, and the company owner who does not conduct energy audits, but has been operating the business for approximately five years. The auditors conduct audits primarily regionally, and only sometimes out of state. The typical types of homes they audit were built between the years 1950-1970, but they have audited older as well as newer homes. The audited homes vary in characteristics and architectural properties. Typical tools/practices used by the auditors include a variety of diagnostic tools such as a blower door, infrared camera, and combusting testing sets. Their typical clients that seek energy audits are predominantly looking to increase the comfort inside their homes and save on energy bills in the process, while others are energy efficiency enthusiasts. The most common energy related problems auditors seem to face are related to air sealing and insulation. There was discussion regarding the awareness of risk associated with retrofit recommendations and the actual results of performed retrofit work, rooted in miscommunication and/or not specific enough instructions. It was a general consensus that their clients (i.e. homeowners) often need to be "convinced" to create buy into the recommendations they provide post audit. One of the company owners identified this as what he believes to be one of the energy auditing industries biggest issues.

Common Strengths. The core findings identified in common strengths include diagnostic tools/tests, certifications, and teamwork.

Diagnostic Tools/Tests:

Many commonly utilized tools and performed tests were observed in the field and also mentioned in the interviews by each auditor. There was general favor in their value for various reasons. It was discussed how some tools are more critical for collecting raw data, while others are more for communicating and presenting information to the homeowner post audit, sometimes even during an audit, as observed during shadowing. The blower door test and an infrared camera are two tools used prevalently in the field by all the auditors as observed during shadowing. These tools were of most interest to the homeowner, and also the most known of by the homeowner, where many times the homeowner asked when those tools and tests would be performed, and were intrigued with the processes when they finally were employed. Viewing the contrast in colors presented on the infrared camera screen as the blower door was running made it easier for the auditor to translate the meaning of what the homeowner saw when looking at it in relation to the condition of their home. This served as a visual aid of sorts in the field where curiosity arose, and also in the audit reports for presenting collected and analyzed data.

Internal benefits of the tools were also discussed. The data of the blower door serves a purpose much like that of a scale, as one auditor described it. It provides numeric values, which they can be used to compare a home's pre and post retrofit state to evaluate improvements. Other tools and tests used for diagnostics such as combustion testing, efficiency tests, and carbon monoxide detectors provide an abundance of raw data not only for the energy assessments, but also for health and safety inspections. A tool mentioned by only one auditor in an interview but seen on every audit shadowed, was the digital camera. This was used to collect an abundance of photos of the interior and exterior characteristics of a home. These photos were used as data in the office to analyze and provide retrofit recommendations. The auditor that discussed this tool in the interview described the camera to act much like that of a pen and paper, but in a more efficient and accurate way.

Certifications:

As mentioned previously, all of the auditors interviewed are BPI Certified Professionals, with some auditors holding multiple other certifications related to energy auditing and building performance. It was a general consensus between all auditors, as well as the company owner, that their certifications add significant value not only to their personal knowledge, but also towards obtaining business and resources. The BPI certification was discussed as an intense course with a lot of information delivered in a short period of time that may not have been absorbed if it were not for them continuing on practicing in the profession as energy auditors. Despite this, there was general favor that the certification training helped to strengthen awareness and knowledge of energy auditing and the associated building sciences. All believed that their certifications provided themselves, as well as their associated company, with credibility, helping them to attain work where the certifications were of particular importance to clients looking for it as a credential. Their certifications also provide them with access to use certain tools they were otherwise restricted from, allowing them to expand the scope of work they can perform. The company owner mentioned that while he believes an individual can have all the knowledge the certification offers in training without becoming certified, however, without it, the credibility is missing.

Teamwork:

When shadowing auditors on local audits, they were observed individually, as well as in auditing teams of two auditors. All the auditors discussed how they favored working together in the field, rather than individually. A big part was that it reduced the time it would take collect data in the field by dividing responsibilities. This also provided opportunities for sharing knowledge and insight in the field while collecting data. This combination allowed for more attention to be applied to areas in the home being inspected due to now reduced time constraints. Less time constraints lead to a reduction in possible overlooked data that could have been omitted if they did not have another team member to converse with and prioritize the scope of work. While observing the auditors in the field, it was also apparent how much more efficient their time was being used while conducting an audit on a home together versus conducting an audit individually.

Common Struggles. The core findings identified as common struggles include the diversity in the local housing stock, lack of time, lack of incentives, communication with the homeowner and report formats, and the use of EPS Score and other energy modeling tools.

Diversity in the Local Housing Stock:

Although a majority of the homes audited by the participating auditors were built between the 1950s and the 1970s, this does not conclude that there is one typical style of home they encounter. All auditors discussed how they face a wide variety of types of homes; some old, some new, some architecturally unique, while others seem “off-the-shelf”. This adds a considerable amount of difficulty to their processes in the field and back in the office when analyzing data.

The variation of homes they audit adds significant time towards collecting data in the field and analyzing the data in the office. The auditors need to know what tools to use and bring with them, which is derived from the scope of work developed for the home before an audit is conducted. This disparity experienced between the types of homes they encounter makes it difficult to use the exact same process for each home. Although there are many of the same tools and processes implemented each time on an audit, what and how they address the home with these tools and processes can be much different. Not having architectural plans to assist with calculating volumes and creating floor plans is another difficulty that relates to the diversity of homes they encounter and the extra time needed to collect that information.

Although this adds difficulty to the auditor’s processes, one auditor mentioned how this difficulty is not always a bad one to have. It was discussed how the added challenge is a good learning experience and helps with the development of an auditor in a positive manner.

Time:

Time consuming processes was a common subject that arose in the interviews in many different ways relating to different issues such as collecting data in the field while on an audit, analyzing collected data, and communicating with the homeowner. For example, a lot of time is consumed when auditing homes due to the architectural and systems variation in the homes as discussed in the previous section. Time is also affected by the tests and tools used in the field, some more critical than others for perhaps presenting recommendations to the homeowner, but maybe not so much when inputting data into an assessment analysis, or vice versa. Many of the auditors discussed that time is, what they believe, the auditing industries weakest link because it is affected by so many different aspects of energy auditing and cannot simply be addressed by one solution.

It is apparent that energy auditors are looking for faster ways to complete audits and it seems to be a constant struggle they face. The time constraints can lead to rushing and overlooked/missed critical data. This can ultimately lead to assumptions being made, and as a result, poor recommendations and a lack there of, as discussed by one of the auditors. As one auditor mentioned, their main obstacle is getting all of the desired data from an audit while still making it cost effective, because the more information that is wanted, the more time it will take to collect and process it.

Lack of Incentives:

All the auditors and the company owners expressed how the lack of incentives provided in the state of Virginia is a limitation to their work and the number of clients they receive. They believe that Virginia lacks in incentives compared to other states, and other countries, which offer more and better incentives to homeowners. It was discussed how incentives not only can encourage energy conservation, but can also spur more business for energy auditing companies. The local block grant institution, which the auditors currently work with, offers incentives to homeowners to seek an energy audit and retrofit work. Incentives can be an asset towards generating new business, but even so, it was discussed how some homeowners are still skeptical towards incentives. This skepticism is speculated to arise from past bad experiences, disappointment in expected pay-offs, and the fear of ulterior motives.

Communication with Homeowners and Report Formats:

The need to “convince” homeowners of the benefits of their retrofit recommendations was a common struggle that came up in all of the interviews. This was due to some homeowner skepticism and communication barriers encountered. This also relates to how the audit reports are presented to the homeowner. Finding ways to improve the effectiveness of how information is communicated to the homeowner is an important issue. This includes aspects such as the terminology used that may not be common knowledge, visual presentation of data, and the pay-off estimates and benefits. How one homeowner responds to the information presented to them by an energy auditor may be completely different for another homeowner, and adapting to this is a challenge they always face.

EPS Score and Energy Modeling:

The interviews revealed a general consensus for unreliability in the energy modeling tool EPS Score's results. One auditor however did mention that considering the amount of inputs required (which is low) the results were remarkably close to actual utility data he had compared it to, thus giving him confidence in the results produced by EPS Score. For the other auditors and company owner interviewed, their views were quite the contrary.

It was discussed that there was a lack in confidence in the results produced by EPS Score because of the simplicity and generalized nature of the tool, which over-valued certain savings estimates, produced problems due to inconsistent input requirements, and contained subjective and generalized inputs. One auditor described that the difficulty faced with EPS Score is due to over predicting results, which leads to homeowner dissatisfaction, and also noted that it is difficult to get the most accurate results without knowing how occupants interact in their homes and use their energy, which EPS Score completely excludes. Despite these dissatisfactions with EPS Score, there were some benefits identified for the tool, which includes providing a good report format for homeowners to easily understand, and its value in providing the "big picture" and ballpark estimates.

One energy auditor discussed how they know that EPS Score and other energy modeling tools cannot be 100% accurate, but despite that, it is always better to utilize them when conducting an energy assessment. He believes that learning the different tools and identifying the inputs and data that have the most significant effect on the results in order to increase accuracy is a learning process, which takes time and practice, something himself and his colleagues are always working to improve upon.

CONCLUSION

Energy auditors and their assessments are a key factor towards successful retrofitting homes and residential energy consumption goals. The recommendations they provide to their clients are crucial towards retrofit decision-making, and can in many ways be seen as the center of influence in the residential energy efficiency industry. The core findings of this study revealed key strengths and struggles faced by local auditors when conducting energy assessments that can contribute to decreased assessment accuracy and reluctant retrofit decision-making. In addition to the barriers identified for the region in this study, there are many comparable barriers present nationwide that are preventing active retrofit decision-making and household energy savings from reaching their potential. Investigating and identifying areas to address these barriers identified additional avenues for future research, which have the potential to translate to a nationwide scale.

Limitations to this study included the small sample size of participants and the Hawthorne Effect. Considering the small size of the local energy auditor population for the study region, and the distribution of energy auditors in each participating company, it is safe to say that a majority of the local energy auditors were included in this study. There were additional energy auditors and companies in surrounding areas who could have been included, but energy auditors in closer proximity to the research location were the preferred focus for this study. In regards to the shadowing that took place for this study, the occurrence of the Hawthorne Effect was inevitable. Every effort was made to not disrupt the normal flow of the auditors activities. But as the Hawthorne Effect describes, when one is being observed, there is always the possibility that what is being observed will change, which is out of the control of the observer.

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EVALUATION OF VENETIAN BLIND ATTRIBUTES FOR ENERGY EFFICENCY

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ABSTRACT

The 2011 Building Energy Databook (DOE, 2011a) reported that buildings use approximately 40% of the nation's total energy use. One method of reducing this value is to utilize window retrofit solutions. While these products are often selected for aesthetic or privacy concerns, they can also provide an effective means of limiting heat transfer (Ariosto and Memari, 2013). Venetian blinds are one of the more common window retrofit solutions. Several researchers have investigated the thermal behavior of these systems. However these studies focused primarily on the heat transfer mechanisms themselves (typically convection and radiation) without translating results into the metrics often used to compare glazing systems - the U-value and SHGC. This makes it difficult for the layman to utilize their results. This paper provides an overview of an investigation of venetian blind performance conducted using the LBNL WINDOW software. A variety of venetian blind attributes were investigated including geometric attributes such as slat width, angle, and spacing as well as material properties such as conductivity and surface emissivity, on the performance indices (U-value, SHGC) of double glazed window systems. The study demonstrated that venetian blinds are capable of reducing the U-value by as much as 60% and the solar heat gain coefficient by nearly 100% depending on their design features and installation measures.

INTRODUCTION

According to the 2011 Buildings Energy Data Book (US DOE, 2011a), buildings consume approximately 40% of the nation's energy. Approximately 56% of this energy is used for space heating and cooling as well as lighting applications, while 25% to 35% of this energy is wasted due to inefficient windows. All of these factors are directly impacted by the building envelope (Totten and Pazera, 2010). In addition to other functions (Kazmierczak, 2010; Sanders, 2006), successful building envelopes shield occupants from outside weather conditions, whether that be excessively hot temperatures in the summer or extremely cold temperatures in the winter, as well as provide a connection to the outside in terms of natural lighting and views.

One of the major challenges facing homeowners is the high capital cost associated with fenestration upgrades. The cost of replacing all the windows in a residential building can be substantial. However, the energy savings associated with replacing windows with their higher efficiency counterparts is typically relatively small. The payback period for replacing single glazed windows with double glazed windows can be as long as 50 years for cold climates. This payback period will also increase as the quality of the existing windows increases. When double glazed uncoated windows are replaced with triple glazed units with argon fill and a low-e coating, the payback period is typically around 100 years for cold climates (Guler et al., 2001). Another study conducted by Frey et al. (2012) demonstrated that high performance window upgrades have a return on investment (ROI) of only between 1.2-1.8% based on climate. This translates to a simple payback period of 55-83 years. Therefore, for most homeowners it is necessary to determine low cost methods of reducing heat flow through their windows. In other cases, homeowners may seek further improvements in the performance of their higher quality window systems.

Several researchers have performed studies to analyze the effect of venetian blind performance on heat transfer. Machin et al. (1998) investigated the impact of slat angle on convective heat transfer. Oosthuizen et al. (2005) expanded this work using numerical solutions for both convective and radiative heat transfer. Shahid and Naylor (2005) analyzed a wide variety of venetian blind attributes on both convective and radiative heat transfer. Yahoda and Wright (2004) investigated the effects of slat angle, width and spacing on the radiative properties on blinds.

The study described herin involves an investigation of the characteristics of venetian blinds conducted using the publically available software WINDOW produced by the LBNL (2013). This analysis was conducted to determine which product characteristics are important when the homeowner is primarily concerned with energy efficiency.

VENETIAN BLIND ANALYSIS

Based on the previously mentioned studies, a set of criteria can be determined that are critical to the performance of venetian blinds. These criteria are slat angle, the distance from the blind to the glass surface, the emissivity of the blinds, the slat width and spacing, and lastly the height of the window.

Figure 1 shows the venetian blind characteristics that were modified using LBNL *WINDOW*. In addition, the slat material can also be modified based on parameters such as conductivity, solar, visible, and infrared transmittance, reflectance and/or emittance.

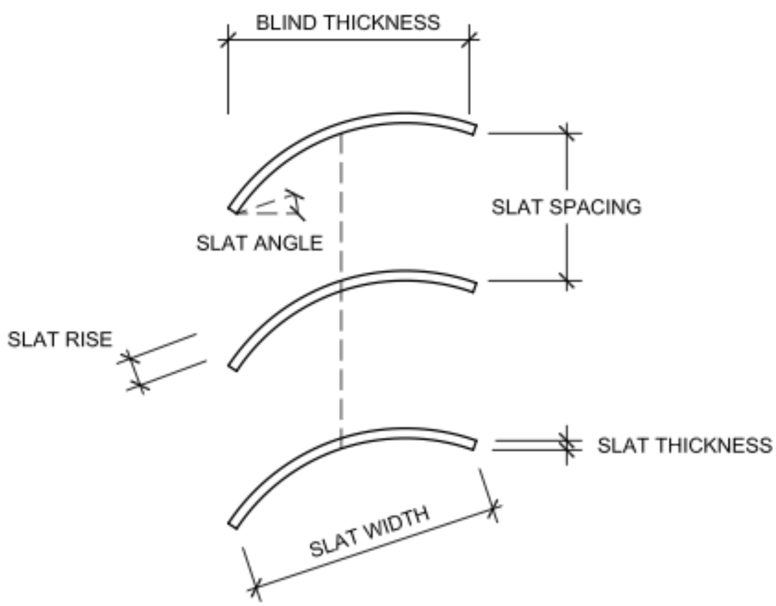

Figure 1: Illustration of venetian blind geometric parameters used in WINDOW.

Each of these properties was evaluated individually and/or in combination with each other to determine the effect of various blind designs. An IGU with a low-e coating on the interior surface of the exterior pane of glass was used for the glazing system in order to establish a baseline for performance. Single-glazed systems will experience greater reductions, while those for triple-glazed systems will be lower. It is important to note that a positive percent reduction translates to improved thermal performance and reduced solar heat gain, while negative values translate to decreased thermal performance and increased solar heat gain. In order to determine the impact of the blinds for a wide variety of different window systems, whole product U-values were assumed for wood, vinyl, and aluminum frames with thermal breaks. In addition, a "center-of-glass" U-value was determined, which assumes an infinitely large glazing area so that "edge-of-glass" framing effects are not present. For each part of the analysis, this data was then converted to a percentage improvement over the glazing system with no venetian blind.

WINDOW uses two standard sets of calculations for the U-value and SHGC analysis. The first is ISO 15099 (ISO, 2003b), "Thermal Performance of Windows, doors, and shading devices – Detailed calculations." The second is ISO/EN 10077 (ISO, 2003a) "Thermal performance of windows, doors, and shutters – Calculation of thermal transmittance."

ISO 15099 specifies the calculation procedures that should be used to determine thermal and optical properties for window and door systems, including single- and multi-pane glazing products with low-emissivity coating, suspended films, gas fills, metallic and nonmetallic spacers, frames and shading devices. ISO/EN 10077 deals with the calculation procedures for thermal and optical transmittance for glazing systems. These algorithms, however, are greatly simplified in comparison to ISO 15099.

One important piece of the discussion that will follow is how the shading layers being modeled relate to the windows. This is especially important when the heat transfer processes of conduction, convection, and radiation are considered. WINDOW works under the assumption that the shading device is mounted inside the frame. The top, left, right, and bottom openings shown in Figure 2 represent the opening area between the shading layer and the frame. Modifying this area is achieved using the D_{top}, D_{left}, D_{right}, and D_{bot} distances found in the glazing system definitions in the glazing system library within WINDOW. The center openings represent the amount of air that is able to move through the shading device. This area is specified as the "openness factor" found in the shading layer library. An openness factor of 1 implies that the shading layer has no effect on limiting transmittance to the surface of the glazing. Conversely, an openness factor of 0 implies that the shading layer is completely effective at limiting air flow.

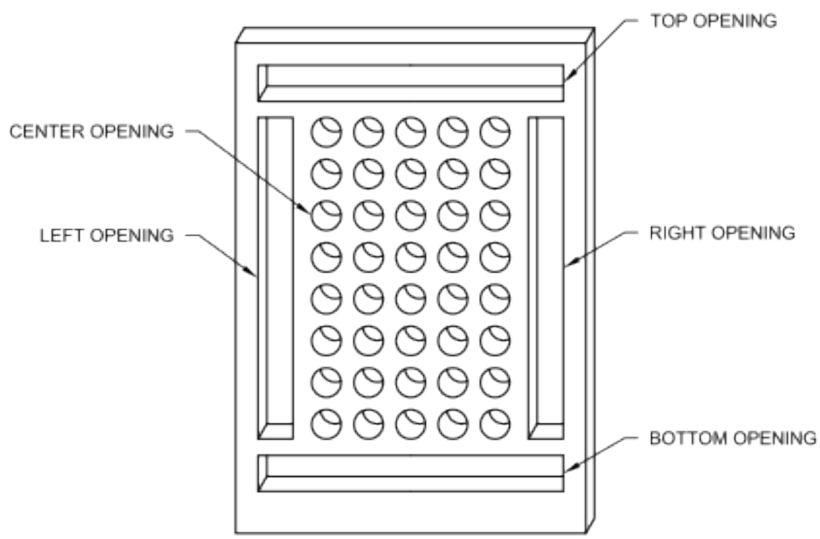

Figure 2: Generalized shading layer geometry.

The openness factor is taken into account in the calculation for the pressure loss through ventilated cavity. A cavity formed by a shading device is considered a ventilated cavity. This value is important for thermally driven ventilation with the glazing system.

The challenges associated with the openness fraction can be illustrated by examining the case of venetian blinds. When the blinds are in use, WINDOW uses a default openness fractions of 0, 0.5, and 1.0 for slat angles of 90°, 45°, and 0°, respectively. However, it is realistic to assume that these values will change continuously based on the configuration of the specific blind. In particular, an openness factor of 0 is unrealistic, as the blinds will never form a perfect seal even when closed. Machin et al. (1998) noted that even if the blinds can reach the full 90° rotation, which most systems will not, "slight axial undulations" of each slat would prevent a tight seal from ever being formed. Therefore, for this analysis, an openness fraction of 0.05 will be assumed for blinds in 90° position.

The first criteria to be investigated was the slat angle. This analysis was first performed for the center-of-glass region for several different slat width to spacing (w/s) ratios. Note that w/s ratio less than one means that the blind will not completely close in the 90° position, as the slat width is less than the spacing between adjacent slats. When the w/s is greater than one, there will be an overlap in the slats when closed. The results of this study are shown in Figure 3. The results were then repeated for a w/s of 1.33 and for several different framing options (Figure 4).

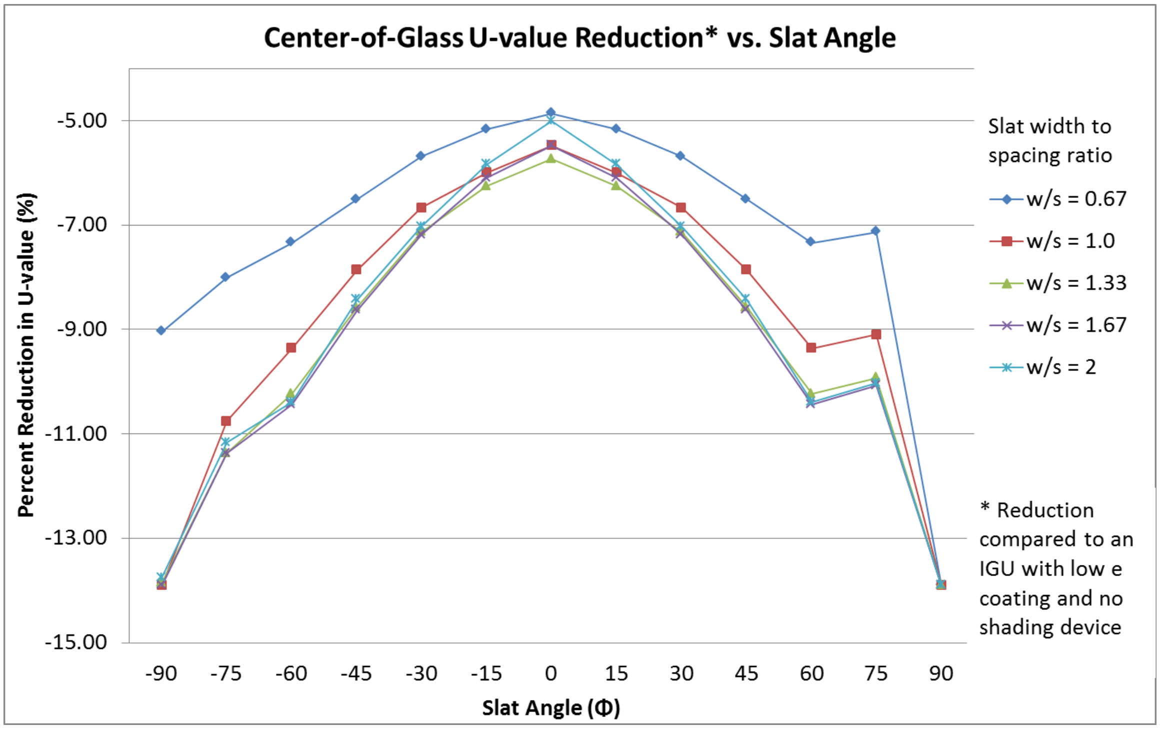

Figure 3: Reduction in center-of-glass U-value vs. slat angle for several different slat width-to-spacing ratios.

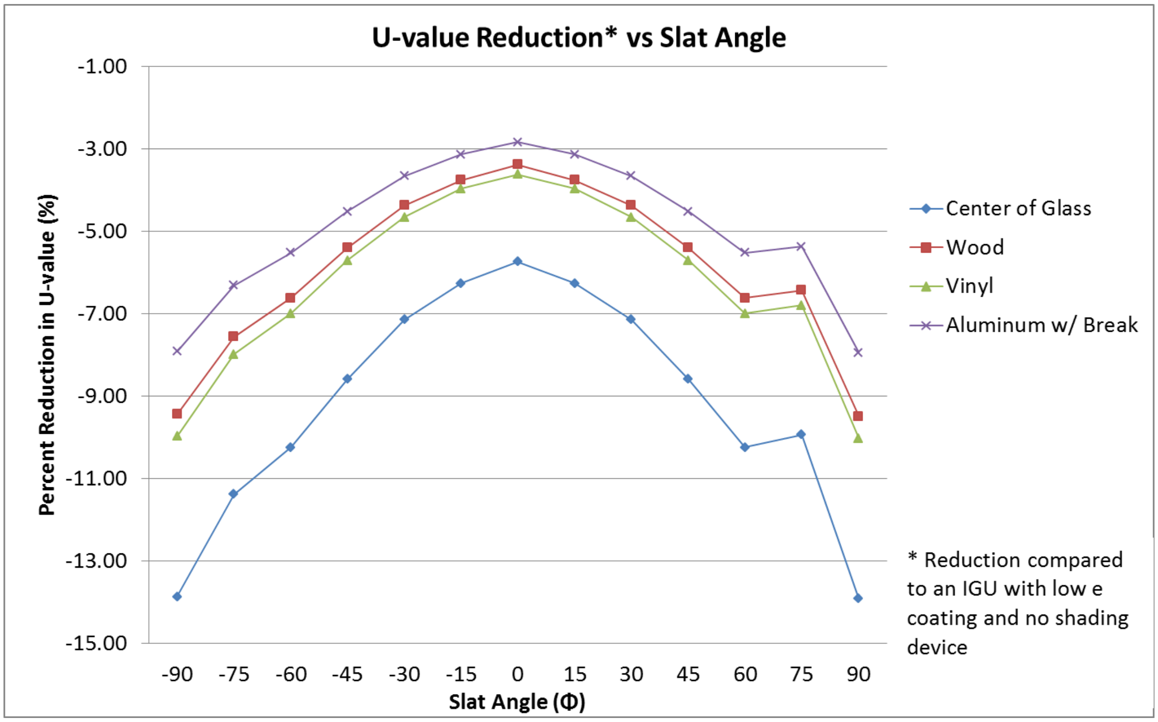

Figure 4: Reduction in U-value vs. slat angle.

Figure 3 illustrates the importance of the w/s ratio for various slat angles. When the slat angle does not equal 0°, the variance for w/s ratios greater than 1 is marginal. When the slat angle is 0°, there is about a 1% variance in performance for w/s greater than one. Based on the findings of Yahoda and Wright (2004), this variance can be attributed to a decreased shading absorptance and transmittance properties at this angle. When w/s is less than 1, the variance from the rest of the ratios is more pronounced. This variance is also in line with Yahoda and Wright, who found that the absorptance, reflectance, and transmittance properties of the blind vary more dramatically for w/s less than one.

When the effect of this criterion was evaluated for the SHGC (Figure 5), it was found that blinds with a width-to-spacing ratio of greater than 1 all performed similarly, reducing between 0% and 50% for blinds in the 0° and ±90° positions, respectively. For blinds with width-to-spacing ratios less than 1, the blinds increased the solar heat gain in the 0° position by nearly 15% and reduced the SHGC by about 23% in the ±90° position. Since the blinds are located on the interior of the glazing, they have a limited effectiveness at reducing solar heat gain. As will be seen later, blinds located on the exterior of the glazing are much more effective in this regard.

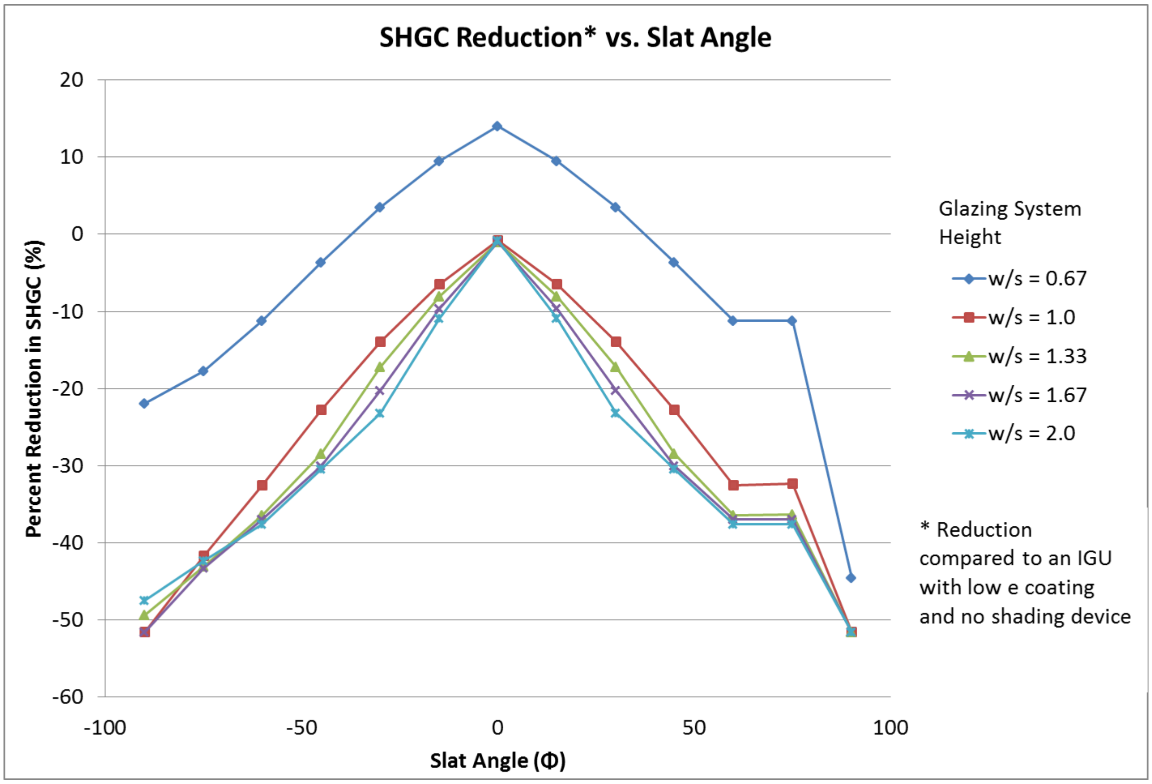

Figure 5: Reduction in SHGC vs. slat angle for several width-to-spacing ratios.

The next criterion investigated was the effect of the width of the shading cavity. This width is defined as the distance between the interior surface of the glass to the centerline of the shade. For this analysis, the shades were in the closed (90°) position. The study was then repeated for several other glazing system heights. The results are shown in Figure 6. For a window with a height of 1500mm (that of the previous investigations), the width of the shading cavity can affect the performance of the system by about 1%. As the height of the glazing system is increased, the effect of the size of the shading cavity becomes slightly more pronounced, resulting in closer to 2% of a variance.

The results of the study by Machin et al. (1998) show that there was a performance peak at about 14.5 mm. This particular feature was not found in the present study. In fact, for short windows, it was found that a shading cavity of ~15mm actually produces the *worst* results. However, it should be noted that those results were specifically for convective heat transfer. In addition, the role of the framing was not taken into account in that study. This seems to indicate that the role of radiative heat transfer is less dependent on the cavity width. In addition, the effect of the more highly conductive framing has the effect of lessening the effect of this particular feature for the size of windows investigated.

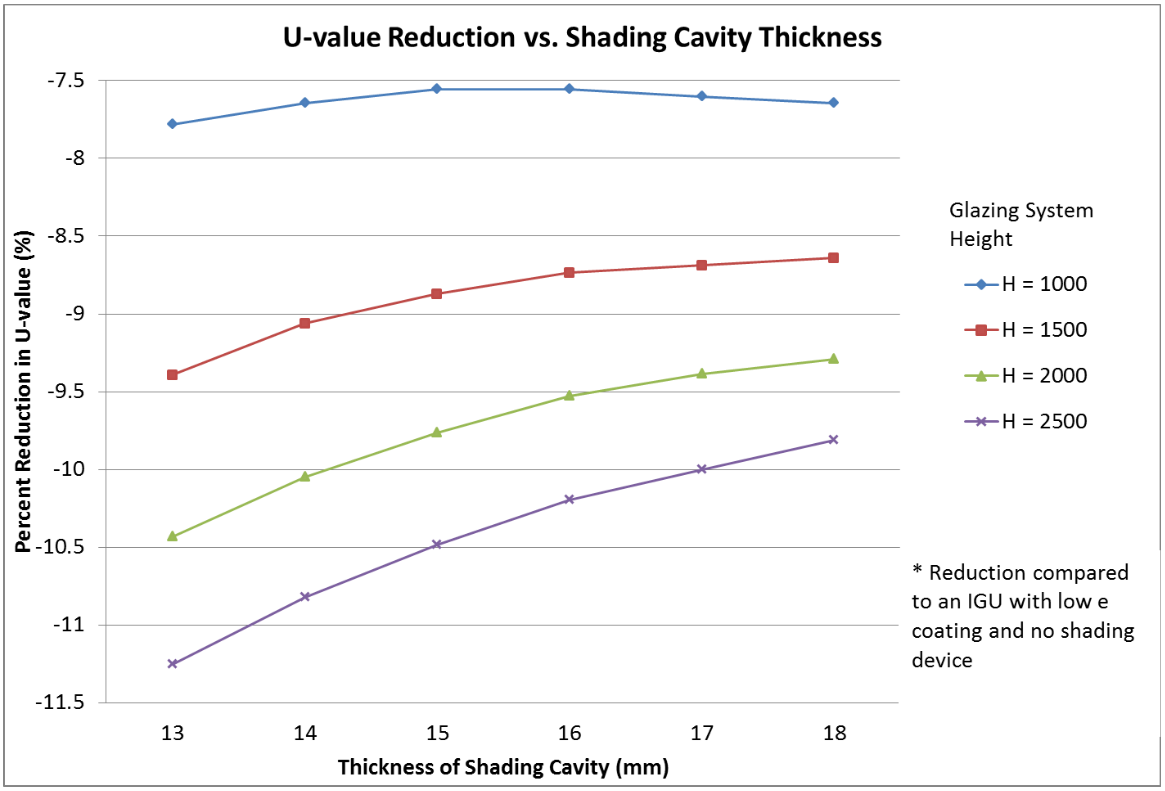

Figure 6: Reduction in center of glass U-value vs. shading cavity thickness for several different window heights.

The next criterion investigated involved the optical qualities of the material used for the slats. There are three types of radiation that are of interest to the performance of shading systems. The first two types are radiation in the solar or visible portions of the electromagnetic spectrum. These wavelengths can be either transmitted through the blind or reflected. Variations in these variables will primarily affect the SHG (solar spectrum) and visual transmittance (visible spectrum) of the system. The default values for opaque white blinds were used ($T_{sol} = 0$, $R_{sol} = 0.7$, $T_{vis} = 0$, $R_{vis} = 0.7$) to account for these effects. The third type of radiation is in the infrared spectrum (heat). This quantity will be of primary interest for the purposes of reducing the thermal transmittance of a glazing system. To determine the effect of these variations, the transmittance (T_{IR}) was set to 0, and values for the emissivity were varied between 0 and 1.0. The results of this variation are shown in Figure 7.

Compared to the other variables examined thus far, it is clear that emissivity has a dramatic effect on the performance of venetian blinds. Variations in emissivity can account for between ~8 and ~15% reduction in U-value. These center-of-glass results are consistent with those of Shahid and Naylor (2005). The effect of the framing materials on the performance of the system is also shown. The increased performance obtained from using low-emissivity solutions is lessened for highly conductive frames (~11%) compared to low-conductivity framing solutions (~15%).

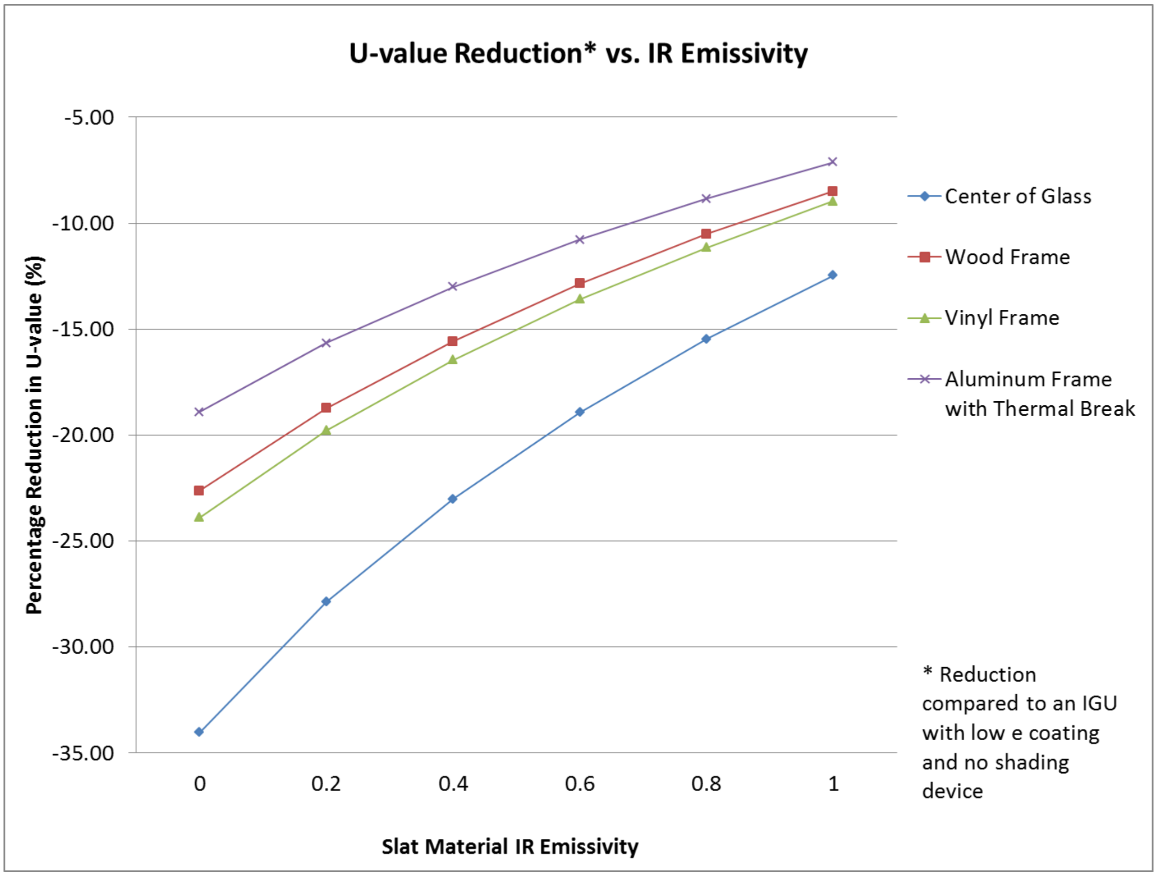

Figure 7: Reductions in U-value obtained based on variations in IR emissivity.

The effect of slat rise was investigated next. Recall from Figure 1 that this characteristic is essentially a description of the curvature of the slats. This criterion was investigated for slats with rises between 0.25-2.25 mm (0.009-0.088 inches). The slat thickness and width were maintained at 0.6mm and 16mm, respectively. The results are shown in Figure 8. For variations in the range of slat rises investigated, it was found that regardless of frame type used, the rise of the slats will only account for a variation in U-value of less than 0.5%. It can therefore be concluded that the impact of slat rise is negligible.

One interesting effect can be observed in Figure 8. As the slat rise increases, there is a slight oscillating behavior in the performance of the blind. Yahoda and Wright (2004) noted that the effect of slat curvature was minimal for large curvatures (low rises using our terminology), but that it is likely that the effect would become more pronounced when the radius of curvature is very slight (large rise values). However, the oscillating behavior of the shades was not noted in their study. This likely indicates that the oscillations are a function of the algorithms used by WINDOW.

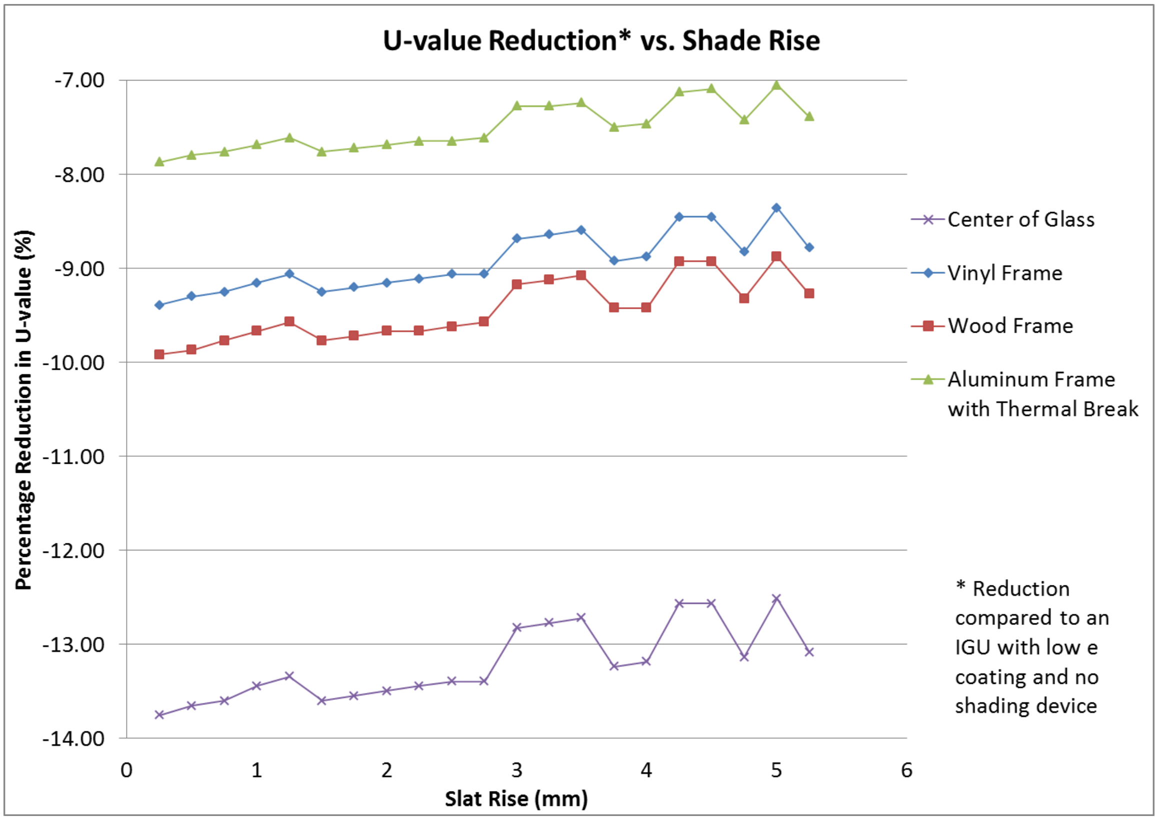

Figure 8: U-value reduction based on variations in slat rise.

The effect of the openness fraction (effective openness) was then investigated. Recall that the openness factor is a measure of the open areas or "holes" in the central portion of the shade through which air can move. In effect, this is a measure of how ventilated the cavity is. The results for openness factors of between 0 (perfectly sealed) and 1 (perfectly open) are shown in Figure 9 for shades in the 90° position. Shades with less than five percent openness are able to achieve significant improvements in performance, while those with greater than 5% openness were very consistent. It is important to remember, however, that most shades currently on the market are not able to achieve a completely sealed condition when closed (Machin et al., 1998) and that a 5% openness was assumed to be the standard conditions for shades at 90°. Investigation of designs that could allow for the 0% openness condition could be an area for future study.

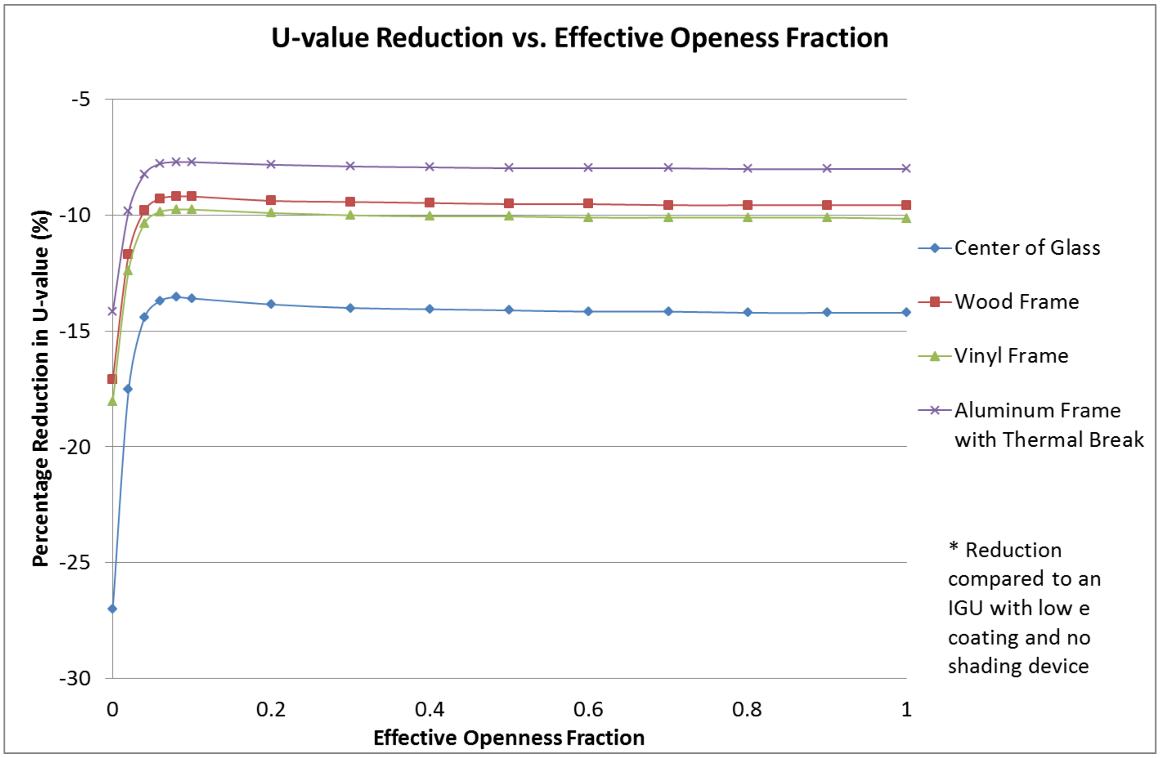

Figure 9: Reductions in U-value as a function of effective openness.

The effect of slat thickness was next investigated. For this analysis, it was assumed that the blinds are in the completely closed position, with a 16 mm (0.63 inches) slat width, a 12 mm (0.47 inches) spacing, and a 0 mm rise. It was assumed that the slats would be in the fully closed condition, as is appropriate for nighttime use when improvement in U-value is most critical. For the initial portion of this analysis, a material conductivity of 160 W/mK was used. The results of this study are shown graphically in Figure 10.

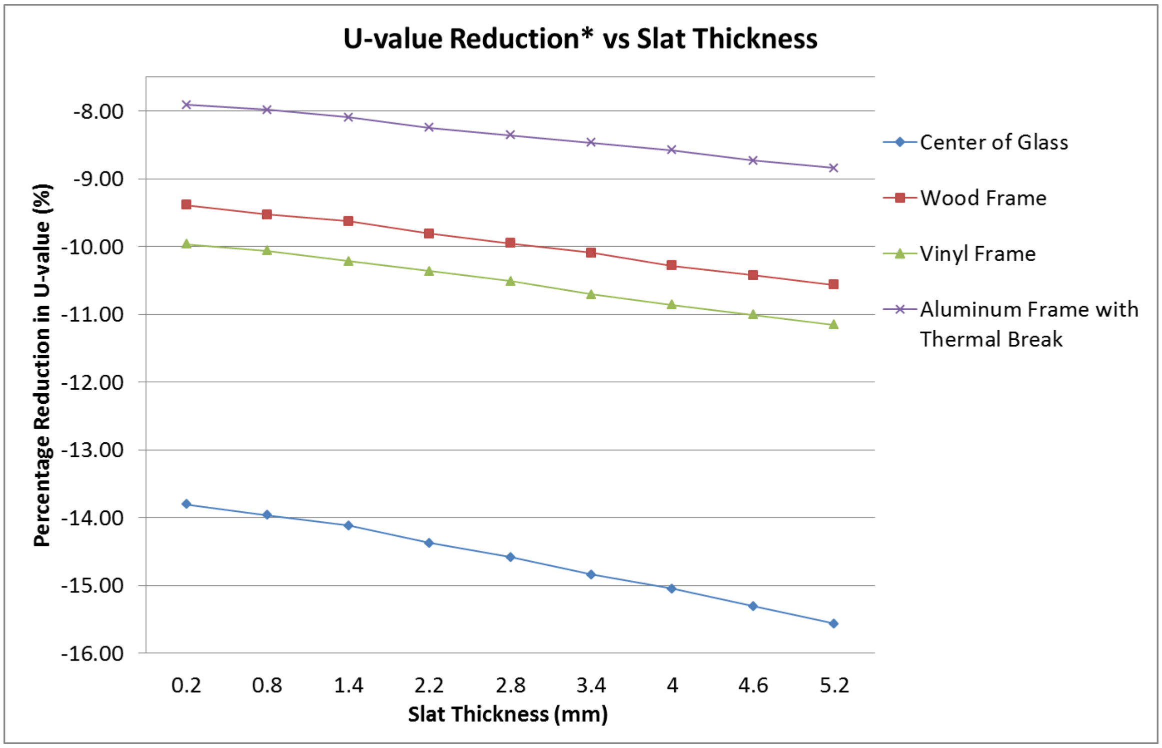

Figure 10: U-value reduction achieved using venetian blinds of various slat thicknesses.

As can be seen in Figure 10, the blind performance improves as the thickness of the slats increases. Over the range of thicknesses examined, the center-of-glass U-value improvement will range of ~13-15% as compared to an IGU with no shading device. The type of window frame present in the system will have a large effect on the performance of the shade. More thermally conductive frames will dominate the performance of the glazing system, allowing the shade to have only a small impact on the improvement of the system. Regardless of the impact of the frame material, variations in the thickness of the slats will only result in a 1-2% variation in shading performance. Therefore, it can be concluded that slat thickness will not be a primary factor affecting shade performance.

In order to determine exactly what role conductance plays in the performance of venetian blinds, the analysis was repeated for conductivities of 200 W/(mK) and 120 W/(mK). For this particular analysis, only center-of-glass U-values were considered. The results of this analysis are shown in Figure 11. This analysis showed that the conductance of the material used for the slats has no effect on the performance of the shade system, as all variations coincide. This makes sense, as thermal performance of the slats is based on reducing radiative and convective heat flow. Since the blinds are such a thin, highly conductive feature of the system, it makes sense that conductance will not be a driving feature of their performance.

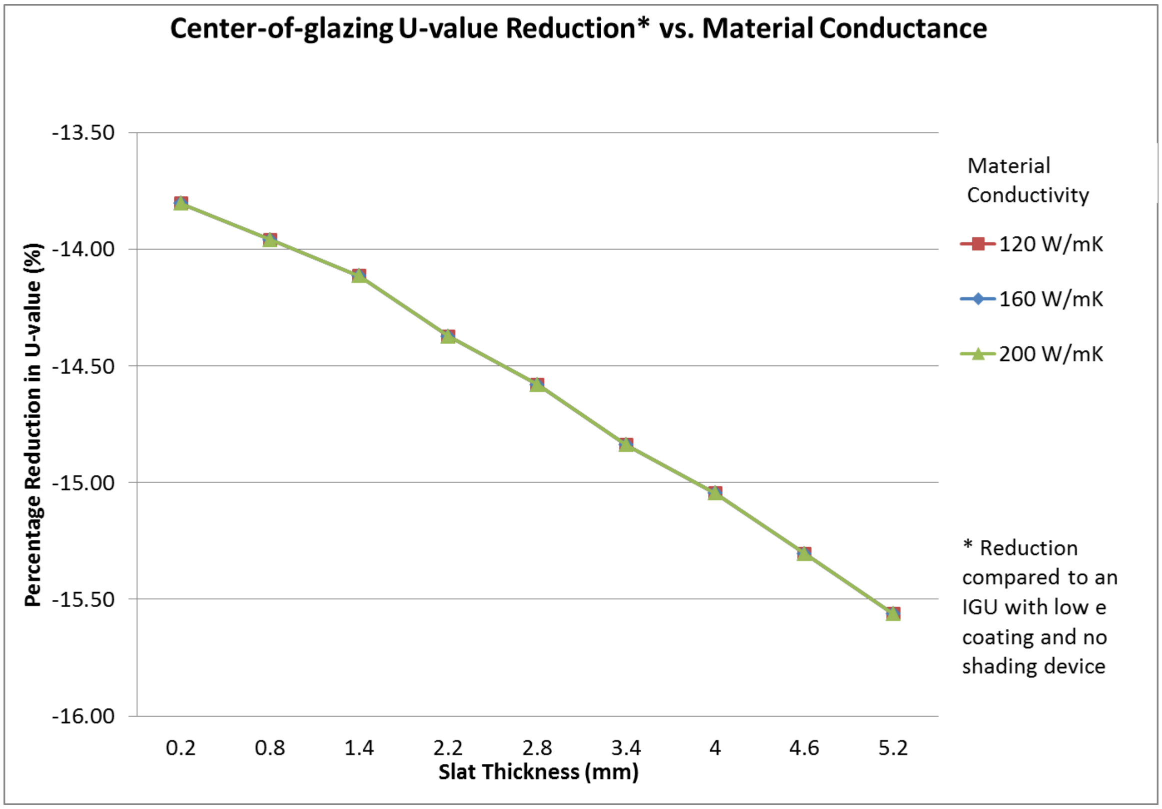

Figure 11: U-value reduction achieved based on the conductance of the shading material used.

From the criteria previously investigated, it can be concluded that the two venetian blind features that are most likely to drive the performance of the system are the openness of the shade and the emissivity of the slat material. A further study was then conducted to evaluate the combined effect of both of these features. The center-of-glass U-values were calculated for systems with openness fractions between 0 and 0.12 and varying emissivity. The results of this study are shown in Figure 12, which seem to indicate that for low-emissivity blinds, with an openness condition of about 2%, approximately 15% to 40% reduction in U-values could be achieved depending on the slat material emissivity. If a 0% openness condition could be reached, this improvement can be increased from 25% to 60%, depending on the slat material emissivity.

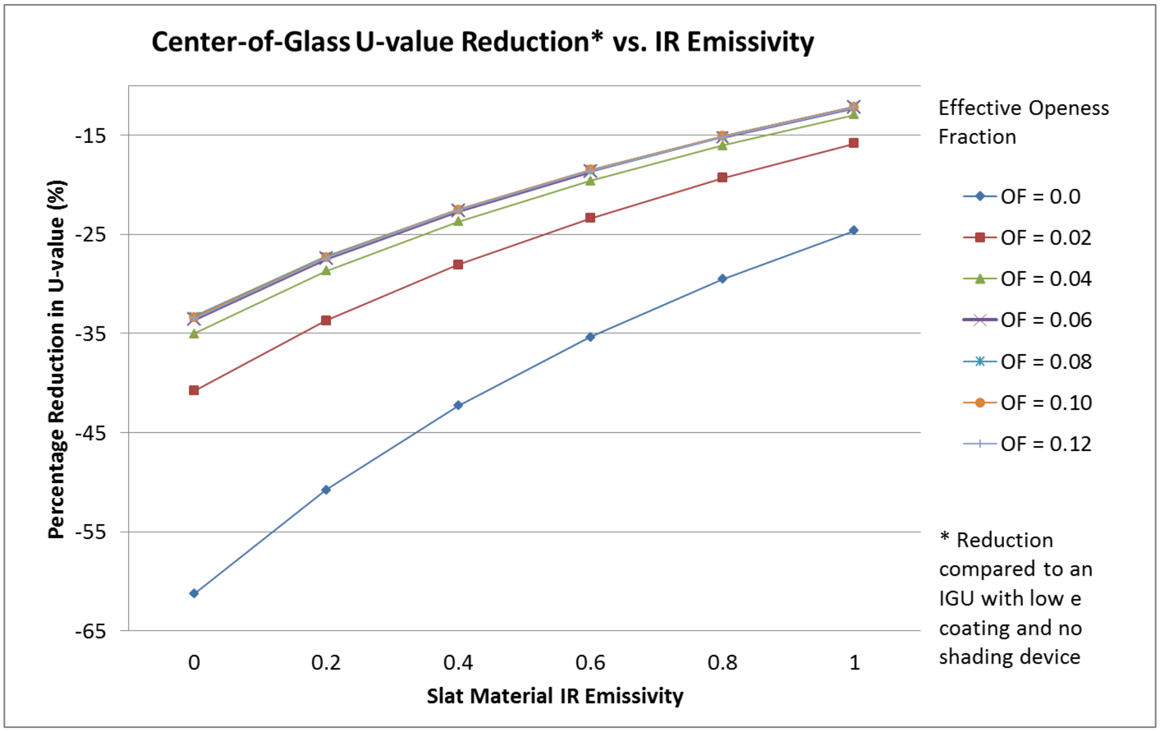

Figure 12: Reductions in center of glass U-value vs. IR emissivity and openness fraction.

The analysis was then repeated to examine the effect of venetian blinds on the exterior side of the glazing. It was found that the venetian blinds reduced the U-value by 20-25% in the center of glass region. The results of this study are shown in Figure 13. Note that the data shown for wood framing was limited to slat angles of -60° to +90°. The data corresponding to slat angles beyond this seemed to be corrupted. The reason for this was not clear, but one possibility seems to be related to internal modeling assumptions.

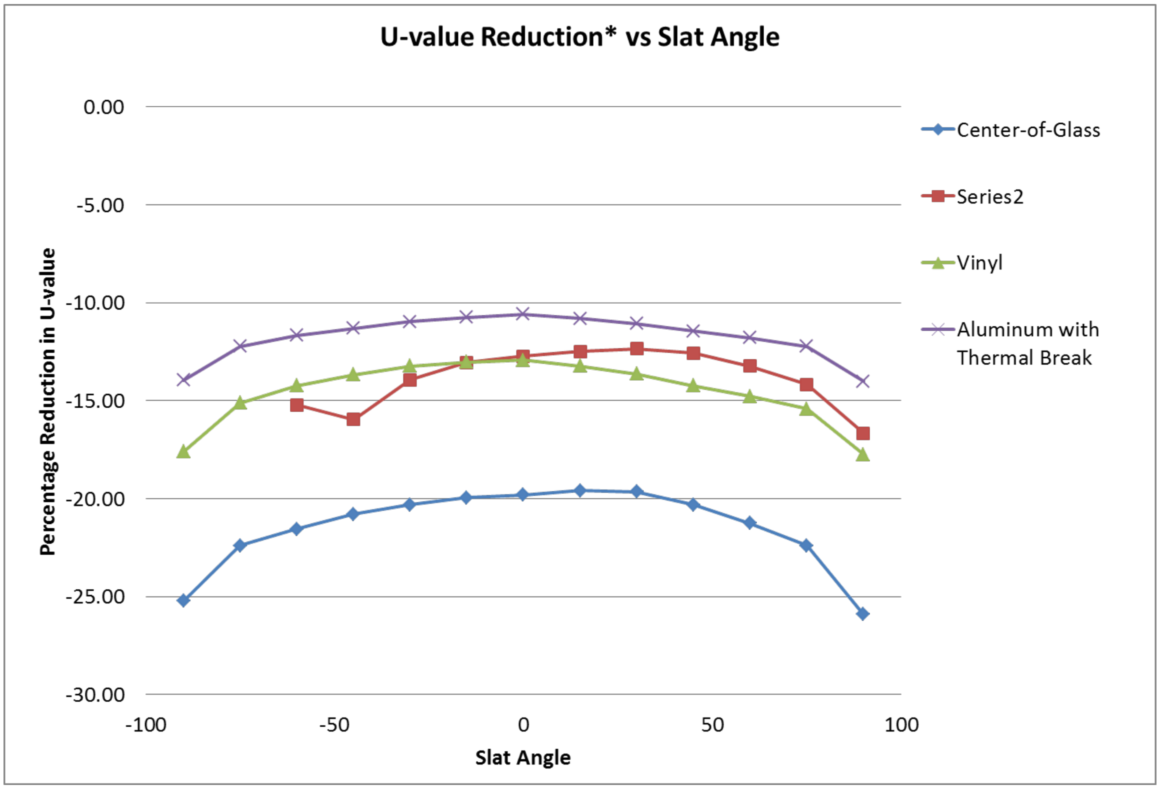

Figure 13: Reductions in U-value vs. slat angle for exterior venetian blinds.

The slat angle had a significant effect on solar heat gain reduction for exterior shades, as is shown in Figure 14. When the slats are in the closed position, the SHGC is reduced by nearly 100%. As the slat angle approaches 0°, however, the reduction decreases. At 0°, there is actually an increase in solar heat gain. This seems to imply that the shades have a magnifying effect at this angle.

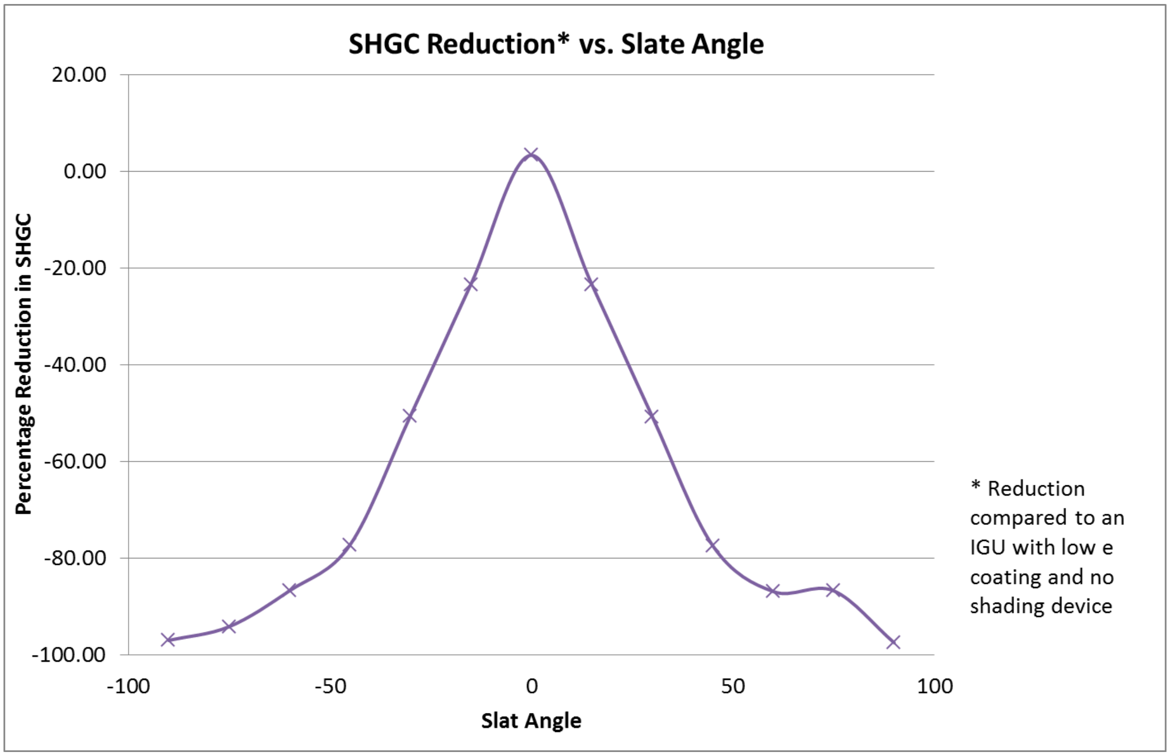

Figure 14: Reductions in SHGC vs. slat angle for exterior venetian blinds.

SUMMARY AND CONCLUSIONS

This study demonstrated that venetian blinds can be an effective retrofit option for reducing the thermal transmittance as well as the solar heat gain coefficient. Numerous criteria were investigated in this portion of the study, including slat angle, the slat width to spacing ratio (w/s), shading cavity thickness, infrared emissivity, openness fraction, slat thickness, and material conductivity. It was found that the least effective criterion was material conductivity, which resulted in no change in performance. The most effective criteria were emissivity of the blinds and the effective openness of the system, which reduced the U-value by as much as 35% and 27.5%, respectively. When these criteria were combined, it was found that up to a 60% reduction in U-value could be achieved.

There were several general conclusions that can be reached from this study.

- Window retrofit solutions generally function by reducing convective and radiative heat loss. Conduction has a small role, if any, in their function.
- Exterior shades are generally more effective at reducing U-value and dramatically more effective at reducing SHGC than those placed on the interior.
- In general, blinds with shiny metallic surfaces will perform better than those matt finishes.
- Blinds should be installed as close to the glazing surface as possible within the frame to limit the flow of convection along the glazing surface.

- Venetian blinds capable of limiting airflow when in the closed (±90°) position have the potential to significantly reduce thermal transmittance of the system.
- Blinds in the 0° position will reduce the U-value without substantially reducing the SHGC. This can be beneficial for passive solar heating.
- Venetian blinds may be particularly useful in mixed climates, wherin the blinds highly adjustable nature will allow the user to selective allow or deny solar heat gain.

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The Future of Housing: The Path to Net-Zero and Beyond

By Ted L. Clifton

Zero-EnergyPlans.com

1

Notes from William McDonnough: (Author of *Cradle to Cradle*)

Regulation is an indicator of design failure –

- Fix the design, no need for regulation!
- Being less bad is not being good, it is still bad! Let's strive for good! After all, trashing the planet is not our intention as a species! Let's get the design right!

2

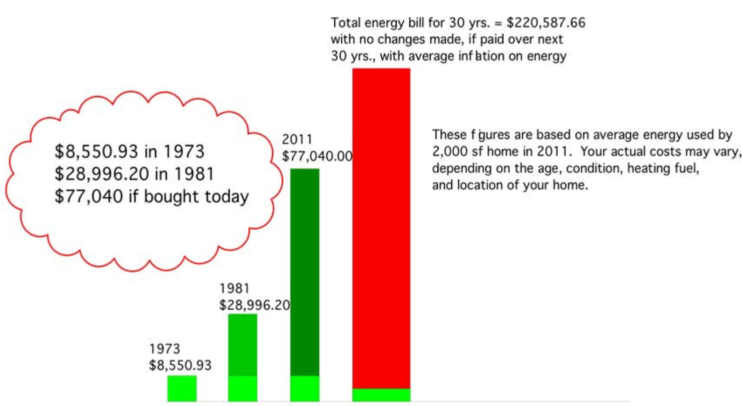
How “less bad” are your homes?

- Is a HERS rating of 41 good?
- Does everyone know what a HERS rating is? Home Energy Rating System
- HERS 100 is home built to the 2006 IECC
- HERS 0 is net-zero-energy home
- 2010 WSEC would be about HERS 82, so a 41 would only be HALF AS BAD!

3

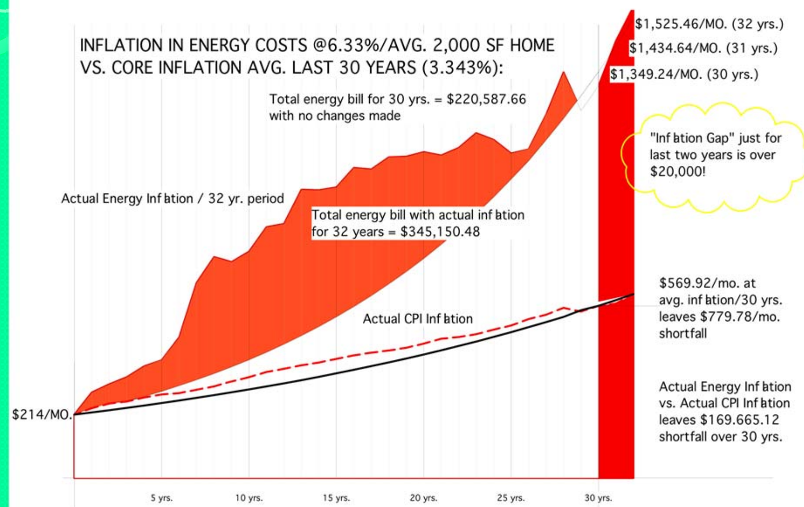
What if you bought all you energy at once?

HOW MUCH WOULD YOUR LAST 30 YEARS WORTH OF HOME ENERGY HAVE COST?



4

How much will your Future Energy Cost?



5

OK, so what can I do about it?

- Design & build better homes!
- Net-Zero Energy homes
- Positive NRG™ Homes

- But HOW????

- That is what this presentation is all about…

6

Presentation Objectives:

To learn how to design and build cost-effective net-zero-energy homes using:

- Building Orientation
- Simple Design
- Window Orientation
- Thermal Mass
- Tight Building Envelope
- Balanced Insulation Levels

7

Presentation Objectives (cont'd):

To learn how to design and build cost-effective net-zero-energy homes using:

- Balanced Ventilation
- Heat Pump Selection and Operation
- Water Heating Choices
- Efficient Appliances
- Efficient Lighting Systems
- Alternative Energy Sources

8

Who are you, and why are you here?

- Architects and Designers?
- Builders?
- Developers?
- Sub-Contractors? HVAC?
- Do-it Yourselfers?
- Policy-Makers?

9

The Future of Housing: The Path to Net-Zero and Beyond

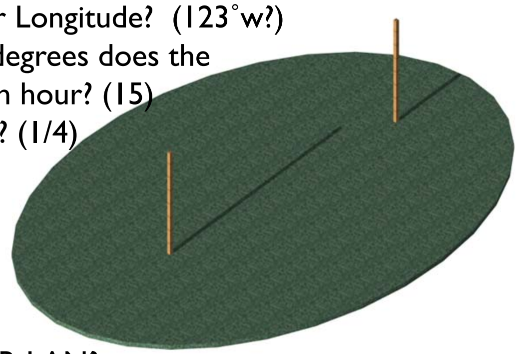
Chapter 1

Building Orientation

10

Where is South?

• Shadows from vertical objects will show true north at Local Apparent Noon (LAN)
• When is LAN?
• What is your Longitude? (123˚w?)
• How many degrees does the sun move each hour? (15)
• Each minute? (1/4)

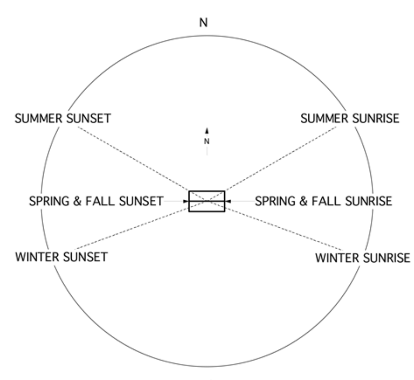


When is YOUR LAN?

11

Where Does the Sun Rise?

- In the Summer?
- In the Winter?
- In the Spring or Fall?

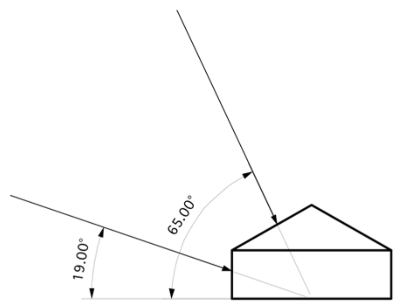


12

How High will the Sun Get?

- In the Summer?
- In the Winter?
- In the Spring or Fall?
- Where is the

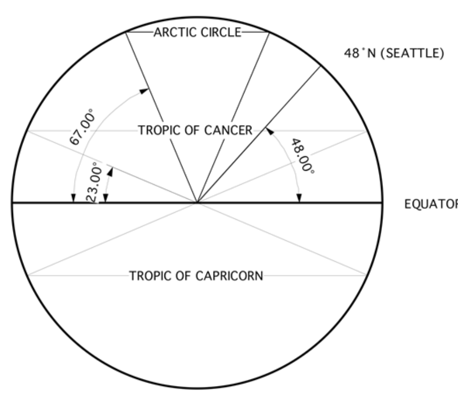
Tropic of Cancer?



How Do we Know this Stuff?

- The tropics are at 23˚ N & S
- Sun will be below the Azimuth by our Latitude (48˚)

Winter sun will be 23˚ lower
Summer sun will be 23˚ higher



14

How do we Capitalize on this?

- Building Orientation
- Roof Height and Orientation
- Window Orientation
- Landscape Design & Orientation
- Must be Climate Specific!

We will look at each in turn…

15

How do we Optimize Building Orientation?

- Long side south if possible?
- Orient roof ridge east-west
- Locate rooms within the house to optimize daylighting during the hours of most activity in those rooms
- Move building location on lot to maximize (or minimize) solar exposure due to natural or man-made restrictions

16

How do we Optimize Window Orientation?

- Most windows facing South?
- East-facing windows will provide morning warmth (when it is most needed)
- Locate rooms within the house to optimize daylighting during the hours of most activity in those rooms
- Consider likely furniture arrangements, make sure windows are not wasted!
- Each Window should provide more than one function!

17

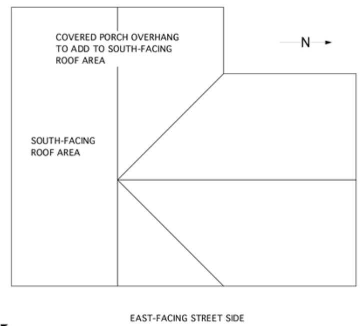
How do we Optimize Roof Height and Orientation?

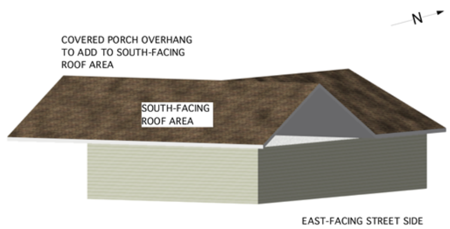
- Largest face of roof should face South
- Eave height should get roof up above natural and man-made restrictions
- Keep plumbing vents and other impediments on the north side of the ridge line
- NO south-facing dormers (unless they are shed-style, and angled to support solar panels)
- Use T-shaped roof where main ridge cannot face south

18

How do we Optimize Roof Height and Orientation?

- T-shaped roof:
- 28'x48' east-facing house has 42' of roof facing South!





19

How do we Optimize Landscaping Choices?

20

The Future of Housing: The Path to Net-Zero and Beyond

Chapter 2

Simple Design

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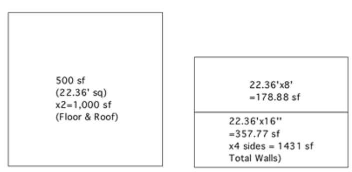
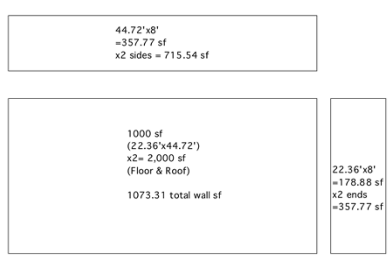
21

What is the Effect of Surface Area?

- Two-story vs. Single story
- Single story house of same size will have about 25% more surface area!



Two-Story Cube has 2,431 sf of Surface Area

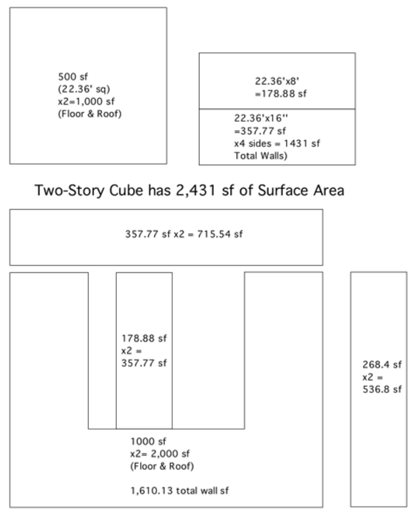


Single-Story same size house has 3,073 sf of Surface Area a 26% Increase!

22

What is the Effect of Surface Area?

- More complex shape?
- Single story house of same size will have about 48.5% more surface area!



Single-Story Complex same size house has 3,610 sf of Surface Area, a 48.5% Increase!

23

Why do we not want Surface Area?

- Surface area is where we lose Energy!
- Surface area is what costs you Money!
  - To build
  - To finish
  - To maintain
  - To dispose of at the end of its life-cycle

What is the real cost in Energy Loss?

24

OK, so how do we make a cube look good??

25

Is this the same cube?

26

The Future of Housing: The Path to Net-Zero and Beyond

Chapter 3

Window Orientation

27

How much South-Facing Glass?

- ICC-700 recommends 7%-10% of floor area in South-Facing Glass, depending on Climate Zone
- ICC-700 recommends not more than 4% for East or West-Facing Glass
- One of our 2,408 sf Net-Zero homes has 208.5 sf (8.66%) of South-Facing Glass, and 85 sf (3.5%) of East-Facing Glass, and zero North or West-Facing Glass!

28

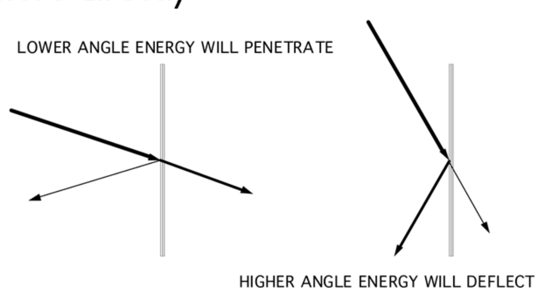
Why have East-Facing Glass?

- In most climates and seasons, homes will lose heat over night, and will need to be heated in the morning hours.
- East-facing glass can allow the sun to provide free solar energy to warm the house in the morning.
- Care must be taken not to over-heat the home in warmer climates or seasons.

29

What are the consequences of West-Facing Glazing?

- West-facing glass can over-heat the house in the afternoon, when the house is already warm from the heat of the day.
- The sun is lower in the sky in the late afternoon, so the energy penetrates the low-e glass more directly



30

What are the consequences of North-Facing Glazing?

- No energy is gained from North-Facing Glazing
- Daylight gained must be reconciled against heat energy lost:
  - Calculate lighting energy needs
  - Balance lighting against 24/7/365 heat loss
  - Can the area be lighted indirectly through other south-facing rooms in the house?

31

What are the consequences of North-Facing Glazing?

- Example 1, Light Cost:

4 hours per day @ 23 watts = 92 w/day

92 x 365 = 33,580 w, or 33.58 Kwh

33.58 Kwh @ .11¢ per Kwh = $3.69/yr.

- Example 2, Heat Cost:

3-0x4-0 window uses 165 btu/hr @ DDD

(50 degree Δt) x 24 hrs x110 (5500 HDD) = 435,600 Btu/year = 127.66 Kwh

127.66 Kwh @ .11¢ per Kwh = $14.04/yr.

32

Provide Shading (landscape features?):

- On East Side during late morning hours in Summer
- On South-facing during Late Spring, Summer, and Fall
- On all West-Facing

What can we do with glass options?

33

What can we do with Glass Options?

		Visible Light						Center of Glass Winter U-Value		Center of Glass R-Value	
			Reflectance								
	IG	Trans.						Btu/hr/ft²/°F			
Product	Construction	%	% Out	% In	SHGC	SC	RHG	Air	Argon 90%	Air	Argon 90%
Two Pane LoE-179 #2	3.0C7/13.0/3.0	79	14	14	0.65	0.75	153	0.32	0.28	3.13	3.57
Two Pane LoE-179 w/i81 #4	3.0C7/13.0/3.0i81	71	21	22	0.59	0.68	139	0.25	0.22	4.00	4.55
Two Pane LoE-272	3.0E4/13.0/3.0	72	11	12	0.41	0.48	98	0.30	0.25	3.33	4.00
Two Pane LoE-272 w/i81 #4	3.0E4/13.0/3.0i81	64	16	20	0.38	0.44	89	0.23	0.20	4.35	5.00
Two Pane LoE-270	3.0E0/13.0/3.0	70	12	13	0.37	0.42	88	0.30	0.25	3.33	4.00
Two Pane LoE-270 w/i81 #4	3.0E0/13.0/3.0i81	63	17	21	0.34	0.39	80	0.23	0.20	4.35	5.00
Two Pane LoE-366	3.0X3/13.0/3.0	65	11	12	0.27	0.31	66	0.29	0.24	3.45	4.17
Two Pane LoE-366 w/i81 #4	3.0X3/13.0/3.0i81	58	15	20	0.25	0.28	59	0.23	0.20	4.35	5.00
Triple Pane LoE-366/Clear/LoE-179 #5	3.0X3/9.8/3.0/9.8/3.0C7 #5	57	14	17	0.25	0.29	60	0.19	0.15	5.26	6.67
Triple Pane LoE-366/LoE-179 #4/i81 #6	3.0X3/9.8/3.0C7/9.8/i81 #6	51	18	24	0.22	0.26	53	0.16	0.13	6.25	7.69
Triple Pane LoE-272/Clear/LoE-179 #5	3.0E4/9.8/3.0/9.8/3.0C7 #5	63	15	17	0.38	0.43	89	0.19	0.15	5.26	6.67
Triple Pane LoE-272/LoE-179 #4/i81 #6	3.0E4/9.8/3.0C7/9.8/i81 #6	57	19	24	0.34	0.39	80	0.16	0.13	6.25	7.69
Triple Pane LoE-179/Clear/LoE-179 #5	3.0C7/9.8/3.0/9.8/3.0C7 #5	69	18	18	0.57	0.65	133	0.20	0.16	5.00	6.25
Triple Pane LoE-179/LoE-179 #4/i81 #6	3.0C7/9.8/3.0C7/9.8/i81 #6	63	24	25	0.51	0.59	119	0.17	0.14	5.88	7.14
Triple Pane LoE-366/Clear/LoE-179 #5	3.0X3/13.0/3.0/13.0/3.0C7 #5	57	14	17	0.25	0.28	59	0.16	0.13	6.25	7.69
Triple Pane LoE-366/LoE-179 #4/i81 #6	3.0X3/13.0/3.0C7/13.0/i81 #6	51	18	24	0.22	0.25	52	0.14	0.12	7.14	8.33
Triple Pane LoE-272/Clear/LoE-179 #5	3.0E4/13.0/3.0/13.0/3.0C7 #5	63	14	17	0.38	0.43	88	0.17	0.13	5.88	7.69
Triple Pane LoE-272/LoE-179 #4/i81 #6	3.0E4/13.0/3.0C7/13.0/i81 #6	57	19	24	0.34	0.39	80	0.14	0.12	7.14	8.33
Triple Pane LoE-179/Clear/LoE-179 #5	3.0C7/13.0/3.0/13.0/3.0C7 #5	69	18	18	0.57	0.65	133	0.17	0.14	5.88	7.14
Triple Pane LoE-179/LoE-179 #4/i81 #6	3.0C7/13.0/3.0C7/13.0/i81 #6	63	24	25	0.51	0.59	119	0.15	0.12	6.67	8.33
Triple Pane LoE-366/Clear/LoE-366 #5	3.0X3/13.0/3.0/13.0/3.0X3 #5	47	13	13	0.24	0.27	56	0.15	0.12	6.67	8.33
Triple Pane LoE-366/LoE-366 #4/i81 #6	3.0X3/13.0/3.0X#/13.0/i81 #6	42	15	22	0.19	0.22	46	0.13	0.11	7.69	9.09

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The Future of Housing: The Path to Net-Zero and Beyond

Chapter 4

Thermal Mass

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How Important is Thermal Mass?

- Controlling the Day/Night temperature swing is the key to Energy Efficiency:

		btu/cf/degree F	Btu/degree	
Cubic volume of house	10088	0.0183	184.6104	Loss w/o Thermal Mass:
btuh on DDD	7800	(from CP Wksht)	42.2511408	Degrees/Hour heat loss
Btuh/12 hours	93600		507.013689	Degrees/night heat loss
Note that the house would not REALLY lose hundreds of degrees in twelve hours, the number shown is merely a reflection of the number of Btus required to keep the home at the desired temperature for this amount of time at the Design Degree Temperature.				
square feet of 2nd floor	584	(concrete slab)		
thickness of 2nd floor	6	292.00	cubic feet	
square feet of lower floor	544	(concrete slab)		
thickness of lower floor	4	181.33	cubic feet	
	125	3,000	Enter Square feet of GWB	
	92.79167	1700	Enter Board Feet of Interior Lumber	
Adjusted volume of thermal mass	691.125	31.61	22031.0717	Loss w/Thermal Mass:
		(Btu/cf/degree f Concrete)	0.35404542	Deg. F/Hr.
			4.24854503	Deg. F/12 Hrs.

36

What will Thermal Mass really Save us?

- We can replace the lost Btus using Passive Solar Energy! Really? Yes, Really!
- Even without good window orientation, or a sunny day, a heat pump will be more efficient when running at warmer daytime temperatures.
- We will explore that further in the Heat Pump chapter below. (27% to 44%!)

37

How much Energy Can We Get From the Sun? Try CC-5:

Climate Consultant 5.0 (Build 3, Oct 19, 2010)

WEATHER DATA SUMMARY

LOCATION: Seattle Seattle Tacoma Intl A, WA, USA
Latitude/Longitude: 47.47° North, 122.32° West, Time Zone from Greenwich -8
Data Source: TMY3 727930 WMO Station Number, Elevation 400 ft

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	44	68	89	118	132	141	150	130	109	79	48	38	Btu/sq.ft
Direct Normal Radiation (Avg Hourly)	45	72	75	97	96	112	140	130	112	86	45	51	Btu/sq.ft
Diffuse Radiation (Avg Hourly)	30	39	49	58	66	61	52	48	48	40	33	25	Btu/sq.ft
Global Horiz Radiation (Max Hourly)	116	166	227	272	323	299	308	278	237	198	130	99	Btu/sq.ft
Direct Normal Radiation (Max Hourly)	271	281	289	297	290	289	294	294	277	285	264	254	Btu/sq.ft
Diffuse Radiation (Max Hourly)	68	87	144	141	181	170	164	156	115	117	69	70	Btu/sq.ft
Global Horiz Radiation (Avg Daily Total)	321	568	895	1375	1735	1879	1975	1598	1165	718	370	282	Btu/sq.ft
Direct Normal Radiation (Avg Daily Total)	340	633	769	1145	1286	1523	1892	1648	1239	818	354	391	Btu/sq.ft
Diffuse Radiation (Avg Daily Total)	226	336	500	685	876	819	703	604	518	368	255	183	Btu/sq.ft
Global Horiz Illumination (Avg Hourly)	1404	2185	2849	3768	4189	4487	4650	4099	3449	2516	1550	1230	footcandles
Direct Normal Illumination (Avg Hourly)	1168	2017	2173	2840	2828	3332	4085	3766	3223	2423	1204	1264	footcandles
Dry Bulb Temperature (Avg Monthly)	40	42	47	51	55	60	64	66	59	52	46	41	degrees F
Dew Point Temperature (Avg Monthly)	34	35	37	41	45	47	50	53	51	44	41	36	degrees F
Relative Humidity (Avg Monthly)	80	76	71	71	71	66	64	66	76	76	83	82	percent
Wind Direction (Avg Monthly)	167	152	167	202	199	207	199	215	145	192	150	136	degrees
Wind Speed (Avg Monthly)	8	8	8	9	8	9	8	8	4	9	8	7	mph
Snow Depth (Avg Monthly)													inches
Ground Temperature (Avg Monthly of 3 Depths)	48	44	43	43	46	50	54	58	60	59	56	52	degrees F

Back Next

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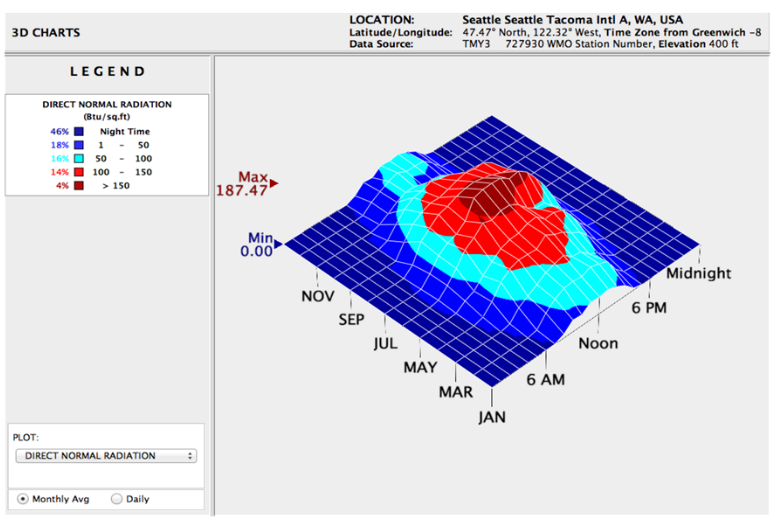
How much Energy Can We Get From the Sun?

- The previous slide showed that Seattle gets up to 1,892 Btu per day per square foot of Direct Normal Radiation in the Summer
- Seattle gets at least 340 Btu per day of Direct Normal Radiation even in the winter
- Diffuse Radiation is less, but still at least 183 Btu/sf/day during the darkest Winter Month!

So how much is that, and what can we do with it?

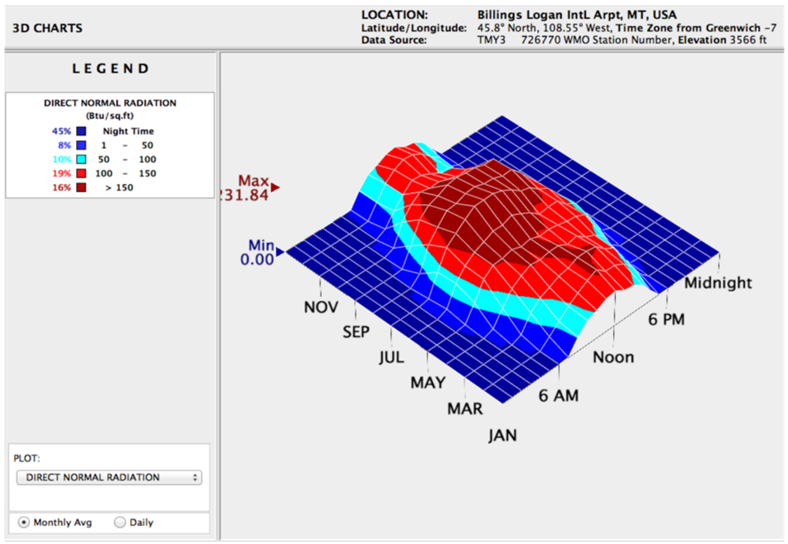
39

How does that graph out?



40

Compare to Billings, Montana:



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How much Energy Can We Get From the Sun? Let's Calculate:

- Diffuse Radiation is less, but still at least 183 Btu/sf/day during the darkest Winter Month!
- If we have 200sf of South-Facing Glass, with an SHGC of .5, we would get 100 times 183, or 18,300 Btu on a cloudy winter day!
- That is about one hour worth of energy on the Design Degree Day for the house in our example
- On a Sunny Winter Day, we would gain about double that amount, 34,000 Btu.

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Big whoop, one hour of Energy…

- Ah, but that is at the Design Degree Day, Based on an outside temperature of 19 degrees… (in Seattle)
- What is the average outside temperature during that same cold winter month?

Let's take another look at Climate Consultant 5:

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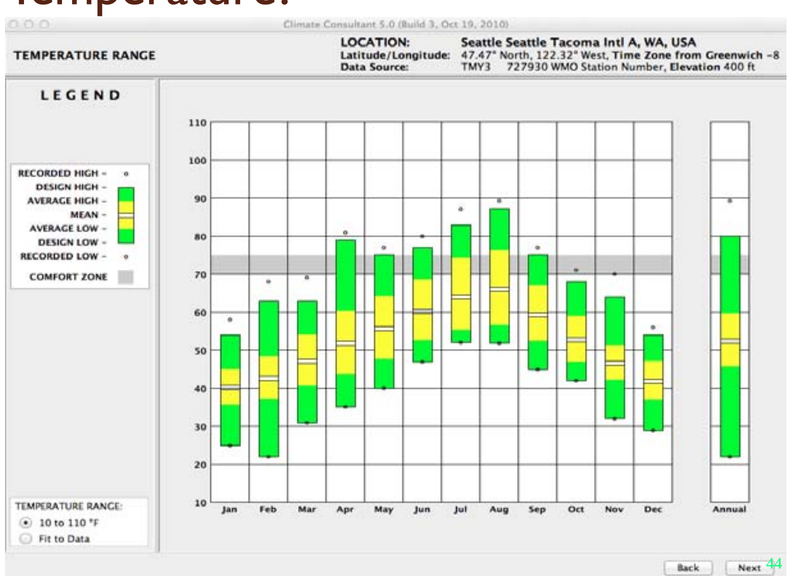
What is our Average Winter Temperature?



44

What is our Average Winter Temperature?

- Looks like about 41 degrees in January…
- Only 57% of the way to the Design Degree Day!
- This means a sunny day would provide at least 3 1/2 hours of energy
- A cloudy day would provide 1 ¾ hours of energy…

This might not seem like much, but it adds up fast over time!

45

What is our Average Annual Temperature?

- Looks like about 52 degrees…
- Only 35% of the way to the Design Degree Day!
- Seattle's Average Annual Direct Normal Radiation is just under 100 Btu/sf/hr
- Six hours of sun will provide 60Kbtu, or enough energy to heat the house for nine hours on the average day.

46

What Happens in the Summertime?

- Does the slab get too hot?
  - It can, in some climates
- Can we cool it off at night?
  - Yes, in most climates
- Where will the excess energy go?
  - Some will be transferred to air, and exhausted to the outside
  - Some can be transferred into the ground
  - Keep your thermal mass stable!

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What can we do to optimize Thermal Mass?

- Keep all Thermal Mass completely within the Building Envelope
- Add Thermal Mass even on second floors, by pouring a slab over your framed wood floor.
- Orient windows to provide direct access to your Thermal Mass.
- Use Thermal Mass walls or stairs to better capture energy from East or West-facing windows

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The Future of Housing: The Path to Net-Zero and Beyond

Chapter 5

Tight Envelope

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What is the Effect of a Tight Building Envelope?

- How much energy is lost through convection?
  - Air contains .0183 Btu per cubic foot per degree (at sea level)
  - If your house is 1,000 sf, with an 8' ceiling (as in our Cube House diagram earlier) you have 8,000 cubic feet of air to lose.
  - Let's do the math: 8,000 x .0183 = 146.4 Btu per degree of temperature difference
  - Our DDD is 50˚ Δt, 50 x 146.4 = 7,320 Btu

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What is the Effect of a Tight Building Envelope?

- How much energy is lost through convection?
  - Our DDD is 50˚ Δt, 50 x 146.4 = 7,320 Btu
  - At .6 ACH, you will lose 4,392 Btu/hr.
  - In a 24-hour day, that would be 105,408 Btu
  - At .35 ACH, you would lose 2,562 Btu/hr.
  - In a 24-hour day, that would be 61,488 Btu
  - At .1 ACH, you would only lose 17,560 Btu in a day. I like that better!

51

How does that compare to the Conductive Heat Loss for the same house?

- With 12% glazing, and a good wall assembly, the 1000 sf Two-Story design will use a total of 10,866 Btuh on the DDD including .6 ACH
- 4,392 Btuh are from air infiltration alone!
- If this is a 2-bedroom home, ASHRAE 62.2 only requires 32.5 cfm, or 1,784 Btuh
- How about we save the other 2,608 Btuh?

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How much does this save us in a Year? Let's do the math:

- 2,608 Btuh x 24 hours x 110 (HDD/DDDΔt) = 6,885,120 Btu per year
- If heating with 92% efficient Natural Gas at .80¢ per therm, this would save $59.87 per year.
- Remember, this is just for a tightening up a tiny 1,000 sf house!
- A 2,000 sf house would save twice as much, and a more complex house would save even more!

53

Walls as Filters? Not a good idea!

- Walls that "Breathe" trap pollens, mold and mildew spores, odors, steam and grease from cooking, and all other sorts of undesirable elements in the insulation layers.
- These can build up, and cause health problems, and degrade the structural integrity of the walls.
- Wall Cavities Must Be Tight!

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The Future of Housing:
The Path to Net-Zero and Beyond

Chapter 6

Balanced Insulation

55

Why are we building houses this way?

- Consider a 10'x10' room, with R-60 insulation on the lid.
- Then remove the insulation from a one-foot square area, what is the net R-value of the entire roof assembly?

56

Let's try something…

- Start with any house for which you have an energy model (we will show one here using the WSU CP Worksheet)
- Skew your insulation levels so that you have very disparate levels in different areas, but so that they add up the same
  - For example, if you downgrade 1000 sf of walls from R-21 to R-11, upgrade the 1000 sf of roof from R-38 to R-49

57

What Happened? Original:

Washington State Energy Code: Component Performance Worksheet, Type R-3 Occupancies

Heating System Size

Ducts are located in unconditioned space.

Equipment size over design load: 100%

Btu/hour output: 12,602

KW: 3.7

Conditioned Floor Area: 1915

Conditioned Building Volume: 2127.217

Weather Station: Seattle: Sea-Tac AP

onent Performance, R-3 occupancies	Code Target Values Area	Code Target Values UA	Proposed Design Values Area	Proposed Design Values UA
Vertical Glazing U = 0.300	287	86.2	255	44.5
Overhead Glazing U = 0.500	0	0.0	0	0.0
Doors U = 0.200	38	7.6	38	9.1
Flat/Vaulted Ceilings U = 0.027	1315	35.5	1315	36.2
Wall (above grade) U = 0.056	2088	116.9	2121	101.8
Floors U = 0.029	0	0.0	0	0.0
Slab on Grade F = 0.360	136	49.0	136	44.9
Below Grade				
2' depth, wall U = 0.042	0	0.0	0	0.0
2' depth, slab F = 0.590	0	0.0	0	0.0
3.5' depth, wall U = 0.041	0	0.0	0	0.0
3.5' depth, slab F = 0.640	0	0.0	0	0.0
7' depth, wall U = 0.037	0	0.0	0	0.0
7' depth, slab F = 0.570	0	0.0	0	0.0

Target UA Total: 295.2 | Proposed UA Total: 236.6

Target Credits from Chpt. 9: 1.0 | Proposed Credits from Chpt. 9: 4.5 **Qualifies**

58

What Happened? Skewed:

The house uses 14% more energy!

Washington State Energy Code: Component Performance Worksheet, Type R-3 Occupancies

Heating System Size
Ducts are located in unconditioned space.
Equipment size over design load 100%
Btu/hour output 14,323
KW 4.2

Conditioned Floor Area 1915
Conditioned Building Volume 2127.217
Weather Station Seattle: Sea-Tac AP

›onent Performance, R-3 occupancies	Code Target Values Area	UA	Proposed Design Values Area	UA
Vertical Glazing U = 0.300	287	86.2	255	44.5
Overhead Glazing U = 0.500	0	0.0	0	0.0
Doors U = 0.200	38	7.6	38	9.1
Flat/Vaulted Ceilings U = 0.027	1315	35.5	1315	28.9
Wall (above grade) U = 0.056	2088	116.9	2121	150.6
Floors U = 0.029	0	0.0	0	0.0
Slab on Grade F = 0.360	136	49.0	136	40.9
Below Grade				
2' depth, wall U = 0.042	0	0.0	0	0.0
2' depth, slab F = 0.590	0	0.0	0	0.0
3.5' depth, wall U = 0.041	0	0.0	0	0.0
3.5' depth, slab F = 0.640	0	0.0	0	0.0
7' depth, wall U = 0.037	0	0.0	0	0.0
7' depth, slab F = 0.570	0	0.0	0	0.0

Target UA Total	295.2	Proposed UA Total	274.0
Target Credits from Chpt. 9	1.0	Proposed Credits from Chpt. 9	4.5 Qualifies

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Consider what Happens when we add windows:

- Remove 12 square feet of R-21 Wall
- Replace it with an R-3 Window
- What do you suppose just happened to the net-R-value of your R-21 Wall?
- Now do that about ten times!
  - Our Cube House just increased Btuh by 21%!
  - With U-21 windows, only 14.6% increase!
- That is how we are building houses!
- We need to do better on our windows & doors!

60

If we use Better Windows, can we use More Glass?

- If we can save 1/3 of the energy loss by using better windows, we could add 33% more windows and get the same result!
- Could we add only those windows that will result in capturing the solar heat gains outlined above?
- Those are questions that must be answered individually for each project.

61

Balanced Insulation Levels, Summary: Heat goes to Cold!

- The closer all the insulation levels are to each other, the better the home will perform, relative to the cost and depth of the insulation.

62

Balanced Insulation Levels, Summary: Heat goes to Cold!

- The closer all the insulation levels are to each other, the better the home will perform, relative to the cost and depth of the insulation.
- Before considering adding even more attic insulation or crawl-space insulation, consider ways of adding more wall insulation, to help even out the insulation levels

63

Balanced Insulation Levels, Summary: Heat goes to Cold!

- The closer all the insulation levels are to each other, the better the home will perform, relative to the cost and depth of the insulation.
- Before considering adding even more attic insulation or crawl-space insulation, consider ways of adding more wall insulation, to help even out the insulation levels
- Use the Lowest U-value Windows and Doors you can find!

64

Balanced Insulation Levels, Summary: Heat goes to Cold!

- The closer all the insulation levels are to each other, the better the home will perform, relative to the cost and depth of the insulation.
- Before considering adding even more attic insulation or crawl-space insulation, consider ways of adding more wall insulation, to help even out the insulation levels
- Use the Lowest U-value Windows and Doors you can find!
- Remember that every cost needs to be weighed against the cost of providing renewable energy!

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The Future of Housing: The Path to Net-Zero and Beyond

Chapter 7

Balanced Ventilation

Zero-EnergyPlans.com

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Balanced Ventilation, Why?

- You can't really suck the spots off a leopard!
- Tight house will not allow air to come in through wall cavities
- Exhaust-only ventilation will not work at design values, and therefore will not provide adequate fresh air
- Cost of operation will be lower when balanced ventilation strategies are used

67

Balanced Ventilation, How?

- Commercial Kitchens are required to have balanced ventilation for the class-one hood system! Air in = Air out.
- Without make-up air, efficiency drops
- Two smaller fans working in concert with each other will use less energy than one fan struggling by itself!
- Compare (2) FR100s, vs (1) FR160:

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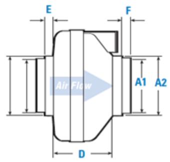
Balanced ventilation uses just 1/4 the energy of exhaust-only:

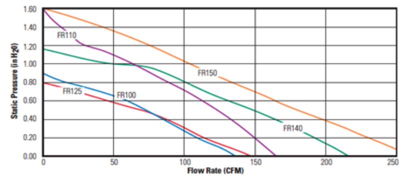


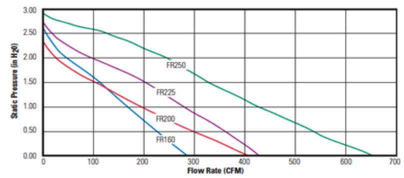
FIVE YEAR WARRANTY

Model	†A1	A2	C	D	E	F
FR 100	4	5	9½	6⅛	⅞	⅞
FR 110	4	5	9½	6⅛	⅞	⅞
FR 125	–	5	9½	6⅛	⅞	–
FR 140	6	6¼	11¾	5⅞	1	⅞
FR 150	6	6¼	11¾	5⅞	1	⅞
FR 160	6	6¼	11¾	5⅞	1	⅞
FR 200	8	10	13¼	6¼	1½	1½
FR 225	8	10	13¼	6¼	1½	1½
FR 250	–	10	13¼	6¼	1½	–

All dimensions in inches.
† Duct connections are 1/8" smaller than duct size.

Look for the Energy Star Rated Models in Performance Data Chart.





PERFORMANCE DATA

Fan Model	Energy Star	RPM	Voltage	Rated Watts	Wattage Range	Max. Amps	Static Pressure in Inches W.G. 0"	.2"	.4"	.6"	.8"	1.0"	1.5"	Max. Ps	Duct Dia.
FR 100	✔	2950	120	21.2	13 – 22	0.18	137	110	83	60	21	—	—	0.9"	4"
FR 110	—	2900	115	80	62 – 80	0.72	167	150	133	113	88	63	4	1.60"	4"
FR 125	✔	2950	115	18	15 – 18	0.18	148	120	88	47	—	—	—	0.79"	5"
FR 140	✔	2850	115	61	47 – 62	0.53	214	190	162	132	99	46	—	1.15"	6"
FR 150	✔	2750	120	71	54 – 72	0.67	263	230	198	167	136	106	17	1.58"	6"
FR 160	—	2750	115	129	103 – 130	1.14	289	260	233	206	179	154	89	2.32"	6"
FR 200	✔	2750	115	122	106 – 128	1.11	408	360	308	259	213	173	72	2.14"	8"
FR 225	✔	3100	115	137	111 – 152	1.35	429	400	366	332	297	260	168	2.48"	8"
FR 250	—	2850	115	241	146 – 248	2.40	649	600	553	506	454	403	294	2.58"	10"

Performance shown is for installation type D - Ducted inlet, Ducted outlet. Speed (RPM) shown is nominal. Performance is based on actual speed of test. Performance ratings do not include the effects of appurtenances in the airstream.

69

Balanced ventilation uses 1/4 the energy of exhaust-only:

- Example:
  FR-100 uses 13w @ 0"wc, 137 cfm
  x 2 = 26w, moving 274 cfm of air

  FR-160 uses 106w @ .2"wc, 260 cfm!

70

What about Air Quality?

- Should our incoming air be filtered?
  - For pollens & other allergens?
  - For dust & dirt?
  - For molds & mildew?

Let's look at how:

- Passive filters
- Active filters

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What about Air Quality?

- In-line Filters:

- Provide filtration
- Do not provide balanced ventilation

72

What about Air Quality?

- Powered filters:

- Provide filtration
- Can provide balanced ventilation

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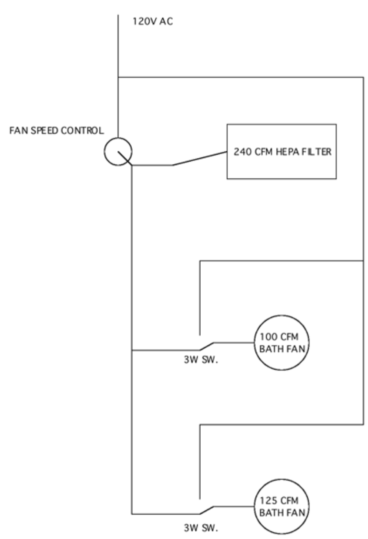
Possible Electrical Schematic:



NOTES:

1. MAKE SURE THAT FANS YOU ARE USING ARE COMPATIBLE WITH SPEED CONTROLS. PANASONIC FANS CANNOT BE USED WITH THIS SYSTEM

2. HEPA FILTER CFM SHOULD BE EQUAL TO OR JUST ABOVE THE COMBINED CFM OF THE BATH FANS TO ACHIEVE NEUTRAL OR SLIGHTLY POSITIVE PRESSURE

3. THE HEPA FILTERS AND FANS I AM USING ARE FAN-TECH BRAND, THE BATH FANS ARE REMOTE FANS, DRAWING AS LITTLE AS 18-19W PER FAN. THE 125 CFN FAN USES 5" PIPE, THE 100 CFM FAN USES 4". THE REMOTE FANS ARE EXTREMELY QUIET, AND LEAVE ONLY A SMALL PENETRATION IN THE CEILING, LOOKING MUCH LIKE A 4" OR 5" RECESSED CAN TRIM. CHECK OUT www.efi.org/wholesale

4. LOCATE THE 3-WAY SWITCH IN THE BATHROOM OR OTHER ROOM SERVED BY THE EXHAUST FAN FOR CONVENIENCE.

5. LOCATE THE SPEED CONTROL IN THE AREA SERVED BY THE HEPA FILTER, FOR BEST COOLING AND AIR HANDLING CONTROL.

6. OTHER MORE AUTOMATED CONTROLS COULD BE USED TO ADJUST THE SPEED CONTROL, BUT MY EXPERIENCE HAS BEEN THAT SIMPLE IS BEST, MY HOMEOWNERS SEEM TO LIKE THE MANUAL CONTROLS OF THIS SYSTEM. NO COMPLICATED BUTTONS OR MANUALS TO READ.

74

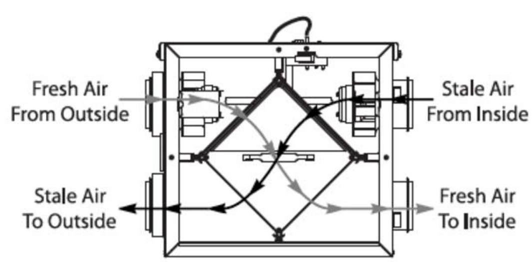
How about HRVs & ERVs?

- The more extreme your winter and summer temperatures, the more energy you will save with an HRV or ERV
- What is the difference between HRV and ERV?
- Energy Recovery Ventilator (ERV) also re-captures moisture content
- Heat Recovery Ventilator only re-captures a percentage of the sensible heat

75

How much energy will an HRV recover?

- It depends on the efficiency of the unit:



- This cross-flow unit is rated at around 60%, depending on temperature and pressure

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How much energy will an HRV recover?

- It depends on the efficiency of the unit:
- This counter-flow unit is rated at around 95%, depending on temperature and pressure
- What does that mean in real dollars?

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How much energy will an HRV recover? Will it be worth the cost?

Fan Vs HRV?

Project Name:	Carlson House		Elect. cost/Kwh:	0.11
Location:	Street Address		Heat system HSPF	15.4
City:	Your City		Heat system COP	4.51
State:	Your State		Heating Degree Days	5400
ZIP:			Avg. Ext. Temp:	51
			ASHRAE 62.2 Req.(CFM)	50
www.Zero-EnergyPlans.com	Copyright 2012 Zero-Energy Plans LLC			
	Intended for comparison purposes only			
Fan Model:	Panasonic Whisper Green		Zehnder ComfoAir 200	
Fan Watts	11		HRV Watts	143
Fan CFM	80		HRV CFM	118
			Reovery %	95%
Fan cost:*	$132.00		Hrv cost:**	$1,495.00
Fan Hrs/Day	15		HRV Hrs/Day	10.1694915
Fan Btuh/Yr lost	9137556		HRV Btuh/Yr. lost	456877.8
Fan Heat Kwh/Yr:	2678.06448	<using HSPF>	HRV Heat Kwh/Yr:	133.903224
Heating system heat recovery Kwh:	593.347792		Heating system heat recovery Kwh:	29.6673896
Fan Op. Kwh/yr:	60.225		HRV Op. Kwh/Yr:	530.79661
Fan Total Kwh/Yr:	653.57		HRV Total Kwh/Yr:	560.46
Fan Total Cost/Yr:	$71.89	interest rate	HRV Total Cost/Yr:	$61.65
20-Yr Ammortization:	($9.71)	4.00%	20-Yr Ammortization	($110.00)
Total cost w/Ammort:	$81.61		Total cost w/Ammort:	$171.66

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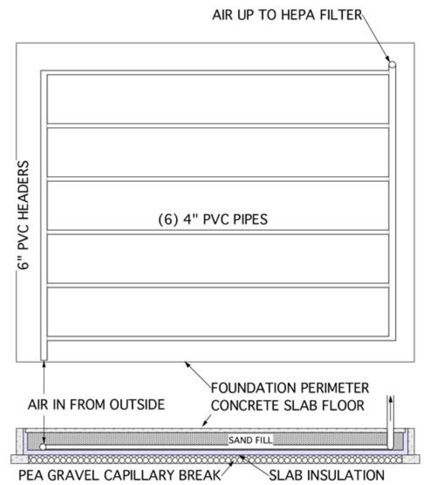
Is there another way? Earth Tubes:

- Under-slab piping
- Cools incoming air during summer
- Warms incoming air during winter
- Must know soil temperatures!
- Works best with in-floor radiant systems!



79

And yet another way…

- Two opening windows, on opposite sides of the house, will allow for <u>Balanced Ventilation</u>
- Remember, warm air rises…
- Even without wind, the stack effect can cause sufficient air movement to ventilate a house, especially two and three stories
- Incorporate this idea into your window placement!

80

Ventilation Summary:

- Always balance large ventilation loads, especially in small, tight homes
- Smaller venting loads can be exhaust-only, especially short-duration loads
- Consider appropriate filtration for incoming air
- Install controls that allow automatic operation, but allow user-adjustment
- Keep it simple!

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The Future of Housing: The Path to Net-Zero and Beyond

Chapter 8

Why Heat Pumps?

Zero-EnergyPlans.com

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Why Heat Pumps?

- We can replace electricity with Wind, Solar, & Hydro
- Once Gas is used, it is GONE!
- When Gas is burned, it contributes to Climate Change
- A Heat Pump only moves heat from one place to another, does not create heat!
- Heat pumps have lower maintenance costs, and higher ultimate efficiency

83

Why Heat Pumps?

- Consider ONLY the efficiency factor:
  - Modern Gas Power Plants produce electricity at about 60% efficiency, delivered to the grid
  - They can be located right in the middle of town, so no line-losses
  - Operate a Heat Pump and see the net energy savings:
  - At 240% efficient x .6 = 144% net efficiency with use of gas, only requires HSPF of 8.2!

84

Why Heat Pumps?

- How efficient are Heat Pumps?
  - Most newer units are 300% efficient, HSPF around 10.1
  - This would be 180% net-efficiency with the gas used to make the electricity!
  - A Ground Source Heat Pump can be up to 450% efficient, which would be 270% efficient with its use of gas!
  - Air-source heat pumps are now available that will work down to -10˚F at 200% efficiency!

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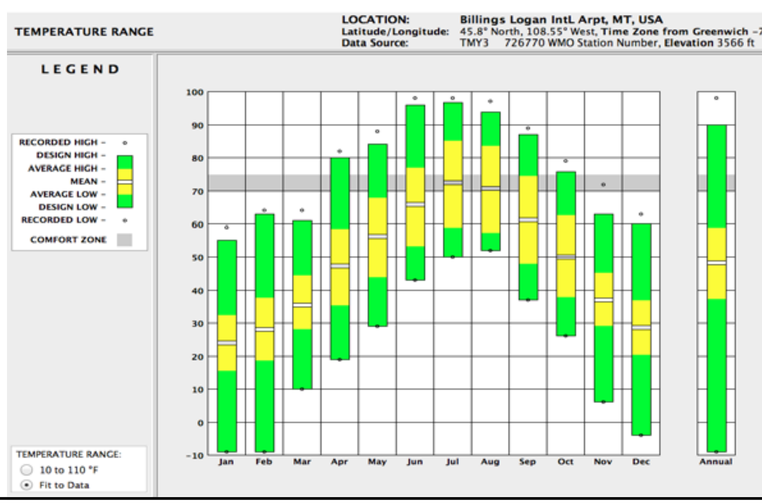
Where will Air-source Heat Pumps NOT work?

- Consider Billings, Montana:



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Where will Air-source Heat Pumps NOT work?

- Consider Billings, Montana:
  - Remember our section on Thermal Mass!
  - For overnight, store heat in the slab
  - Re-heat the home during the day using the air-source heat pump
  - The difference between the low (-9˚F) and the average winter temperature (+26F) is 35˚F!
  - This represents a 44% savings in energy required to heat the home!

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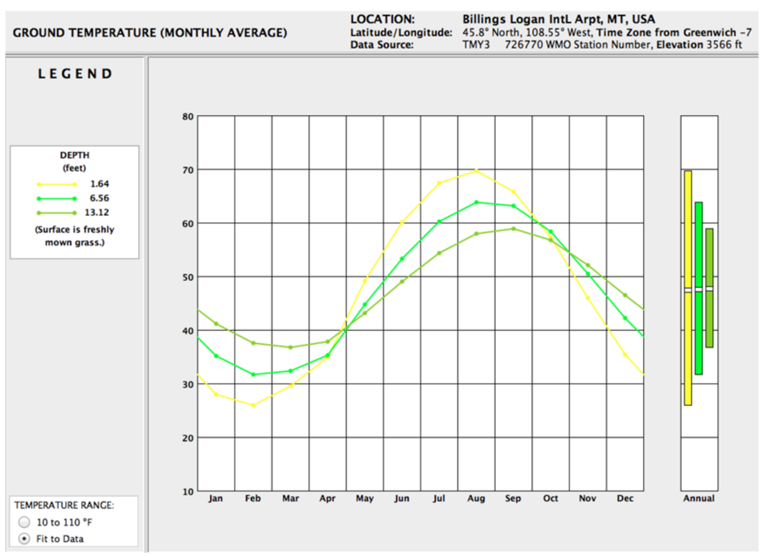
Where might Ground Source Heat Pumps have problems?



88

Where might Ground Source Heat Pumps have problems?

- Again, look at Billings, MT:
  - Ground temperature drops to near 32˚F at 2 meter depth
  - Ground temperature at 4 meter depth is warm enough to operate safely

HEATING PERFORMANCE

Based on 5.3 GPM load and 6.5 GPM source fluid flow

Leaving Load Fluid (F)	Entering Source Fluid (F)	Heating Capacity (MBtuH)	Power Input (kW)	COP	Heat of Absorb. (MBtuH)
100°	35°	25.73	2.01	3.75	18.87
	40°	27.33	2.00	4.01	20.50
	50°	30.82	1.97	4.57	24.08
	60°	34.74	1.95	5.23	28.09
	70°	39.11	1.92	5.96	32.55
110°	35°	25.53	2.28	3.28	17.74
	40°	27.06	2.27	3.49	19.31
	50°	30.40	2.24	3.97	22.75
	60°	34.15	2.21	4.53	26.60
	70°	38.34	2.18	5.15	30.89

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How to make the Ground Source Heat Pump work in Billings, MT?

- Deep bore system may be preferred!
- Remember: Thermal Mass slabs will take several days, or even weeks to initially bring up to temperature, so take your time on start-up!

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Limitations on Air-Source Heat Pumps:

- Cold weather hard limits (-10˚F)
- Reduced capacity at the lower end of the operating range
  - Requires careful sizing of unit to match peak demand
  - Could require back-up system

What can inverter-based units do for you?

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Inverter-based Heat Pumps

- Ductless Mini-splits, and other newer heat pump designs now operate using DC motors
  - Can start slow, & ramp up to full load as needed
  - Can operate at part-load conditions at greater than rated efficiency
  - This is because they can operate at lower temperatures, using their larger, oversized surface areas

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Heat with Heat, Cool with Air!

- Put your hand against your mouth, & puff softly… warm, isn't it? 98.6° air!
- Now move your hand a few inches away, and blow hard… it feels cold! Still 98.6° air, but now it is moving
- Lesson: When warm air moves, it feels cold.
- Factor this into your HVAC plan
- Radiant heat will be more comfortable!

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HVAC summary:

- Heat Pumps provide superior ultimate efficiency
- Augment Heat Pumps in colder climates, do not eliminate them!
- Use newer, inverter-based heat pumps when available
- Use Thermal Mass to allow your Air-Source Heat Pump to operate only during the day in colder climates
- Heat with heat, cool with air!

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The Future of Housing: The Path to Net-Zero and Beyond

Chapter 9

Water Heating

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How Important is Water Heating?

- Is usually the largest energy use, after space conditioning
- Can be the largest energy use, when the right measures are put into the building envelope, passive solar, thermal mass, etc.
- Water heating loads can be cut by more than 90%!

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Water Heating, What are the Options?

- Tank-type water heaters
  - Electric (100% efficient, x.6 = 60% net use of gas)
  - Fossil Fuel (up to 95% efficient for condensing units
- On-demand water heaters
  - Electric (same efficiency, no storage capacity)
  - Fossil Fuel (up to 98% efficient, no storage)
- Heat Pump water heaters
  - Up to 240% efficient (x .6 = 144% NU/Gas)

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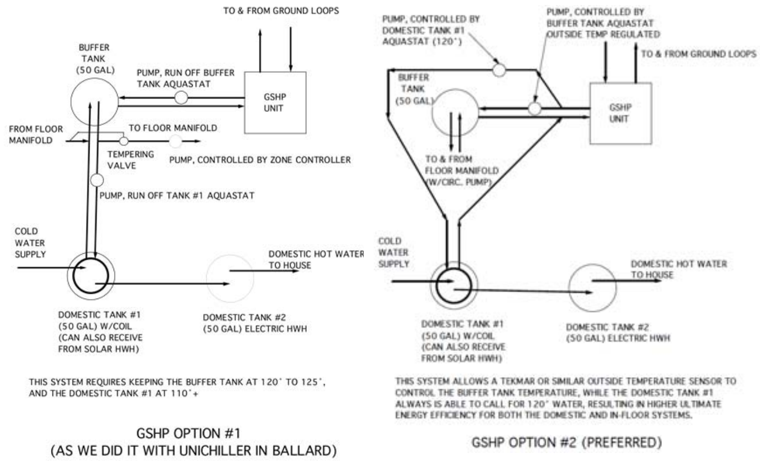
Water Heating, What are the Options, Cont'd

- GSHP Desuperheaters
  - Up to 450% efficient (x .6 = 270% NU/Gas
  - How about without a Desuperheater?
  - Desuperheaters only work when GSHP is heating the house
  - These two options prioritize the production of Domestic Hot Water:

98

Two GSHP/Domestic HW options:



99

Water Heating, What are the Options, Cont'd

- GSHP Desuperheaters
  - Up to 450% efficient (x .6 = 270% NU/Gas
- Solar hot water heaters
  - Require electricity to run pumps only
  - May not provide enough hot water during cold & rainy weather
  - Can be used in combination with other heating sources
  - Match very well with Ground Source Heat Pumps, and Air-to Water Heat Pumps

100

Solar Water Heating Options?

- Flat-plate collectors
  - Work best in sunny climate
- Evacuated-tube collectors
  - Work best in cloudy climate
- Closed-loop system
- Drain-back system
  - Can shock Evacuated Tube system

101

Why, and where, to use a Tank…

- In cold climate, if tank is inside the conditioned building, residual heat is used by the building
- In warm climate this is not desirable, it adds to the cooling loads

  What effect will a Heat Pump Water Heater have?

102

Why, and where, to use a Heat Pump Water Heater…

- In cold climate, if HPWH is inside the conditioned building, it will be robbing heat from the building…
- In warm climate this is desirable, it reduces the cooling loads!
- In a moderate climate, the HPWH can be placed in an attached garage. On average, the garage temperature will be warm enough to benefit the HPWH

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Why, and where, to use an On-Demand Water Heater…

- In a cold climate, the On-Demand unit is only supreme when hot water use is irregular (as for vacation homes)
- In warm climate the On-Demand water heater will not contribute to the cooling loads
- On-Demand units can be located nearest the point of use
- They can be used as back-up to Solar Hot Water Heaters

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Water Heating Summary:

- Water Heating is VERY climate specific!
- Water Heating can also be user-specific
- Calculate your loads, consult your climate, then specify your system!
- In a moderate or cold climate, residual heat is usually desirable, and can help offset space-heating loads

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The Future of Housing: The Path to Net-Zero and Beyond

Chapter 10

Efficient Appliances

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Define the Loads:

- In most Net-Zero-Ready homes, Cooking will be the largest remaining energy load!
- Clothes Dryers could be the next largest Appliance load
  - They not only create a lot of heat, they also suck conditioned air out of the house!
- The Refrigerator will likely come next
- The Dishwasher will use two to three times as much energy as the Clothes Washer

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Get out the Hatchet!

- Start by chopping the largest loads
  - Induction Ranges are saving up to 60% of cooking loads!
- Then the next largest
  - Condensing clothes dryers re-circulate the same air, wringing the moisture out of it
  - Heat gets recovered, and re-used!
- Then tighten up on the smaller loads
  - Check the Energy Star stickers closely!

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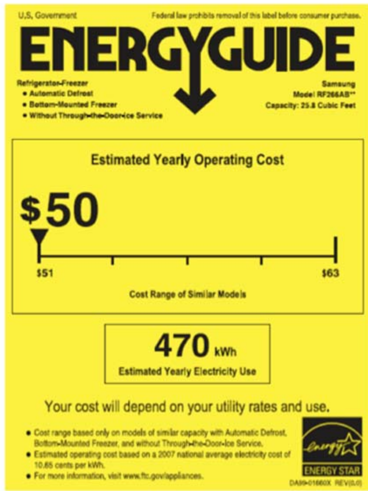
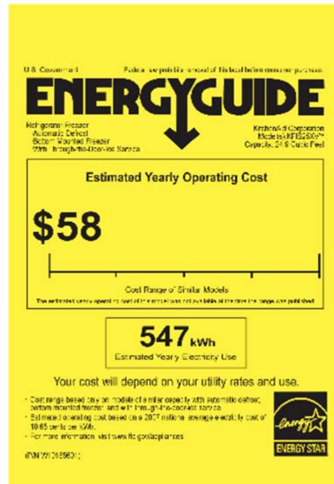
Check the EnergyGuides carefully: Both are Energy Star!





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What is $8 over time?

Year	inflation	Cost/Kwh	Make/Model	Alt. Make/Model	size	cost/year	cost/ time	save/ time	alt. cost/yr	alt. cost/time
1	1.0605	0.1070	R-1/XX	R-2/YZ	26 Cu.Ft.	$60.00	$60.00	$8.00	$52.00	$52.00
2	1.0605	0.1135	R-1/XX	R-2/YZ	26 Cu.Ft.	$63.63	$123.63	$16.48	$55.15	$107.15
3	1.0605	0.1203	R-1/XX	R-2/YZ	26 Cu.Ft.	$67.48	$191.11	$25.48	$58.48	$165.63
4	1.0605	0.1276	R-1/XX	R-2/YZ	26 Cu.Ft.	$71.56	$262.67	$35.02	$62.02	$227.65
5	1.0605	0.1353	R-1/XX	R-2/YZ	26 Cu.Ft.	$75.89	$338.56	$45.14	$65.77	$293.42
6	1.0605	0.1435	R-1/XX	R-2/YZ	26 Cu.Ft.	$80.48	$419.05	$55.87	$69.75	$363.17
7	1.0605	0.1522	R-1/XX	R-2/YZ	26 Cu.Ft.	$85.35	$504.40	$67.25	$73.97	$437.15
8	1.0605	0.1614	R-1/XX	R-2/YZ	26 Cu.Ft.	$90.52	$594.91	$79.32	$78.45	$515.59
9	1.0605	0.1712	R-1/XX	R-2/YZ	26 Cu.Ft.	$95.99	$690.91	$92.12	$83.19	$598.79
10	1.0605	0.1815	R-1/XX	R-2/YZ	26 Cu.Ft.	$101.80	$792.71	$105.69	$88.23	$687.01
11	1.0605	0.1925	R-1/XX	R-2/YZ	26 Cu.Ft.	$107.96	$900.67	$120.09	$93.56	$780.58
12	1.0605	0.2042	R-1/XX	R-2/YZ	26 Cu.Ft.	$114.49	$1,015.16	$135.35	$99.22	$879.80
13	1.0605	0.2165	R-1/XX	R-2/YZ	26 Cu.Ft.	$121.42	$1,136.57	$151.54	$105.23	$985.03
14	1.0605	0.2296	R-1/XX	R-2/YZ	26 Cu.Ft.	$128.76	$1,265.34	$168.71	$111.59	$1,096.62
15	1.0605	0.2435	R-1/XX	R-2/YZ	26 Cu.Ft.	$136.55	$1,401.89	$186.92	$118.35	$1,214.97
16	1.0605	0.2583	R-1/XX	R-2/YZ	26 Cu.Ft.	$144.81	$1,546.70	$206.23	$125.51	$1,340.48
17	1.0605	0.2739	R-1/XX	R-2/YZ	26 Cu.Ft.	$153.58	$1,700.28	$226.70	$133.10	$1,473.57
18	1.0605	0.2904	R-1/XX	R-2/YZ	26 Cu.Ft.	$162.87	$1,863.15	$248.42	$141.15	$1,614.73
19	1.0605	0.3080	R-1/XX	R-2/YZ	26 Cu.Ft.	$172.72	$2,035.87	$271.45	$149.69	$1,764.42
20	1.0605	0.3267	R-1/XX	R-2/YZ	26 Cu.Ft.	$183.17	$2,219.04	$295.87	$158.75	$1,923.16
21	1.0605	0.3464	R-1/XX	R-2/YZ	26 Cu.Ft.	$194.25	$2,413.29	$321.77	$168.35	$2,091.52
22	1.0605	0.3674	R-1/XX	R-2/YZ	26 Cu.Ft.	$206.00	$2,619.29	$349.24	$178.54	$2,270.05
23	1.0605	0.3896	R-1/XX	R-2/YZ	26 Cu.Ft.	$218.47	$2,837.76	$378.37	$189.34	$2,459.39
24	1.0605	0.4132	R-1/XX	R-2/YZ	26 Cu.Ft.	$231.68	$3,069.44	$409.26	$200.79	$2,660.18
25	1.0605	0.4382	R-1/XX	R-2/YZ	26 Cu.Ft.	$245.70	$3,315.14	$442.02	$212.94	$2,873.12
26	1.0605	0.4647	R-1/XX	R-2/YZ	26 Cu.Ft.	$260.57	$3,575.71	$476.76	$225.82	$3,098.95
27	1.0605	0.4928	R-1/XX	R-2/YZ	26 Cu.Ft.	$276.33	$3,852.04	$513.61	$239.49	$3,338.43
28	1.0605	0.5226	R-1/XX	R-2/YZ	26 Cu.Ft.	$293.05	$4,145.09	$552.68	$253.98	$3,592.41
29	1.0605	0.5542	R-1/XX	R-2/YZ	26 Cu.Ft.	$310.78	$4,455.87	$594.12	$269.34	$3,861.75
30	1.0605	0.5878	R-1/XX	R-2/YZ	26 Cu.Ft.	$329.58	$4,785.45	$638.06	$285.64	$4,147.39

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Appliance Efficiency Summary

- Small reductions in larger loads will have more impact!
- Ratchet down all loads as much as feasible
- Be on the watch for newer technology, such as Induction Ranges, Condensing Dryers… Remember the Microwave?
- Without spending any extra money, better energy efficiency numbers can be found
- Counter-top cooking appliances are more efficient than ranges or cook-tops!

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The Future of Housing: The Path to Net-Zero and Beyond

Chapter 11

Efficient Lighting

Zero-EnergyPlans.com

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Energy Efficient Lighting: It begins with the Design!

- Remember to light Surfaces, not Rooms!
  - Surfaces may be stationary, like counter tops
  - They can be portable, like a newspaper or book
  - Think about where these surfaces will be, and design for them!
- Design multi-purpose lighting systems
  - Task lighting can also provide general room illumination
  - Ambience lighting can also be used for general illumination
  - Fewer systems means fewer lights to be left on when not being used!

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Also consider Lighting Controls:

- Dimmers can reduce loads when brightness is not required
- Specialty controls can light scenes instead of rooms
  - Can aid in reducing total connected load
  - Can provide dimming where full brightness is not needed
- Motion sensors or infrared detectors can shut lights off when not in use

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What type of fixture should you use?

- Linear fluorescents are the most economical, but not often popular in homes
- Compact fluorescent lamps are gaining in popularity and quality
  - Select fixtures that use type A screw-in bulbs!
  - LEDs are only being made for this type of base!
- LEDs are improving in quality and price

What is the difference, over time?

Light bulb cost/time

Year	inflation	Cost/Kwh	watts	alt. watts	hours /day	cost/day	cost/year	cost/ time	save/ time	alt. cost/yr	alt. cost/time
1	1.0605	0.1070	100	23	4	$0.0428	$15.62	$15.62	$12.03	$3.59	$3.59
2	1.0605	0.1135	100	23	4	$0.0454	$16.57	$32.19	$24.79	$3.81	$7.40
3	1.0605	0.1203	100	23	4	$0.0481	$17.57	$49.76	$38.31	$4.04	$11.44
4	1.0605	0.1276	100	23	4	$0.0510	$18.63	$68.39	$52.66	$4.29	$15.73
5	1.0605	0.1353	100	23	4	$0.0541	$19.76	$88.15	$67.88	$4.54	$20.27
6	1.0605	0.1435	100	23	4	$0.0574	$20.96	$109.11	$84.01	$4.82	$25.09
7	1.0605	0.1522	100	23	4	$0.0609	$22.22	$131.33	$101.12	$5.11	$30.21
8	1.0605	0.1614	100	23	4	$0.0646	$23.57	$154.90	$119.27	$5.42	$35.63
9	1.0605	0.1712	100	23	4	$0.0685	$24.99	$179.89	$138.51	$5.75	$41.37
10	1.0605	0.1815	100	23	4	$0.0726	$26.51	$206.39	$158.92	$6.10	$47.47
11	1.0605	0.1925	100	23	4	$0.0770	$28.11	$234.50	$180.57	$6.47	$53.94
12	1.0605	0.2042	100	23	4	$0.0817	$29.81	$264.31	$203.52	$6.86	$60.79
13	1.0605	0.2165	100	23	4	$0.0866	$31.61	$295.93	$227.86	$7.27	$68.06
14	1.0605	0.2296	100	23	4	$0.0919	$33.53	$329.45	$253.68	$7.71	$75.77
15	1.0605	0.2435	100	23	4	$0.0974	$35.55	$365.01	$281.05	$8.18	$83.95
16	1.0605	0.2583	100	23	4	$0.1033	$37.70	$402.71	$310.09	$8.67	$92.62
17	1.0605	0.2739	100	23	4	$0.1096	$39.99	$442.70	$340.88	$9.20	$101.82
18	1.0605	0.2904	100	23	4	$0.1162	$42.41	$485.10	$373.53	$9.75	$111.57
19	1.0605	0.3080	100	23	4	$0.1232	$44.97	$530.07	$408.16	$10.34	$121.92
20	1.0605	0.3267	100	23	4	$0.1307	$47.69	$577.76	$444.88	$10.97	$132.89
21	1.0605	0.3464	100	23	4	$0.1386	$50.58	$628.34	$483.82	$11.63	$144.52
22	1.0605	0.3674	100	23	4	$0.1469	$53.64	$681.98	$525.12	$12.34	$156.85
23	1.0605	0.3896	100	23	4	$0.1558	$56.88	$738.86	$568.92	$13.08	$169.94
24	1.0605	0.4132	100	23	4	$0.1653	$60.32	$799.18	$615.37	$13.87	$183.81
25	1.0605	0.4382	100	23	4	$0.1753	$63.97	$863.15	$664.63	$14.71	$198.53
26	1.0605	0.4647	100	23	4	$0.1859	$67.84	$931.00	$716.87	$15.60	$214.13
27	1.0605	0.4928	100	23	4	$0.1971	$71.95	$1,002.94	$772.27	$16.55	$230.68
28	1.0605	0.5226	100	23	4	$0.2090	$76.30	$1,079.24	$831.02	$17.55	$248.23
29	1.0605	0.5542	100	23	4	$0.2217	$80.92	$1,160.16	$893.32	$18.61	$266.84
30	1.0605	0.5878	100	23	4	$0.2351	$85.81	$1,245.97	$959.40	$19.74	$286.57

How do I get my customers to accept CFLs?

- Select the right CFLs and LEDs!
  - Remember 2700° Kelvin Temperature
  - This is the best color range (warm white)
  - Select CFLs that are instant-on
  - Select dimmable CFLs where needed
- Use the LEDs in the highest use locations, they will provide the biggest benefit there!
- Just DO IT, they never need to know! <☺

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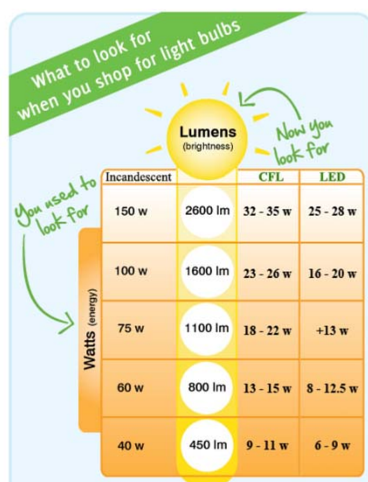
Lumens vs. Watts?

- Learn to select bulbs by the number of lumens they produce, not the number of watts they consume!



This chart shows the number of lumens produced by common incandescent bulbs. If you're looking to buy a bulb that will give you the amount of light you used to get from a 60-watt bulb, you'll now look for 800 lumens.

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What about Plug Loads?

- Education is the key to Consumer Awareness!
- Advise your customers on the selection process, so they can choose TVs and other large energy users based on energy loads
  - LED backlit LCD TVs use just a fraction of the energy of a similar-sized plasma TV, with similar clarity!
  - Install switches to turn off plugs at night

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Energy Efficient Lighting Summary:

- Not all that shines brightly is gold!
- Light surfaces, not rooms
- Use CFLs for most applications
- Use LEDs for heavy-use areas
- Educate your customers
- Learn to select bulbs by the number of lumens they produce, not the number of watts they consume!

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The Future of Housing:
The Path to Net-Zero and Beyond

Chapter 12

Alternative Energy

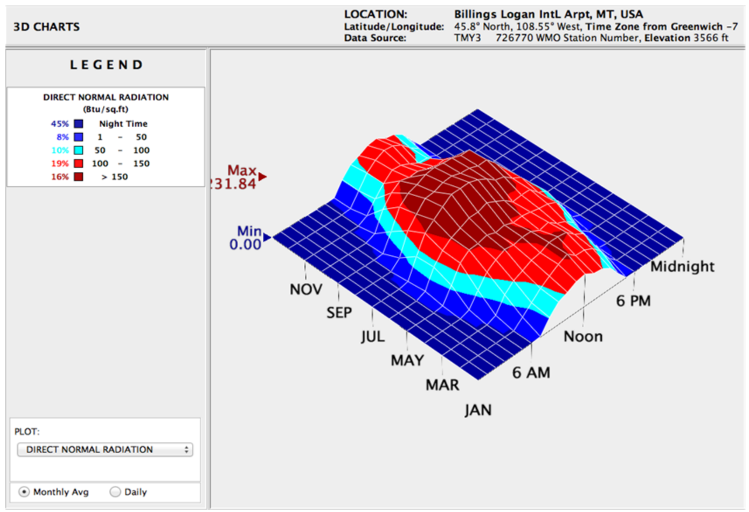
121

What are your design tools?

- Climate Data (CC-5)
  - What time of year you get sun will help determine ideal roof pitch
- Sharp Solar Calculator
  - http://www.sharpusa.com/SolarElectricity.aspx
  - Estimates annual production based on roof pitch and direction
- Local Installer
  - Will have more specialized tools for more accurate and specific assessment

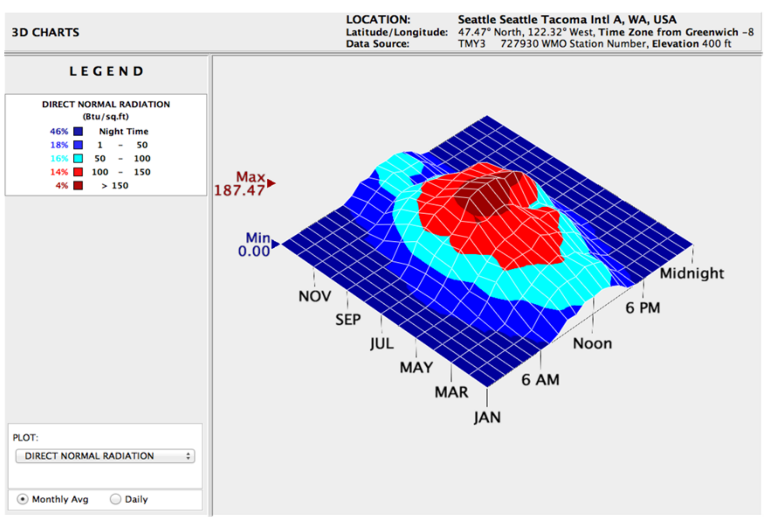
122

Climate Consultant 5:



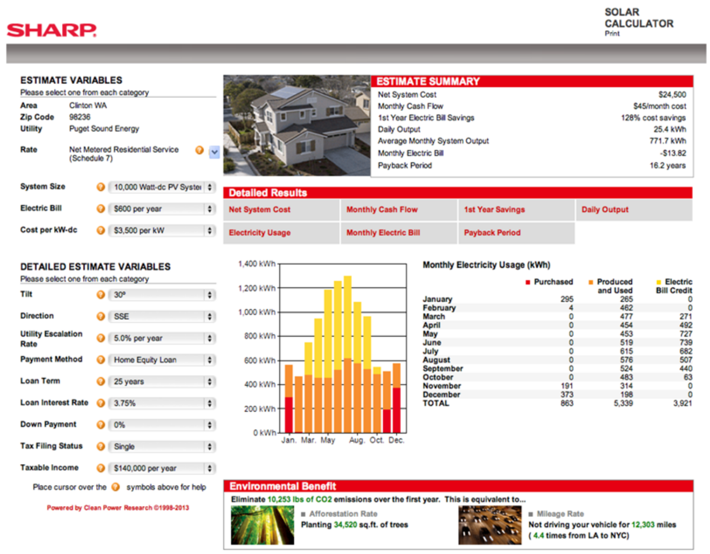
123

Climate Consultant 5:



124

Sharp Savings Estimator:



125

Calculate Energy Needs

- HERS rating will provide annual estimate of power usage
  - For heating & cooling
  - For water heating
  - For appliances
  - For lighting & plug loads

126

RemRate Energy Usage Report:

Weather Site:	Seattle, WA	Rating Type:	Confirmed Rating
File Name:	Thomas_final.blg	Rating Date:	9/28/2011

		Thomas
Annual Energy Cost ($/yr)		
Annual End-Use Cost ($/yr)		
Heating	$	85
Cooling	$	0
Water Heating	$	92
Lights & Appliances	$	476
Photovoltaics	$	-665
Service Charges	$	87
Total	$	74
Annual End-Use Consumption		
Heating (kWh)		968
Water Heating (kWh)		1063
Lights & Appliances (kWh)		5527
Photovoltaics (kWh)		-7716
Annual Energy Demands (kW)		
Heating		3.0
Cooling		0.7
Water Heating (Winter Peak)		0.2
Water Heating (Summer Peak)		0.1
Lights & Appliances (Winter Peak)		0.4
Lights & Appliances (Summer Peak)		1.2
Total Winter Peak		3.6
Total Summer Peak		2.0

Be sure to deduct Service Charges from actual usage!

127

Match Energy Production to Needs:

- Use Sharp Savings Estimator or Local Solar Installer's Estimate for system sizing
- Explore electric car usage:
  - Chevy Volt will go 2.86 miles per Kwh
  - Nissan Leaf will go 3.45 miles per Kwh
  - Mitsubishi i-MIEV will go up to 3.33 miles per Kwh

A surplus of less than 3,000 Kwh per year could power a car for 10,000 miles!

128

How much is that worth?

- My Honda Civic gets 34.5 MPG avg.
  - At $3.85 per gallon, 10,000 miles costs me $1,115.94
- The Leaf gets 3.45 Miles/Kwh
  - If the 2,899 Kwh required to go 10,000 miles is worth the same as my gasoline, then it is worth $1,115.94, or 38.5¢ per Kwh!
  - Average that out with the 7,000 Kwh of production that ran the house:

129

How much is that worth?

- 2,899 x 38.5¢ = $1,115.94
- 7.000 x 10¢ = $ 700.00
- Total value of Energy = $1,815.94
- Value per Kwh = over 18¢ per Kwh!
- This is in addition to any State or Federal incentives!

130

How about Wind Power?

- It depends on where you are!
  - Billings, Montana looked pretty good!
- Trees and tall buildings are Major impediments to successful wind power
  - Trees could make Western Washington pretty difficult!
- All renewable energy sources are Local!
- Consult with your Local Installer!

131

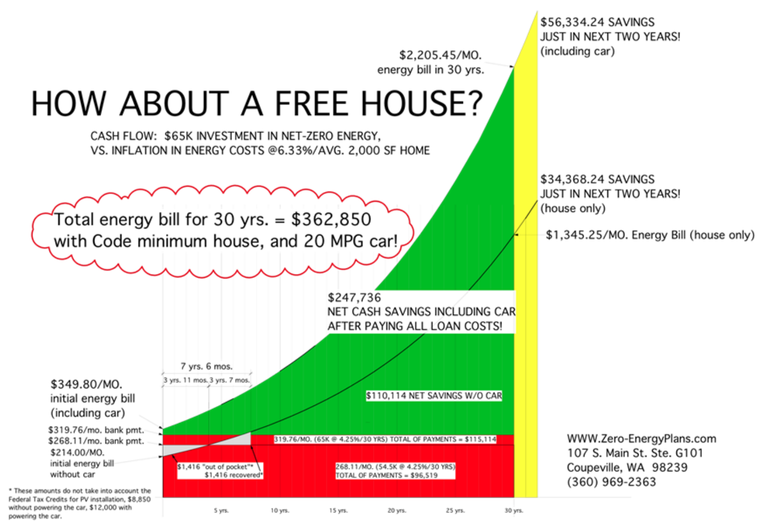
How much does it cost to get to Net-Zero-Energy?

Thomas House additional costs over code-minimum house

Item	Description	Cost
Foundation Insulation	4" XPS foam	$1,250
SIPS Walls & Roof	6.5" walls, 10.25" roof	$12,000
Air Sealing Labor	Saved 8 hrs labor w/SIPS	-$800
Heating System	Unico UniChiller in-floor Radiant	$10,000
Balanced Ventilation	FanTech HEPA Filter system	$1,000
Water Heating	Unichiller, extra tank w/coils, pump	$1,500
PV System	6.44 KW	$29,500
Total:	(As-Built, to power house only)	$54,450
Less Federal Tax Credits:		$8,850
Net Out of Pocket:	(net-zero home only)	$45,600

132

How much does a new Positive NRG™ Home Cost? How fast does it Pay Off?



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Questions????

www.zero-energyplans.com

Ted L. Clifton

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Cost Effective Strategies to Construct ENERGY STAR Certified Homes

&

Building Science basics

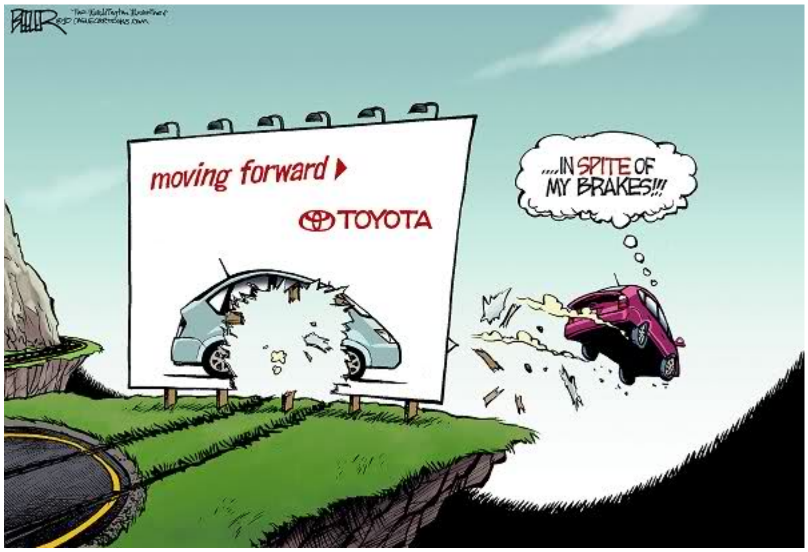
February 19th, 2014

Rick Gazica

Learn more at energystar.gov

Mix & match…

.. versus systems approach



System 1: Thermal enclosure system

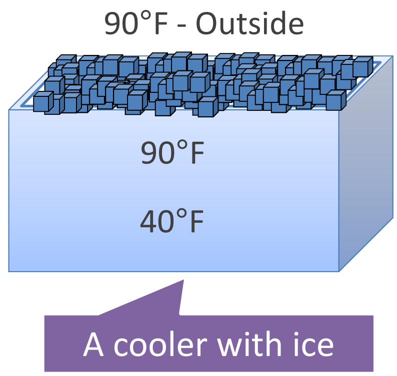
1

Thermal Enclosure System

- A well-insulated and air-sealed home, with good windows and doors, reduces the amount of energy needed to keep the home comfortable.

Thermal enclosure system: Basic concepts

1. Energy moves from more to less.



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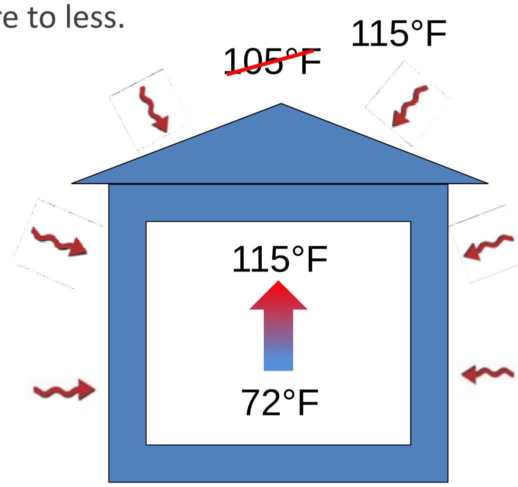
Thermal enclosure system: Basic concepts

1. Energy moves from more to less.



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Thermal enclosure system:
Basic concepts

- Heat transfer can be quantified in British Thermal Units (Btu's).
- 1 Btu is approximately equal to the energy in a single match.

7

Thermal enclosure system:
What we're avoiding

Attic air infiltration into the wall

Item 5.2.3:
Drywall sealed at the top plates

Default:
Foam

Alternative:
Sill sealer

Alternative:
Construction Adhesive

9

Item 5.2.3:
Drywall sealed at the top plates

Default:
Insulation
at the ceiling

Alternative:
Insulation
at the roof deck

Ducts in conditioned space, no attic hatch, no air sealing drywall

10

System 2:
HVAC system

2

Heating, Cooling, & Ventilation System

- Heating and cooling equipment that is:
  - High efficiency
  - Properly designed and installed
  - Combined with a duct system that's insulated, sealed, and balanced

… maintains comfort with less energy.

- Ventilation systems that remove low-quality air, provide outdoor air, and filter contaminants to improve indoor air quality

HVAC system:
Basic concepts

Design:

1. Calculate the heating and cooling loads.
2. Select equipment that meets those loads.
3. Design a duct system that gets air from the equipment to the rooms in the house, and back.

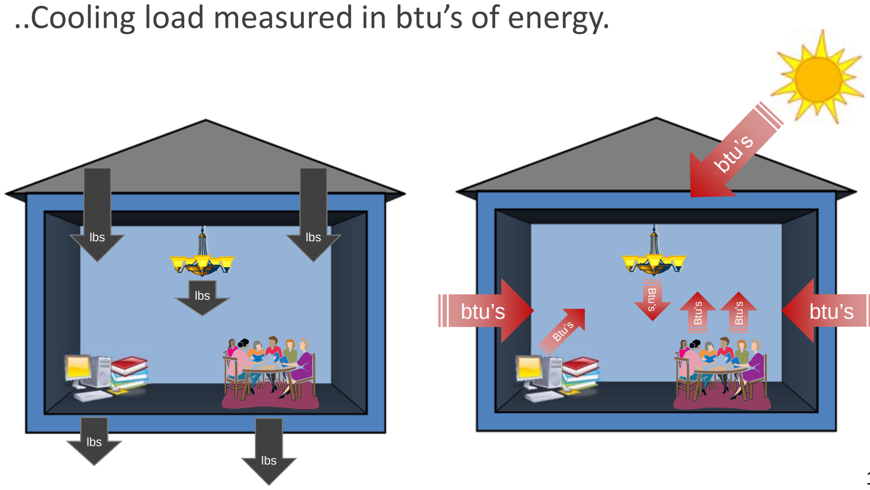
Commission:

A. Check airflow at air handler.
B. Check refrigerant charge.
C. Measure airflow at registers.

12

HVAC system: Basic concepts
Calculate the heating & cooling load

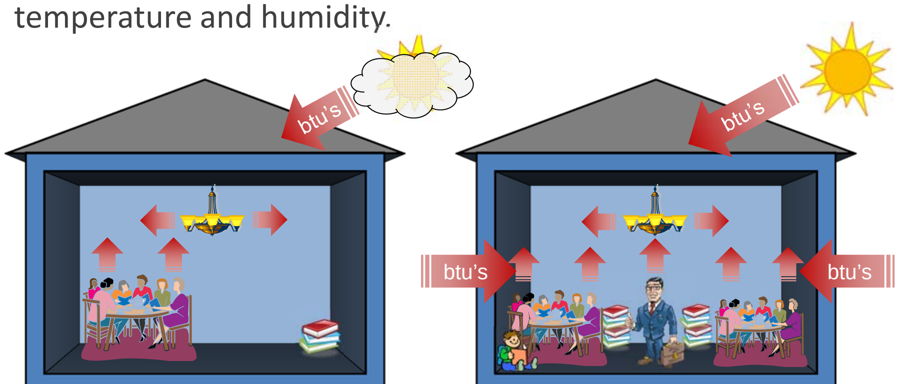
- Structural load measured in pounds of weight..
  ..Cooling load measured in btu's of energy.



13

HVAC system: Basic concepts
Calculate the heating & cooling load

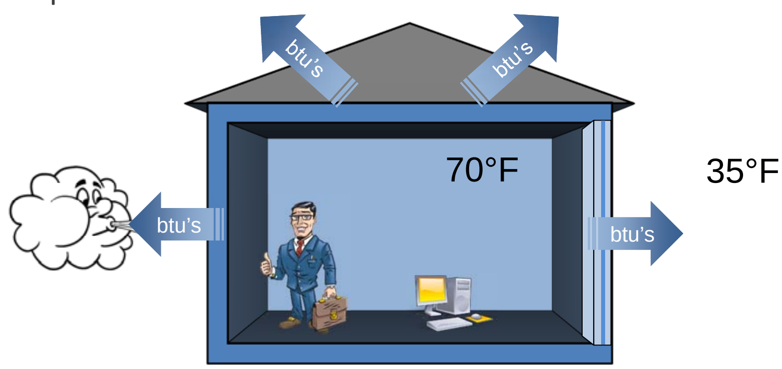
- Cooling Load varies for each hour of the year.
- Cooling Peak Load: The maximum energy that's added to the home in a single hour, and must be removed to maintain temperature and humidity.



14

HVAC system: Basic concepts
Calculate the heating & cooling load

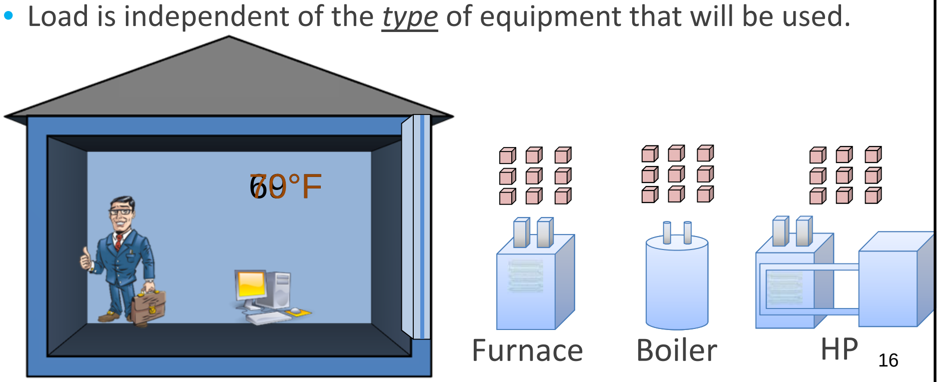
- Heating Load varies for each hour of the year.
- Heating Peak Load: The maximum energy that lost from the home in a single hour, which must be added back to maintain temperature.



15

HVAC system: Basic concepts
Calculate the heating & cooling load

- Cooling & heating equipment are "btu machines" that add or remove btu's to offset the load.
- The cooling and heating load tell you how many btu's the equipment has to be capable of removing or adding.
- Load is independent of the *type* of equipment that will be used.



16

HVAC system: Heating & cooling load
What we're avoiding

Random Acts of Sizing

17

Section 2 of the HVAC-C & Section 1 of the HVAC-R

	Input Type	Low Input	Correct Input	High Input	Cooling Load kbtu Low	Cooling Load kbtu High	Cooling Load % Low	Cooling Load % High
	Baseline	-	-	-	35.1		-	-
1	Outdoor Design Temperature	103 F	108 F	113 F	32.4	38.0	-8%	8%
2	Home Orientation	N	E	W	31.7	36.1	-9%	3%
3	Number of Occupants	1	4	7	34.4	36.3	-2%	4%
4	Conditioned Floor Area (Sq. Ft.)	2,160	2,400	2,640	33.9	36.3	-3%	3%
5	Window Area (Sq. Ft.)	324	360	396	33.7	36.4	-4%	4%
6	Predominant Window SHGC	0.20	0.30	0.40	32.8	36.4	-6%	4%
	Combined Impact From First Six Parameters				**25.1**	**43.0**	**-29%**	**23%**

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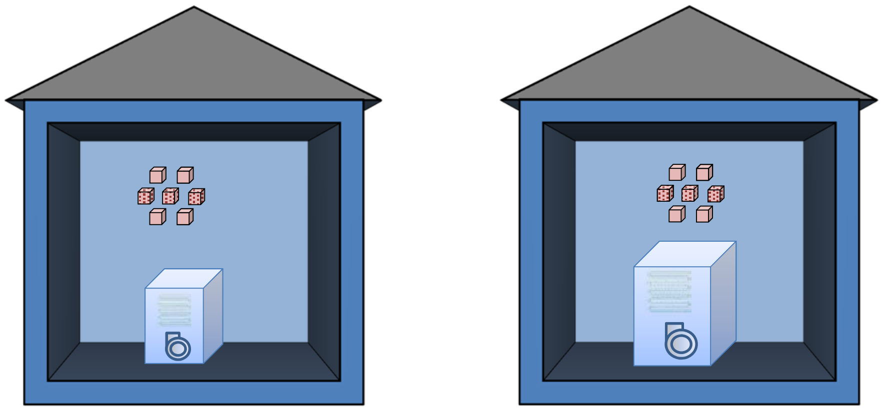
HVAC system: Basic concepts
Select equipment that meets those loads

- Heating and cooling equipment generally has just two modes – on & off.



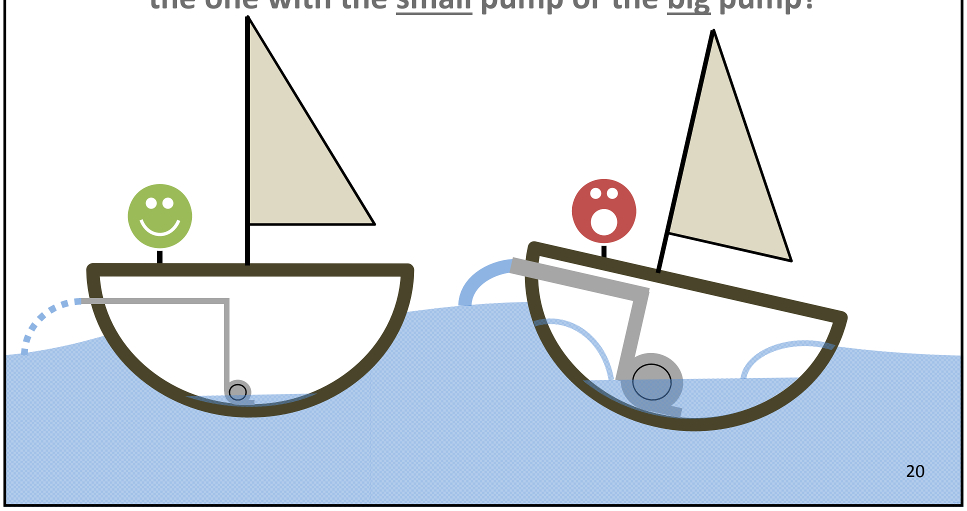
Equipment < Load   Equipment > Load

19

HVAC system: Heating & cooling load
What we're avoiding

Which boat would you want -

the one with the <u>small</u> pump or the <u>big</u> pump?



20

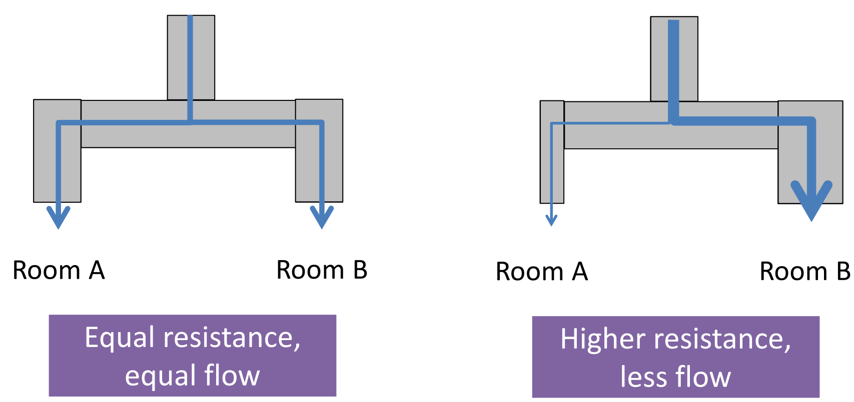
Item 3.12 of the HVAC-C & Item 1.2.9 of the HVAC-R

- Verify that the equipment capacity is right-sized relative to the heating and cooling load.

21

HVAC system: Basic concepts Design the duct system

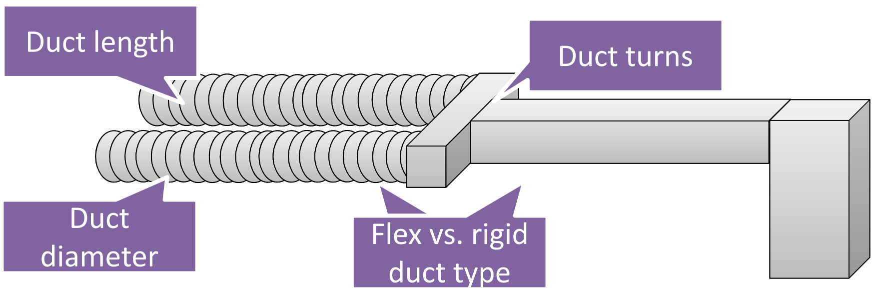
1. Air follows the path of least resistance.



22

HVAC system: Basic concepts
Design the duct system

- Factors that influence the airflow of the ducts:
  - Duct length
  - Duct diameter
  - Duct type
  - Duct turns
  - Other components, like filters



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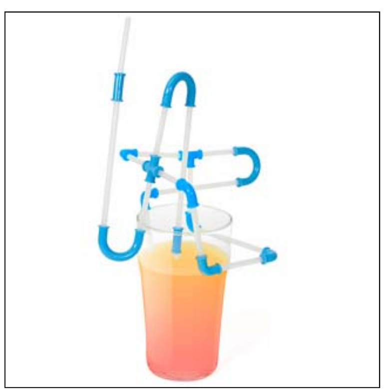
HVAC system: Basic concepts
What we're avoiding



24

HVAC system: Basic concepts
What we're avoiding

ENERGY STAR

Poorly installed ducts

Section 9 of the HVAC-C &
Item 1.4 & Sections 2, 3, & 4 of the HVAC-R

ENERGY STAR

- Verify that the ducts are balanced, insulated, tight, and installed without major defects.

26

System 3:
Water management system

3

Water Management System

- A water management system that directs water off the roof, down the walls, and away from the foundation and site, as well as keeping building materials from getting wet, improves durability and indoor air quality.

Water management system:
Basic concepts

- Many materials used in building homes are not durable when wet.
- Especially important in high performance homes, regardless of whether the home is ENERGY STAR certified.

28

Water management system: What we're avoiding

Missing step & kick-out flashing

Item 3.1: Step & kick-out flashing

- Step and kick-out flashing at all roof-wall intersections, extending ≥ 4" on wall surface about roof deck and integrated with drainage plane above.
- Step flashing goes behind the water barrier on wall and under shingles on the roof.

30

But who cares about Building science anyway?

For builders:

- Greater quality and process control.
- Reduced costs from warranty issues & customer complaints.
- Maximum value for money invested.

For HVAC contractors:

- Reduced callbacks for comfort issues.
- Justification to invest in higher-value products and services.

For homeowners:

- Lower utility bills.
- Better comfort, durability, and quality.
- A more livable home.

ENERGY STAR Certified Homes

Web:

Main: www.energystar.gov/newhomespartners
Technical: www.energystar.gov/newhomesguidelines
Training: www.energystar.gov/newhomestraining
HVAC: www.energystar.gov/newhomesHVAC

Email:

energystarhomes@energystar.gov

Social Media:

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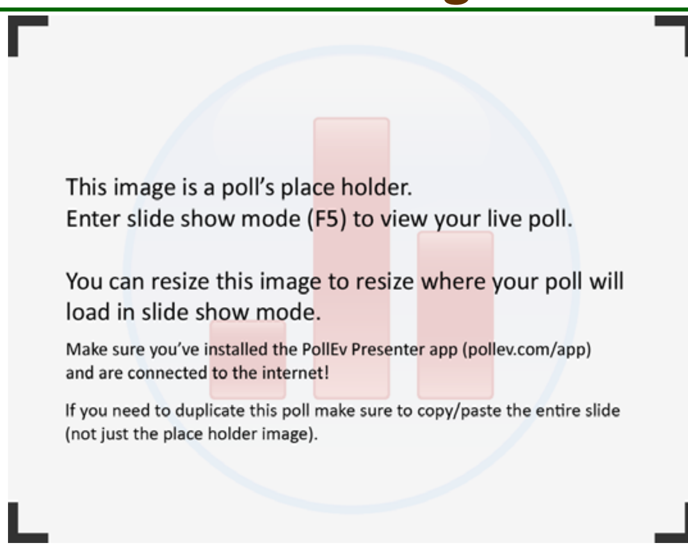
AMERICAN WOOD COUNCIL

2009 International Energy Conservation Code: Design for Code Acceptance #7

Loren Ross, John Showalter, & Lori Koch

Presented by:
Loren Ross

Polling



Outline

- ❖ **Applicability**
- ❖ **Methods and Examples**
  - Prescriptive
    - R-Value
    - U-Factor
    - UA-Alternative
  - Performance
- ❖ **Design Aid**
  - DCA #7
- ❖ **Take Away**
- ❖ **Questions**

Applicability

- ❖ **New Construction**
- ❖ **Additions, alterations, renovations or repairs**
  - Non-exposed cavities
  - Exposed, but insulated cavities
  - Reroofing where sheathing isn't exposed
  - Glass only replacements
  - Storm windows
  - Less than 50% luminaries
  - Bulb and ballast replacements that don't increase power

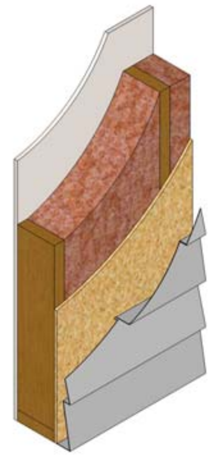
5

Methods

❖Prescriptive methods

- R-Value
- U-Factor
- UA-Alternative

❖Performance



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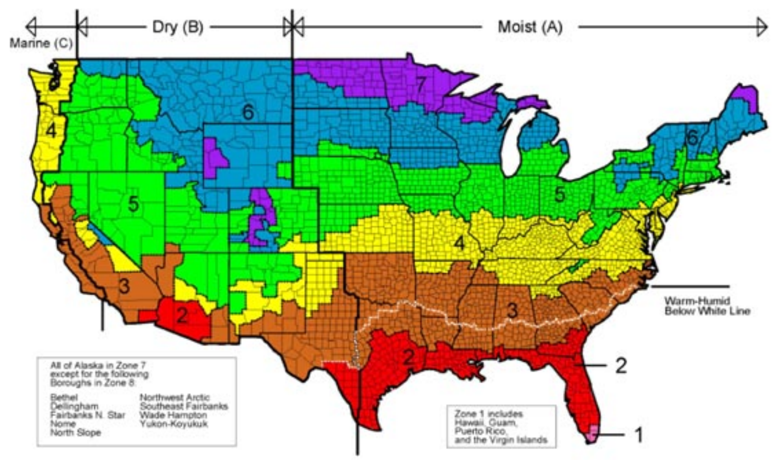
6

Methods



Source: IECC 09

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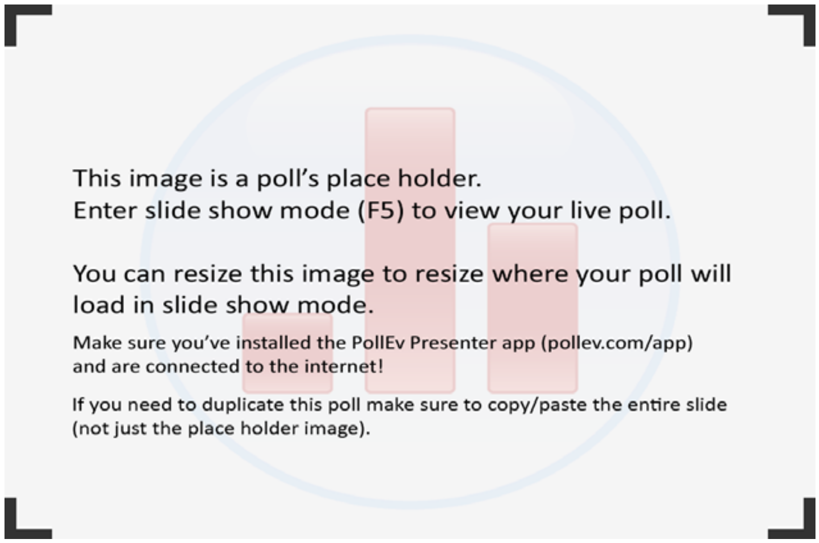
Methods



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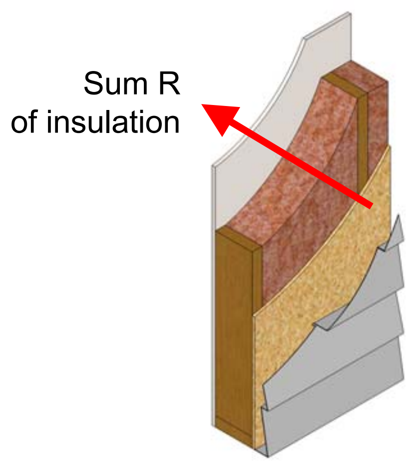
Prescriptive: R-Value



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Prescriptive: R-Value

Climate Zone	Fenestration U-Factor	Ceiling R-Value	Wood Frame Wall R-Value	Floor R-Value
1	1.2	30	13	13
2	0.65	30	13	13
3	0.50	30	13	19
4 except Marine	0.35	38	13	19
5 and Marine 4	0.35	38	20 or 13+5[h]	30
6	0.35	49	20 or 13+5[h]	30
7 and 8	0.35	49	21	38

Table 402.1.1: 2009 IECC

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Prescriptive: R-Value

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Prescriptive: R-Value

❖**Footnote h:**

- Intended to maintain uniform thickness
- "If structural sheathing covers 25 percent or less of the exterior, insulating sheathing is not required where structural sheathing is used.
- "If structural sheathing cover more than 25 percent of the exterior, structural sheathing shall be supplemented with insulated sheathing of at least R-2."

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Prescriptive: R-Value

❖**Other exceptions:**

- Glazed Fenestration
  - 15 square ft.
- Opaque Door
  - 24 square ft.
- Ceiling Insulation
  - Above R-30, but no room

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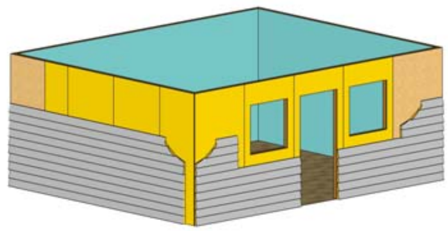
Example: R-Value

❖Follow the Table 402.1.1

Climate Zone	Fenestration U-Factor	Ceiling R-Value	Wood Frame Wall R-Value	Floor R-Value
5	0.35	38	20 or 13+5[h]	30



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Examples: R-Value

❖Options

- Footnote h:
  - Less than 25% WSP, no C.I. needed over WSP
- Opaque Door
  - 24 Square Ft.
- Glazed Fenestrations
  - 15 Square Ft.
- Ceiling Height
  - R-30 over top-plates

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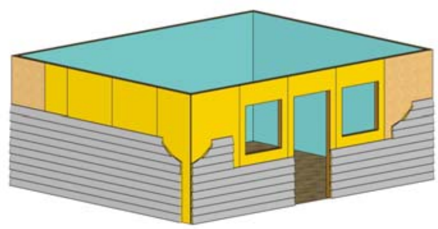
Examples: R-Value

❖ Follow the Table 402.1.1

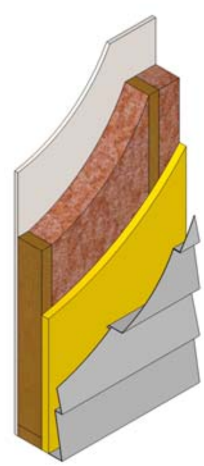
Climate Zone	Fenestration U-Factor	Ceiling R-Value	Wood Frame Wall R-Value	Floor R-Value
5	0.35	38	20 or 13+5[h]	30



Prescriptive: U-Factor

❖ Assembly Based:

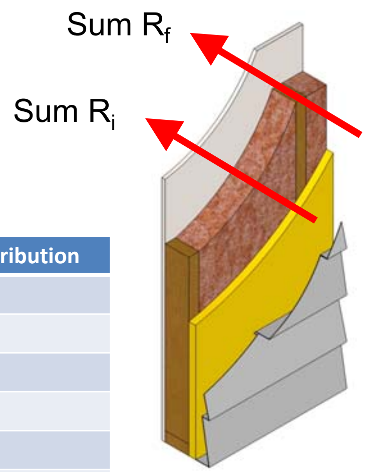
- Includes all components
  - Inside Air Film
  - Gypsum
  - Batt Insulation and Studs
  - Continuous Insulation
  - Siding
  - Outside Air Film
- Area Weighted Average
  - Framing Factor



Prescriptive: U-Factor

$$UA_{tot} = \sum_i U_i A_i$$

$$U_{tot} = \frac{F_f}{\sum R_s} + \frac{1-F_f}{\sum R_c}$$



Component	Framing Factor Contribution
Studs 16” o.c.	9%
Studs 24” o.c.	6%
Plates	1.5% each
Headers	4%
Rim Joist	4%
Misc	3%

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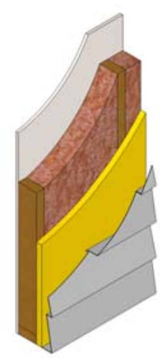
Prescriptive: U-Factor, R13+5

Component	R-Value Cavity	R-Value Stud
Inside Air Film	0.68	
Gypsum	0.45	
Studs 2x4 @16”		1.25*3.5=4.38
Insulation	13	
C.I.	5	
Siding	0.59	
Outside Air Film	0.25	
Sum	19.97	11.35



$$U_{tot} = \frac{F_f}{\sum R_s} + \frac{1-F_f}{\sum R_c} = \frac{0.25}{11.35} + \frac{0.75}{19.97} = 0.060$$

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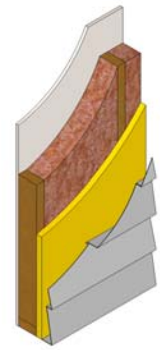
Prescriptive: U-Factor, Adv. Frm.

Component	R-Value Cavity	R-Value Stud
Inside Air Film	0.68	
Gypsum	0.45	
Studs 2x4 @24"		1.25*3.5=4.38
Insulation	13	
C.I.	5	
Siding	0.59	
Outside Air Film	0.25	
Sum	19.97	11.35



$$U_{tot} = \frac{F_f}{\sum R_s} + \frac{1 - F_f}{\sum R_c} = \frac{0.17}{11.35} + \frac{0.83}{19.97} = 0.057$$

Prescriptive: U-Factor

Climate Zone	Fenestration U-Factor	Ceiling U-Factor	Wood Frame Wall U-Factor	Floor U-Factor
1	1.2	0.035	0.082	0.064
2	0.65	0.035	0.082	0.064
3	0.50	0.035	0.082	0.047
4 except Marine	0.35	0.030	0.082	0.047
5 and Marine 4	0.35	0.030	0.057	0.033
6	0.35	0.026	0.057	0.033
7 and 8	0.35	0.026	0.057	0.028

Table 402.1.3: 2009 IECC

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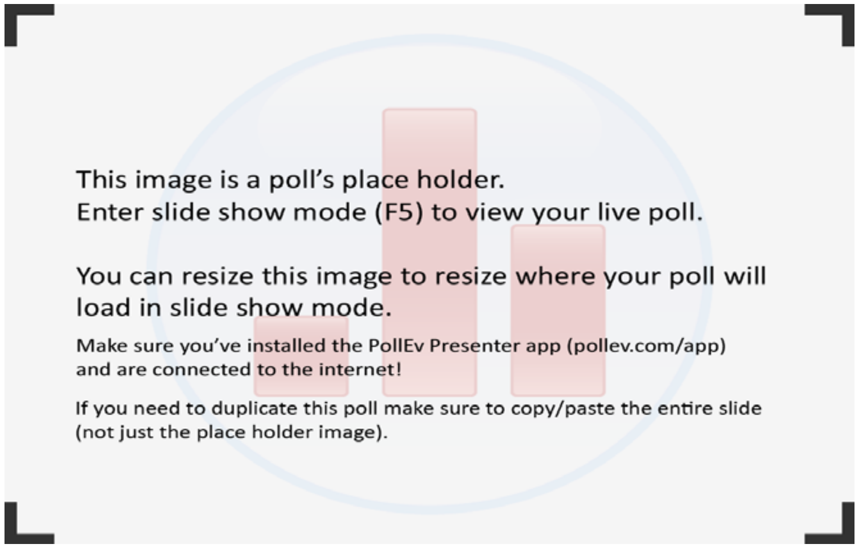
Prescriptive: U-Factor



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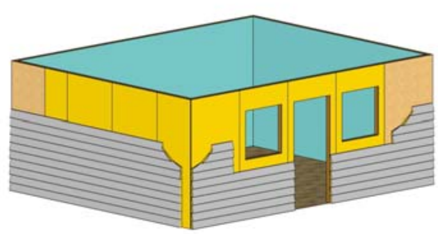
Example: U-Factor

- Follow the Table 402.1.3

Climate Zone	Fenestration U-Factor	Ceiling U-Factor	Wood Frame Wall U-Factor	Floor U-Factor
5	0.35	0.030	0.057	0.033



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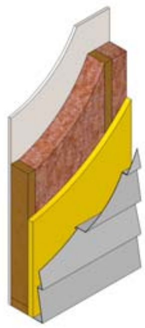
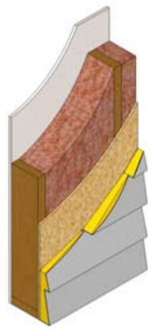
Example: U-Factor





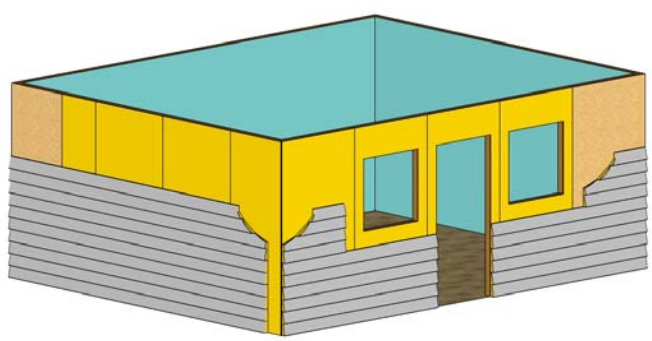
2x6
R-19
Insulated Siding R2

$U = 0.060$ $U = 0.056$

Climate Zone	Fenestration U-Factor	Ceiling U-Factor	Wood Frame Wall U-Factor	Floor U-Factor
5	0.35	0.030	0.057	0.033

Prescriptive: UA-Alternative

$$\sum_i A_i U_{Table} \geq \sum_i A_i U_{proposed}$$



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Prescriptive: UA-Alternative

Climate Zone	Fenestration U-Factor	Ceiling U-Factor	Wood Frame Wall U-Factor	Floor U-Factor
1	1.2	0.035	0.082	0.064
2	0.65	0.035	0.082	0.064
3	0.50	0.035	0.082	0.047
4 except Marine	0.35	0.030	0.082	0.047
5 and Marine 4	0.35	0.030	0.057	0.033
6	0.35	0.026	0.057	0.033
7 and 8	0.35	0.026	0.057	0.028

Table 402.1.3: 2009 IECC

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Example: UA-Alternative

Component	Area	Table U-Factor	Proposed U-Factor
Door	18	0.35	0.34
Windows	18	0.35	0.33
C. I.	228	0.057	0.060
WSP	192	0.057	0.074
Floor	320	0.033	0.028
Roof	320	0.030	0.023

$$\sum_i A_i U_{Table} \geq \sum_i A_i U_{proposed}$$

$$\sum_i 56.7 \geq \sum_i 56.3$$

16'x20'

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Performance

❖ **Modeling:**
- Annual Energy Cost of Proposed
- Annual Energy Cost of Standard Reference
  - No Equipment Tradeoffs
- Table 405.5.2(1)

Design Aid

❖ **Based on UA Method**
- Gives U-Factors of Walls
- Finds Unknown in UA Equation

$$UA_{tot} = \sum_i U_i A_i$$

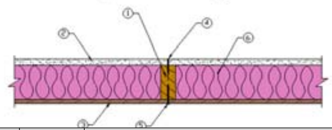
$$U_{tot} = \frac{F_f}{\sum R_s} + \frac{1 - F_f}{\sum R_c}$$

$$\sum_i A_i U_{Table} \geq \sum_i A_i U_{proposed}$$

Design Aid

❖Gives U-Factor

2x4 Wood-Frame Wall Assembly w/ R13 Cavity Insulation (WSP sheathing)



Siding Type	Average Thickness	R_{siding}	Framing Factor 15%	20%	25%
			Wall + Siding U-value		
Baseline (no siding)		-	*0.072*	*0.077*	*0.082*
Aluminum, Steel, or Vinyl siding					
uninsulated (hollow-back)		0.62	0.068	0.073	0.077
insulated (R-2)		2.00	0.062	0.065	0.068
insulated (R-3)		3.00	0.058	0.060	0.063
Brick veneer (¾" air space)	3-5/8"	1.26	0.065	0.069	0.072
Hardboard siding	7/16"	0.67	0.068	0.072	0.076
Plywood siding (edges lapped)	3/8"	0.59	0.069	0.073	0.077
Wood siding					
Drop (8")	1"	0.79	0.068	0.072	0.076
Bevel (8", lapped)	1/2"	0.81	0.067	0.071	0.075
Bevel (10", lapped)	3/4"	1.05	0.066	0.070	0.074

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Design Aid

❖Finds Unknown

Ref: $U_{wall} = 0.057$, $U_{fen} = 0.35$

Average U-value for Exterior Walls	Percentage of Fenestrations Area in Total Wall Area: 10%	12%	14%	16%	18%	20%	22%	24%	26%	28%	30%
	Average U-value for Fenestrations										
0.057	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
0.058	0.34	0.34	0.34	0.34	0.35	0.35	0.35	0.35	0.35	0.35	0.35
0.059	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.35
0.060	0.32	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.34
0.061	0.31	0.32	0.33	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34
0.062	0.31	0.31	0.32	0.32	0.33	0.33	0.33	0.33	0.34	0.34	0.34
0.063	0.30	0.31	0.31	0.32	0.32	0.33	0.33	0.33	0.33	0.33	0.34
0.064	0.29	0.30	0.31	0.31	0.32	0.32	0.33	0.33	0.33	0.33	0.33
0.065	0.28	0.29	0.30	0.31	0.31	0.32	0.32	0.32	0.33	0.33	0.33
0.066	0.27	0.28	0.29	0.30	0.31	0.31	0.32	0.32	0.32	0.33	0.33
0.067	0.26	0.28	0.29	0.30	0.30	0.31	0.31	0.32	0.32	0.32	0.33
0.068	0.25	0.27	0.28	0.29	0.30	0.31	0.31	0.32	0.32	0.32	0.32

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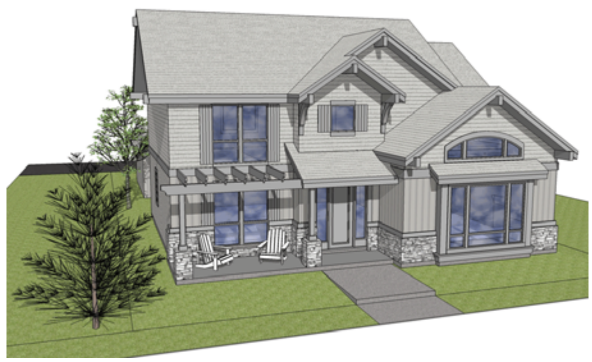
Design Aid: Example

- 2 Story 30x40 House = CFA 2400 square feet
  - 28% Fenestrations



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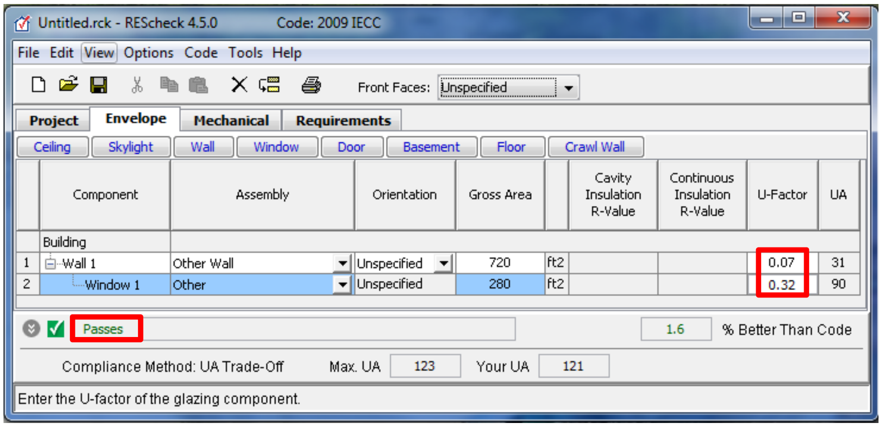
Design Aid

Average U-value for Exterior Walls	Percentage of Fenestrations Area in Total Wall Area: 10%	12%	14%	16%	18%	20%	22%	24%	26%	28%	30%
	Average U-value for Fenestrations										
0.057	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
0.058	0.34	0.34	0.34	0.34	0.35	0.35	0.35	0.35	0.35	0.35	0.35
0.059	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.35
0.060	0.32	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.34
0.061	0.31	0.32	0.33	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34
0.062	0.31	0.31	0.32	0.32	0.33	0.33	0.33	0.33	0.34	0.34	0.34
0.063	0.30	0.31	0.31	0.32	0.32	0.33	0.33	0.33	0.33	0.33	0.34
0.064	0.29	0.30	0.31	0.31	0.32	0.32	0.33	0.33	0.33	0.33	0.33
0.065	0.28	0.29	0.30	0.31	0.31	0.32	0.32	0.32	0.33	0.33	0.33
0.066	0.27	0.28	0.29	0.30	0.31	0.31	0.32	0.32	0.32	0.33	0.33
0.067	0.26	0.28	0.29	0.30	0.30	0.31	0.31	0.32	0.32	0.32	0.33
0.068	0.25	0.27	0.28	0.29	0.30	0.31	0.31	0.32	0.32	0.32	0.32
0.069	0.24	0.26	0.28	0.29	0.30	0.30	0.31	0.31	0.32	0.32	0.32
0.070	0.23	0.25	0.27	0.28	0.29	0.30	0.30	0.31	0.31	0.32	0.32
0.071	0.22	0.25	0.26	0.28	0.29	0.29	0.30	0.31	0.31	0.31	0.32
0.072	0.22	0.24	0.26	0.27	0.28	0.29	0.30	0.30	0.31	0.31	0.32

 Ref: $U_{wall} = 0.057$, $U_{fen} = 0.35$ www.awc.org

Design Aid vs Res Check

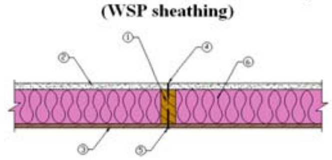


 Ref: $U_{wall} = 0.057$, $U_{fen} = 0.35$

Design Aid

- **Gives U-Factor**

2x4 Wood-Frame Wall Assembly w/ R13 Cavity Insulation (WSP sheathing)

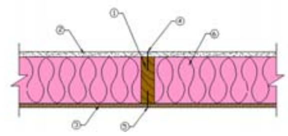


Siding Type	Average Thickness	R_{siding}	Framing Factor 15%	Framing Factor 20%	Framing Factor 25%
			Wall + Siding U-value		
Baseline (no siding)		-	*0.079*	*0.083*	*0.087*
Aluminum, Steel, or Vinyl siding					
uninsulated (hollow-back)		0.62	0.074	0.078	0.082
insulated (R-2)		2.00	0.067	0.070	0.073
insulated (R-3)		3.00	0.062	0.065	0.067
Brick veneer (¾" air space)	3-5/8"	1.26	0.071	0.074	0.077
Hardboard siding	7/16"	0.67	0.074	0.078	0.082
Plywood siding (edges lapped)	3/8"	0.59	0.075	0.078	0.082
Wood siding					
Drop (8")	1"	0.79	0.073	0.077	0.081
Bevel (8", lapped)	1/2"	0.81	0.073	0.077	0.081
Bevel (10", lapped)	3/4"	1.05	0.072	0.075	0.079

Design Aid

❖Gives U-Factor

2x6 Wood-Frame Wall Assembly w/ R17 Cavity Insulation (WSP sheathing)



Siding Type	Average Thickness	R_{siding}	Framing Factor 15%	20%	25%
			Wall + Siding U-value		
Baseline (no siding)		-	*0.061*	*0.064*	*0.067*
Aluminum, Steel, or Vinyl siding					
uninsulated (hollow-back)		0.62	0.058	0.061	0.064
insulated (R-2)		2.00	0.054	0.056	0.058
insulated (R-3)		3.00	0.051	0.053	0.054
Brick veneer (¾" air space)	3-5/8"	1.26	0.056	0.058	0.061
Hardboard siding	7/16"	0.67	0.058	0.061	0.063
Plywood siding (edges lapped)	3/8"	0.59	0.058	0.061	0.064
Wood siding					
Drop (8")	1"	0.79	0.058	0.060	0.063
Bevel (8", lapped)	1/2"	0.81	0.058	0.060	0.063
Bevel (10", lapped)	3/4"	1.05	0.057	0.059	0.062

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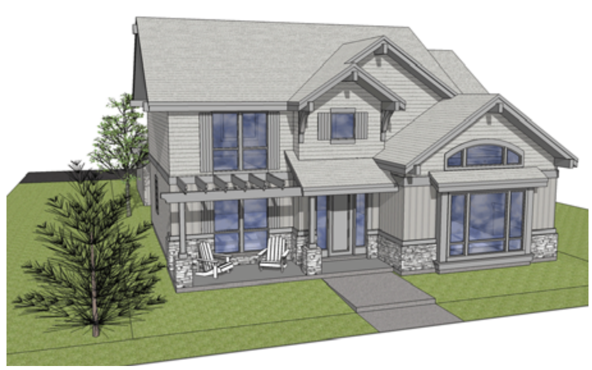
Design Aid: Example

❖2 Story 30x40 House = CFA 2400 square feet

- 28% Fenestrations



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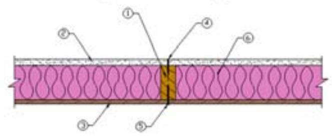
Design Aid

❖Gives U-Factor

2x4 Wood-Frame Wall Assembly w/ R13 Cavity Insulation (WSP sheathing)



Siding Type	Average Thickness	R_{siding}	Framing Factor 15%	20%	25%
			Wall + Siding U-value		
Baseline (no siding)		-	*0.079*	*0.083*	*0.087*
Aluminum, Steel, or Vinyl siding					
uninsulated (hollow-back)		0.62	0.074	0.078	0.082
insulated (R-2)		2.00	0.067	0.070	0.073
insulated (R-3)		3.00	0.062	0.065	0.067
Brick veneer (¾" air space)	3-5/8"	1.26	0.071	0.074	0.077
Hardboard siding	7/16"	0.67	0.074	0.078	0.082
Plywood siding (edges lapped)	3/8"	0.59	0.075	0.078	0.082
Wood siding					
Drop (8")	1"	0.79	0.073	0.077	0.081
Bevel (8", lapped)	1/2"	0.81	0.073	0.077	0.081
Bevel (10", lapped)	3/4"	1.05	0.072	0.075	0.079

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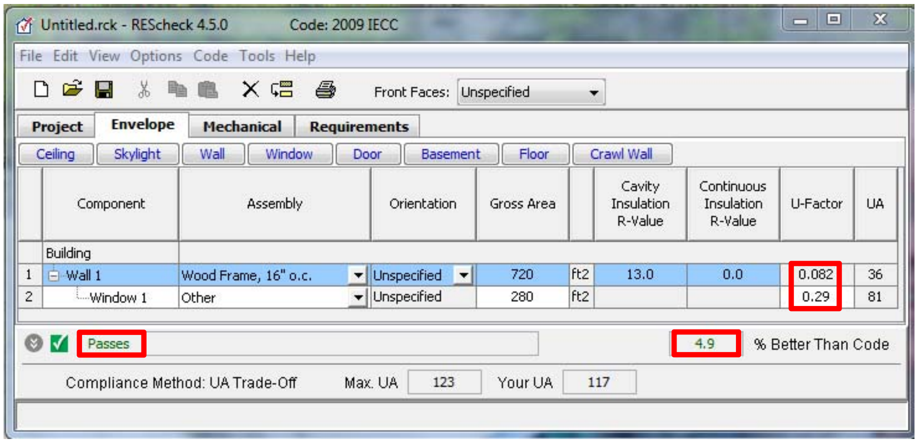
Design Aid

Average U-value for Exterior Walls	Percentage of Fenestrations Area in Total Wall Area 10%	24%	26%	28%	30%
	Average U-value for Fenestrations				
0.057	0.35	0.35	0.35	0.35	0.35
0.072	0.22	0.30	0.31	0.31	0.32
0.073	0.21	0.30	0.30	0.31	0.31
0.074	0.20	0.30	0.30	0.31	0.31
0.075	0.19	0.29	0.30	0.30	0.31
0.076	0.18	0.29	0.30	0.30	0.31
0.077	0.17	0.29	0.29	0.30	0.30
0.078	0.16	0.28	0.29	0.30	0.30
0.079	0.15	0.28	0.29	0.29	0.30
0.080	0.14	0.28	0.28	0.29	0.30
0.081	0.13	0.27	0.28	0.29	0.29
0.082		0.27	0.28	0.29	0.29

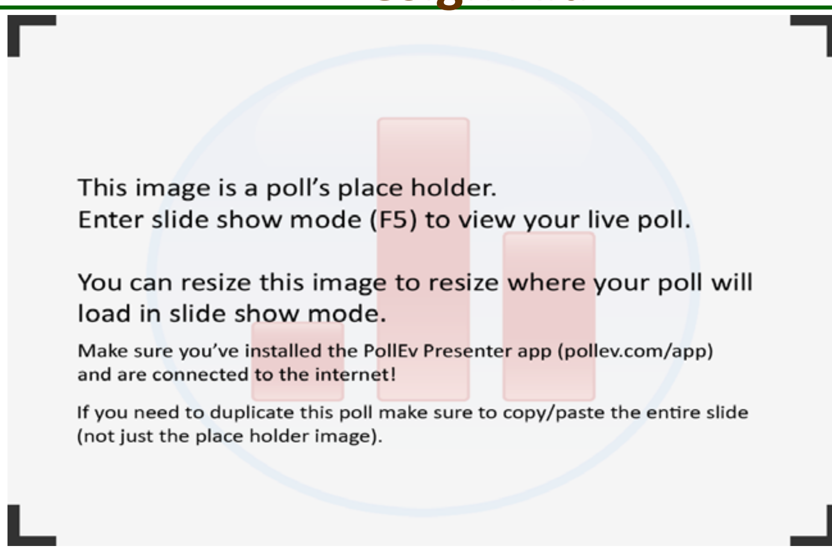
 Ref: U_{wall} = 0.057, U_{fen} = 0.35 www.awc.org

Design Aid vs Res Check



Ref: $U_{wall} = 0.057$, $U_{fen} = 0.35$

Design Aid



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Take Away

- R-Value Method is easiest
- U-Factor Method is inconsistent
  - ’09 and ’12
  - Fixed in ‘15
- Design Aid
  - UA Method – Like ResCheck
  - Trade-off windows and wall

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Questions?

http://www.awc.org/codes/dcaindex.html

American Wood Council

www.awc.org

info@awc.org

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SECTION 2:

Modular Construction and BIM

Performance Optimization & Development of a Home Modular Delivery System

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ABSTRACT

The objective of this research is to expand affordable home energy performance by developing an optimized modular delivery system, a Kit-of-Parts (KoP), applicable for infill development of new homes and for retrofitting existing homes. This innovative system of components is projected to result in homes that surpass Energy-Star performance for energy-efficiency, have improved indoor air quality, and provide realistic options for aging-in-place. Most notably it will provide a way to deliver high quality, well-designed, small affordable housing projects on a broad scale with a specific aim of revitalizing existing communities. This paper will present precedents, urban analysis and potential solutions for the modular home delivery system, KoP. KoP includes a carefully considered and flexible modular system for new and retrofit homes that can accommodate contextual adaptation to multiple infill sites and program needs. Modular construction can effectively achieve the level of quality control requisite for healthy and energy efficient homes. Multiple KoP modules can be combined and configured for the delivery of new houses and small housing projects on a variety of site conditions. Modular augmentation cores, that include well-integrated mechanical and plumbing systems, will also be advanced. These cores can be employed to save, update, transform and retrofit existing residences, especially in adapting homes for the accessible single floor living desirable for aging-in-place. Another benefit of the KoP is the potential for densification and revitalization of existing towns.

INTRODUCTION

> *"For Pennsylvania's economy to thrive, it needs a housing market that meets the needs of low- to moderate-income residents. Those needs are far from being met and are increasing along with the demand for housing by the Marcellus Shale gas industry,"* State Sen. Eugene Yaw, R-Loyalsock Township (Thompson, 2011).

Recent estimates project that population increases and loss of housing due to demolition will translate into a need for about 1.5 million additional new housing units in the U.S. each year (McWilliams, 2013). Existing towns are an obvious choice for investing in housing to address this growing need. The walk-able, mixed-use character of existing communities make them inherently sustainable, and the benefits of redevelopment are obvious - a vibrant small town has the potential to be a very desirable place to live. Cost-effective new infill housing and retrofitting of existing homes hold promise for revitalizing existing towns by addressing housing options that will allow aging residents to remain in their community.

The project described herein endeavors to expand affordable home energy performance by developing an optimized modular delivery system, a Kit-of-Parts (KoP), applicable for infill development of new homes and for retrofitting existing homes. This coordinated system of components will result in homes that surpass Energy-Star performance for energy-efficiency, have improved indoor air quality, and provide realistic options for aging-in-place. Most notably it will provide a way to deliver high quality, well-designed, small affordable housing projects on a broad scale.

KoP differs from most modular housing approaches in that it is not intended, marketed or presented as complete houses, buildings or groups of homes. Rather, the KoP is envisioned as a process built around a set of detailed components. These "parts" represent a UL listed product that would be specified much like doors or windows, benefiting from the strengths of the modular industry, but requiring the sensitivity of a qualified architect.

PROJECT OBJECTIVES

The home modular delivery system, KoP, is intended as the core building blocks for realizing infill housing on a broad scale. This standard geometric template will conform to the common constraints typical of infill development in small towns, modest houses, and efficient modular construction. Application would not be universal, but if planned properly it could be reasonably ubiquitous (Quigley and Iulo, 2012). KoP fabrication documents will meet tight manufacturing standards and tolerances; designed to a level of coordination unprecedented in the design of individual affordable houses. Customization for each project design would occur during site adaption for individual application of the modular components and through the integration of local materials. Investment in the development of these fabrication-ready building modules will allow for the high up-front costs of integrative design to be spread over many small projects. Previous studies suggest that local modular plants can build to the high-standards required for the KoP. This facilitates integration of local materials and methods and takes advantage of existing relationships.

Currently most new subsidized housing development focuses on multifamily and larger projects inappropriate for the majority of Pennsylvania's town fabric and small rural communities. This project recognizes the need for a delivery model that uses resources to deliver high-performance affordable single homes and small projects. Modular construction holds promise for enhancing the quality, energy efficiency, sustainability, and durability of residential construction for new and existing homes. Development of a modular "kit-of-parts" has significant potential for the delivery of homes that are affordable to construct and maintain. Energy-efficiency measures developed and integrated into the KoP will protect financial investment since according to the UNC Center for Community Capital and the Institute for Market Transformation "the more efficient the house, the lower the default risk;" Energy-Star homes are 32% less likely to go into default and for each additional point reduced on the Home Energy Rating System (HERS) index the default rate drops" (UNC, 2013). Towards this end, it is critical that KoP homes perform well below energy code requirements and Energy-Star certification standards (see www.energystar.gov) on the HERS index.

KoP makes use of a well-established and widespread module housing industry in the United States and in Pennsylvania especially. The KoP includes a carefully considered and flexible modular system for new and retrofit homes that can accommodate contextual adaptation to multiple infill sites and program needs. Modular construction can effectively achieve the level of quality control requisite for healthy and energy efficient homes. Multiple KoP modules can be combined and configured for the delivery of new houses and small housing projects on a variety of site conditions. Modular augmentation cores, that include well-integrated mechanical and plumbing systems, will also be developed to a high level of efficiency and integration. Coupled with improvements to building envelopes and careful attention to air quality, these cores can be employed to save, update, transform and retrofit existing residences, especially in adapting homes for the accessible single floor living desirable for aging-in-place. The highly efficient core modules can improve the overall performance of existing homes (Iulo, 2013).

This research explores modular building as a response to multiple apparent and specific needs for housing in Pennsylvania and beyond, including:

1. Modest housing for an aging population – emerging demographics are driving a strong need for high quality, low maintenance housing that is modest in size and cost.
2. The need for the production of healthy, energy efficient housing and retrofit of existing homes.
3. Demand for housing related to the natural gas industry - The rapid expansion of the natural gas industry because of drilling in Marcellus Shale formation is causing unprecedented growth in established towns throughout a region unaccustomed to growth (Thompson, 2011).

CONTEXT

This project is a collaborative effort between the Energy Efficient Housing Research group at Penn State and the Union County Housing Authority. Union County is an ideal location to address the needs summarized above and explore the proposed housing delivery method. The geographic majority of the Commonwealth of Pennsylvania comprises rural communities like Union County. These communities are home to nearly 30% of Pennsylvania's 1.27 million people. On average, rural populations are older than residents of more urban areas. According to The Center for Rural Pennsylvania, "from 2000 to 2030, the number of senior citizens in rural Pennsylvania is projected to increase 58%", resulting in an estimated 25 percent of the total rural population being age 65 or older by 2030. "At that time, there will be more senior citizens than children and youth in rural Pennsylvania" (Center for Rural PA). The population of Union County has steadily grown since 1900, with 8 percent growth realized in the decade since 2000; the current population of 44,947 is projected to grow to 52,280 by 2030 (Center for Rural PA). The county includes sparsely populated agricultural areas, but the majority of the county's population resides in municipalities considered to be "urban" by The Center for Rural Pennsylvania. The densest areas are the boroughs of Lewisburg, a college town with a population of approximately 6,000, and Mifflinburg with a population of +/- 3,500. The Borough of Lewisburg ranks a walk score of 85, "Very Walkable" on www.walkscore.com, with restaurants, groceries, parks, schools, shopping and other amenities within walking distance. Even the small rural borough of New Berlin has churches, a courthouse, two banks, a senior center and fairgrounds within walking distance of the majority of the residents. These community connectivity characteristics are important to the overall livability and sustainability of the towns; specifically they are consistent with principles of Smart Growth, Enterprise Green Communities, and USGBC LEED® Green Building standards, all associated with reducing energy use and environmental impact. Further, according to a National Association of Realtors survey, the majority of Americans favor "walkable, mixed-use neighborhoods" (Martin 2014).

Union County is also representative of other regions of Pennsylvania and throughout the United States in that the cost of housing is a significant burden on a large segment of the population. Between 2005 and 2009, 24% of homeowners and 44% of renters were expending more than 30 percent of their household income for housing; up to 30 percent of total household income is the commonly accepted cap on the amount that Americans should spend on overall housing-related costs, including utilities. Directly related to overall shelter costs are expenses related to home energy. Union County is especially impacted by home energy expenses since the majority of homes are heated using expensive fuel oil or electricity (USA.com). The Home Energy Affordability Gap, developed by Fisher, Sheehan & Colton (FSC), is used to qualify the gap between "affordable" home energy bills and "actual" home energy bills (http://www.homeenergyaffordabilitygap.com). According to the FSC 2012 report (2013), the Home Energy Burden for Union County is 41.9 percent. Those of low to moderate income are most adversely affected. In Pennsylvania, households below 50 percent of the poverty level (which represents 19.9 percent of Union County's households) are expending a "crippling" 36 percent of their household income on utility bills alone (6 percent or less is considered affordable). Even Pennsylvania households with incomes between 185 and 200 percent of the Federal Poverty Level have energy bills that exceed the affordable 6 percent of income (FSC 2013). Younger (under 25) and older (65 or older) households “experience similar housing burden to each other” and a higher overall housing-cost burden than other age groups (Swartz 2008). Exacerbating the problem, findings have shown that as housing prices increase, low-income households are increasingly forced out of higher-quality, higher-priced homes into older lower-quality, less-energy efficient homes (LIFE 2011). These facts point to the importance of energy efficiency considerations in all homes, new or existing.

Finally, although only the tip of a very small finger of Pennsylvania’s Marcellus Shale formation extends into Union County, the county is surrounded by actual and potential Marcellus Shale activity on the north, east and along the southern border. Therefore, housing demand related to this energy industry extends into Union County, especially from the north (Lycoming, Tioga and Bradford Counties) where Marcellus shale wells are concentrated.

Union County Housing Authority Energy Efficient Housing Program

The Union County Housing Authority has embarked on a program to address the long-term affordability of their clientele. Pennsylvania’s Union County Housing Authority launched the Energy Efficient Housing Program (EEHP) to demonstrate a way to reduce utility costs in order to make homes more affordable and sustainable for “Prime-Time” homebuyers, people age 55 and older living on a modest budget (less than 80% of the area median income). The projects were intended to demonstrate green design and development principles. The four homes, a duplex and retrofit of two existing homes designed and constructed as pilot projects for the EEHP, were recently completed and new homeowners occupy three of the four. An initial assessment shows that these homes are quite successful in meeting goals for a reasonable initial construction cost ($70 - $108 / S.F.) and long-term expenses related to energy performance (duplex = 46 HERS; Retrofits = HERS of 68 and 77 respectively). This pilot project is being monitored by the EEHR group and findings will inform decisions on the KoP development. Development of the KoP builds off of the lessons learned from the design for modular housing and energy efficiency improvements deployed in the Union County EEHP homes.

PREFABRICATION AS A MODEL

A yet unmet goal of the EEHP is its ability to be replicated. Rarely do we see small green affordable housing projects. A significant reason is the size since small projects, like infill houses, cannot bear the soft costs required by a rigorous design process. Nor does one design “fit all.” The concept for the modular home delivery system KoP being developed for this research is intended to address that.

Precedent Review

This study began with an analysis of precedents for residential prefabrication. Although there is a long history of prefabrication worldwide, attention was dedicated to post-war U.S. examples of prefabrication where modern construction materials are used. The precedents examined fell into three broad categories: those examined based on spatial configuration and repetition; types of prefabrication; and component construction. Constructability, affordability, sustainability and flexibility of the selected exemplars were studied.

Throughout modern history, the industrialized manufacturing of building materials led to designers speculating about different approaches to the manufacturing of homes. Manufacturing processes associated with wartime aircraft construction, followed by assembly line manufacturing in the automobile industry excited speculation in particular. Certainly the influence of the aircraft industry was still evident in the late 1960s in Architect and educator Paul Rudolph's extruded cylindrical home modules. However mass-production wasn't the only thing underlying design – flexibility in combining the modules allowed for significant customization of the modules to particular site and cultural contexts. The pinwheel parti of Rudolph's site design for Oriental Masonic Gardens in New Haven, Connecticut created a dynamic central community space using similarly shaped and stacked module units. Rudolph also explored modular construction in high-density residential configurations for New York City. Buckminster Fuller's explorations using manufactured kits to "overcome shortcomings in existing homebuilding techniques" include the famous Dymaxion Houses (first developed between 1927 - 1929 and redesigned in 1945. http://en.wikipedia.org/wiki/Dymaxion_house). Of particular interest for this study, however, is the Dymaxion Bathroom. This 1936 ultra-efficient plumbing core encapsulated the sanitary functions of the home into a hygienically sealed module. This bathroom module was constructed from four molded plastic or metal sheets light enough to be carried by two workers and small enough to be used in the retrofit of existing structures. All plumbing and ventilation was centralized in the core. Although the fixtures were arranged "to ease the care of children and seniors," ultimately, the space-capsule aesthetic proved too sterile for mass consumption (http://www.weirduniverse.net/blog/comments/2824/). The radical transformation of housing typology in Rudolph's Oriental Masonic Gardens was also eventually rejected and demolished. Thus showing that the appearance/perception of modular construction must be carefully considered. Carl Koch's Lustron House, a kit of factory-produced "parts that could be assembled in many configurations" is credited with "not perverting conventional image" (Davis, 1995). Koch, according to Davis, anticipated that to be successful factory-produced housing must support the market, considering "a network of financiers, sellers, and maintenance support. Illustrating success in this area, "as recently as 1991 the magazine *Progressive Architecture* sponsored an affordable housing competition based on the Lustron model, intended to awaken the housing profession to the pressing need for housing to demonstrate, yet again, the benefits of mass-production" (IBID, pg. 25-26). Abacus Architects award-winning project for this competition was manufactured in Pennsylvania and showcased on a site in Cleveland, Ohio. The architect has adapted the design of the Progressive Architecture Affordable House Prototype for "different family types and site conditions, including grouped houses with lower level parking built for a Neighborhood CDC on a hillside site in Pittsburgh" (www.abacusarchitects.com).

More recently there is an increased interest in modular construction for achieving modern, affordable and sustainable homes. Allison Arieff and Bryan Burkhart examined architect designed prefabrication for the "homes of the future" in their 2002 book, *PREFAB*. Author Jill Herbers continued this theme in *Prefab* modern (2004). These ideals were brought to public attention by Dwell magazine when they dedicated an issue of the magazine to prefab homes and subsequently challenged architects with designing modern prefabricated homes for $200,000 (Arieff (2005). Modern prefabricated home designs were further promoted on fabprefab, "a web resource dedicated to tracking developments in the market for 'modernist prefab dwellings" (www.fabprefab.com). In 2002 the potential for "sustainable" prefabrication was realized, perhaps inadvertently, with the first DoE Solar Decathlon competition, when collegiate teams constructed their solar home designs on the National Mall. Shortly thereafter, in 2005, Architect Michelle Kaufmann's modular GlideHouse was exhibited in the National Building Museum to showcase the potential for achieving Green Homes. Today, the Santa Monica, California company LivingHomes (http://www.livinghomes.net/homesCommunities.html) has expanded their portfolio to offer LEED certified prefabricated homes designed by well known architects including Ray Kappe, FAIA and the Philadelphia based partnership KieranTimberlake Architects. The C6/CK series LivingHomes are cataloged on the website based on size and price and can be customized by interested homebuyers. The U.S. Department of Housing and Urban Development (HUD) has acknowledged the potential for prefabrication in the facilitation of well-designed affordable housing. According to HUD researcher Carlos Martin, PhD, " the trick is finding that magic tipping point where you can use prefabricated materials, components, systems and modules and still create innovative and site-specific buildings" (Arieff 2013). Several university Design/Build programs have managed to successfully merge modular building conventions with sustainable building practices. Of most interest for this study are Auburn University's DESIGNhabitat Program, specifically the DESIGNhabitat 2 house that addresses site-specific design by marrying room-sized home modules with site-constructed components (Hinson & Norman 2008) and U.VA's various ecoMOD solutions for urban infill, community densification, and renovation of existing homes (Quale 2012). Notable in merging high-performance building strategies with innovation in modular construction is the Philadelphia-based develop-design-build firm Onion Flats. Recent work of Onion Flats utilizes existing housing typologies of row-houses and courtyard apartment blocks while rethinking the construction, spatial layout, and efficient home energy systems, allowing for innovation within an already accepted context while greatly improving the energy-performance of their projects.

Limitations of prefabrication

The revitalization and densification of existing towns and community fabric is one goal of the proposition addressed with the KoP. Currently modular manufacturers do not target infill development. As articulated by U.VA ecoMOD professor John Quale:

> *Homeowners are typically restricted to placing their prefab house on a suburban site, where land is cheaper. In addition to cost considerations, most*

manufacturers and modular houses are designed for the orientation of wider suburban lots. No major manufactured home company offers models designed for narrower but deeper urban lots with the entry side facing the street. The typical singlewide module for these homes measures 12' to 14' wide by 48' long – a size difficult to transport into many tight urban areas. As a result, families in the affordable housing market are being pushed to the periphery of the city, where they have the added financial burden of being fully dependent on a car. (Quale 2012, pg. 39.)

The several projects that ecoMOD has completed between 2004 and today demonstrate that modular home design can be dimensioned to be feasible and contextually appropriate for different infill site conditions. Additionally, the addition to ecoMOD3/SEAM house and the schematic designs for ecoMOD XS hold promise for the densification of existing communities by adding small accessory dwelling units to existing building lots (see: http://ecomod.virginia.edu/projects).

The limited use of modular construction as key to a delivery method for publically funded affordable housing projects is another issue that we hope to address with the KoP. The UC EEHP Duplex home was funded primarily through a HOME grant. Two conventional builders and one modular home manufacturer responded to the public call for bids. The low-bid presented by the modular builder was accepted for construction of this phase of the project (the EEHP pilot project included the energy-efficient retrofit of two existing homes; see proceedings from the 1st RBDC conference for lessons learned from the retrofit process). The majority of affordable housing rental projects are funded in part through Low-Income Housing Tax Credits (LIHTC). In *The Architecture of Affordable Housing* author and architect Sam Davis critiques the process imposed by the application process for LIHTC projects, stating:

The [developer] must have control of the land on which it intends to build before it can apply for the tax credits. Finding developable property and ensuring its suitability, both technically and politically, takes time, pushing the organization against application deadlines. It is usually at the last minute that the architect is given instructions as to the site and program, and thus the design – the element that will have the greatest effect on the costs and the most lasting effect on the project – is a hasty set of decisions. Although the design can be refined if the application is approved, changes in unit size or mix and in overall costs are not allowed. And since so little of the public review process can be undertaken before the land is optioned and the application submitted, there is an inevitable disjunction between what is contractually required for funding and what may be most desirable for the community. Finally, the deadline for spending the funds once they have been granted is also much shorter than is feasible under the best of circumstances. Since any hitches may jeopardize the financing, the CDC [developer] and the architect must get it right from the onset, without much opportunity to work with the community (Davis 1995, pg. 20).

Ideally the KoP can address the issues identified by Davis above by providing a building block for schematic design that can be used by the design team for the purposes of site planning and establishing the unit numbers and sizes, basic building massing and general project elements. Further, schematic drawings generated using the KoP can provide visualization tools for community input and "buy-in". Thus the KoP will facilitate upfront planning and allow for refinement later in the process. Additionally, as evidenced by the 2002 rehabilitation and addition to Archer Court in Chicago, Illinois, successful implementation of a kit-of-parts for structural and finishing elements can save construction time and, in turn, labor costs (Schmitz et al 2005, pg. 56).

PREFABRICATION AS A SOLUTION

The precedents discussed above explore some of the ways that the post-war building industry has responded to the need for housing with a mass replicable approach that can be faster and more controlled than site-built construction. However a critique of the assembly line ideals of mass-production is that the resulting houses are uniform and repetitive, lacking the flexibility necessary to adapt to different sites, building types and resident needs. Despite this seeming lack of flexibility, modular home building has become a prominent part of the housing industry. Recognizing a need for flexibility, architects, homebuilders and manufacturers have responded with several variable modular components and panelized systems. These include volumetric modules typical in the modular housing industry, wall and floor panels such as structurally insulated panels (SIPs) and the panelized approach to homes typical in Europe, and structural elements such as the readily customizable truss industry.

Opportunities with Prefabrication

The highly coordinated and integrated system of components envisioned for the KoP includes volumetric modules and element parts that are appropriate in many different configurations for both new construction and retrofit of existing buildings. Based on initial schematic design proposals, components will be selected and refined based on energy-performance criteria. The resulting components can be custom configured based on building requirements, site conditions and local industries, and material availability.

KoP Design Goals

Durability: high-quality long-lasting materials and details that are easily maintained and/or upgraded; favor local regional materials as a means for embracing customization.

Flexibility: flexible and adaptable living space to accommodate changing needs of residents. The focus of the KoP is on providing small homes appropriate for those homebuyers seeking their first home or those looking to downsize, resident demographics that align with those most affected by shelter and home energy costs. Further, small homes better meet changing home demographics in general; throughout the U.S. there are increasingly more individual households. In Union County, 72.9 percent of the households are "without own children," including 34.7 percent married couples without children and 27.6 percent single person households (Center for Rural PA). With regard to this goal, KoP homes are designed to be accessible and the interior spaces meet Universal Design Standards. Each home designed using the KoP includes a space at the entry level that can serve as a bedroom. Modules for adapting existing homes for Aging-in-Place include accessible bathroom and individual bedroom modules.

Scale-ability: Small-scale, scattered site development provides opportunity for the densification and revitalization of existing communities. Towards that end, several approaches are addressed in developing the KoP:

- Densification through ancillary units that can provide income as a rental property or space for a caregiver;
- Renovation of large, older homes as a multiple-family dwelling;
- Retrofit of existing homes for energy efficiency and aging in place;

Infill of underutilized sites at a scale appropriate to the developable land and the community including single-family infill (detached or semi-attached), duplex or townhome (attached), and multifamily making it possible to apply the KoP for larger-scale projects and urban applications.

<u>Preliminary thoughts on KoP components</u>

To date the KoP team has explored schematic designs for modular layouts that meet the criteria outlined about. The small home configurations are flexible in their layout and adaptable to different building densities and site conditions.

Hybrid panelized / modular approach

Based on the precedent analysis and successful energy performance of the duplex pilot study, a hybrid panelized / modular approach is used for these preliminary studies. This approach was used in two of U.Va's ecoMod Homes (ecoMOD 1 and 3) and the strategy was successfully employed on the assembly line in a manufacturing plant for the EEHP duplex. Rather than walls being framed on tables and lifted into place, as is typical with modular construction, pre-sized and cut Thermasteel SIP panels were delivered to the manufacturer and attached to the completed floor assembly. Although the use of the SIPs did not greatly affect the production line, considerations for material procurement and schedule had to be taken into account – there were additional fabrication drawings to be approved prior to the SIPs being manufactured and a lead time for arrival – considerations not necessary with framing (especially since most manufacturers buy framing materials at bulk prices and have them in stock).

Analyzing the initial KoP schematic drawings, the following elements of the design were identified for further development as energy-saving components in new housing and for the renovation and retrofit of existing housing stock:

Mechanical & Plumbing Cores: Based on lessons learned from Penn State's previous Solar Decathlon entries, the *MorningStar* and *Natural Fusion* solar homes and a study of InHouse OutHouse, an AIA Housing Knowledge Community project developed by a team from Rice University, the efficiency of centralized mechanical & plumbing cores appropriate for different KoP scenarios are explored. The core has been implemented in modular construction and panelized systems, as well as for retrofitting existing homes. This strategy is used for a variety of reasons including improved energy efficiency, restoration of an existing home, and potentially as an addition to a home for aging-in-place. Although the concept of a core unit is projected as a flexible solution for a variety of home situations, in fact it can be somewhat limiting. Therefore the defined parameters, spatial layout, and impact of the core on the more flexible living spaces of the home are carefully studied. The layout of the bathroom, kitchen and utility spaces take universal design and ADA adaptability into account. The cores are designed to accommodate all plumbing and mechanical needs into the conditioned envelope of the home. Further studies of mechanical and plumbing systems for cost and energy efficiency will be explored as KoP research and development continues.

Stair modules: Overall circulation space in the KoP designs is minimized to maximize living space. Vertical circulation has been efficiently limited to two configurations accommodating a straight stair and a u-shaped "scissor" stair. These configurations are appropriate for connecting floors in single family or multifamily dwellings and can be used for adding code-compliant fire stairs in converting existing homes to multifamily dwellings. The stair modules are studied in plan and section for passive solar benefits, specifically, getting natural light to central living spaces and accommodating natural ventilation.

Two components are identified for further development because of their potential for flexible use in different dwelling types and their contextual significance for enhancing community. These are:

Auxiliary units: Room-size modules that can be used for additions or the retrofit of existing homes are proposed. Combined with a mechanical/plumbing core module they can provide accessory dwelling units on an existing lot. How these units meet the ground is of special consideration to assure proper detailing of the modular units and to allow entry to each unit to be fully ADA accessible. The interiors of the units will comply with Universal Design and Visitability standards.

Sun Space: Another element explored for the KoP is an extension of the living space. This module may be contiguous with the residence entry and vertical circulation. Depending on community context this element will be manifest in different ways, as a porch, sunroom or entryway. Orientation and location of this module and its connection to the dwelling unit will vary in order to provide an effective isolated gain space for passive solar benefits. The side porch/entrance seen in Scattered Site Infill Housing, Charleston, SC by the architecture firm Bradford Associates highlights some of the benefits of this component (Davis 1995, pg. 152-156).

A PROCESS, NOT JUST A PRODUCT

The KoP components may hold promise as a construction delivery product aimed at improving the energy efficiency of new housing and for the retrofit and renovation of existing houses. But the product described cannot be separated from the design process. Importantly, a shift in process has to happen for the KoP to be successfully implemented. In a conventional design process, the most time and project fee is dedicated to the construction documentation phase of the project. This shift is facilitated by integrated project delivery (IPD); therefore acceptance of these principles and techniques is necessary (for information on IPD see AIA 2007). Once this occurs, KoP components can be applied as a part of the integrated design process. Since small projects generally cannot absorb the soft costs of a rigorous design process, this cost is spread over many projects. The benefits of a project-specific integrative design process for improving project performance would be "baked" into the individual components, resulting in high performance fabrication for each part. To achieve this result, the development of each component is considerably more involved than architectural design/specification; it must include precise details for means and methods, tolerances, and performance testing – analogous to a UL listing for each component. The KoP components are defined though the parameters of modular construction, a major player in the Pennsylvania housing industry. Rather than every component of the dwelling or building being defined, ultimately dictating the design outcome, the KoP focuses on components that will improve the overall performance of housing. A catalog analogy would be more synonymous with Sweets than Sears. The KoP, as envisioned, provides a valuable role for designers in providing affordable housing, while playing to the strengths of the manufacturing industry. Because KoP establishes the assembly details, the focus of the designer is on the schematic design and construction administration phases of the project. The initial focus of the design professional is on the selection and configuration of KoP components that are most appropriate for the selected site conditions. We imagine that the KoP would simplify project construction documentation by limited the details and calculations necessary. Finally, design expertise centers on the selection of durable, contextually appropriate materials and finishes that will support the local economy. The architect's role is to holistically consider the short- and long-term project goals and efficiently compose the parts in response to the site, client, program, green benchmarking, aesthetic decisions, and community. Allowing the design professional to add maximum value, while limiting time requirements per unit and potentially some professional liability. Ultimately it provides a role for design professionals in small projects where frequently there is none.

CONCLUSIONS

The KoP describes a series of prefabricated interventions that work integrally at three nested scales: 1) core systems; 2) flexible modules for building design; 3) for community enhancement. Individualized contextually appropriate results can be achieved through informed, careful consideration, selection and configuration of KoP elements.

Next step:

Refinement of proof-of-concept will take place over the course of the spring semester. The research team will be looking to industry specialists and stakeholders including representatives of the modular building industry for design advise, pricing and feedback on the practicality and replicability of the concept. Representatives from business will be consulted for real estate advise and strategies for revitalization. The expertise of researchers in HHD and the Penn State Aging and Psycology Lab

(APL) will be consulted on issues related to flexibility and aging-in-place. Two teams of undergraduate engineering students will be engaged to work on this project as their senior capstone requirement. The first will determine appropriate energy performance criteria based on monitoring and assessment of the pilot homes and the second will be developing components of the KoP for optimal energy performance.

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Structural BIM Processes for Modular Multi-story Buildings in Design and Construction

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ABSTRACT:

Modular construction and prefabrication is a growing trend in the Architecture, Engineering, and Construction (AEC) Industry based on a series of technological developments and its historical exposure to design and construction practitioners. Some of these technological developments come from a computing side such as Building Information Modeling and advanced parametric studies or in new methods of structural modularity in the systems. Modular systems are inherently different in structural behavior, construction, design, and modeling in relation to traditional stick-built structures. Methods to develop efficient solutions differ just as their other attributes do. Furthermore, the inclusion of modular and prefabrication design notions into the design process is often limited based on a lack of well thought out processes; the same can be said for the construction phase. Because of the need for better understanding of how modular systems function and interact with systems is limitedly known, defined processes in how to account for these behaviors can reduce the current high variability that relates to system effectiveness and project teams willing to implement it. This paper will focus on describing current design and construction processes and identify where modular aspects need to be considered at different lifecycle phases such as conceptualization design where the scale of modularity must be determined as an example. Beyond the current status of industry processes, recommendations will be made on where more effort needs to be placed on defining more detailed processes around new technologies like Building Information Modeling. Additionally, the ties between defined processes and how they help software developers will be discussed.

INTRODUCTION

Modular construction and prefabrication in the Architecture, Engineering, and Construction (AEC) Industry is a growing trend (Giles and Lara 2006). From a definitional standpoint, modular construction refers to one or more factory-built building units from the fabrication site then transported and assembled on-site (Pasquire 2002; Lu and Klorman 2010). Examples of the varying complexities of modules can be seen in Figure 1. The production of modular units are best suited in an industry that thrives from a supply chain process, which accounts in developing a few parts as possible to build the end project (Giles 2008). These systems have the ability to impact many sectors and building types such as residential, multi-family dwellings, educational, correctional and high-rise (Schoenborn 2012). With its unique requirements, modular construction is not feasible for all architectural styles and building classifications, particularly those with little repetition (based on current practices and technologies).

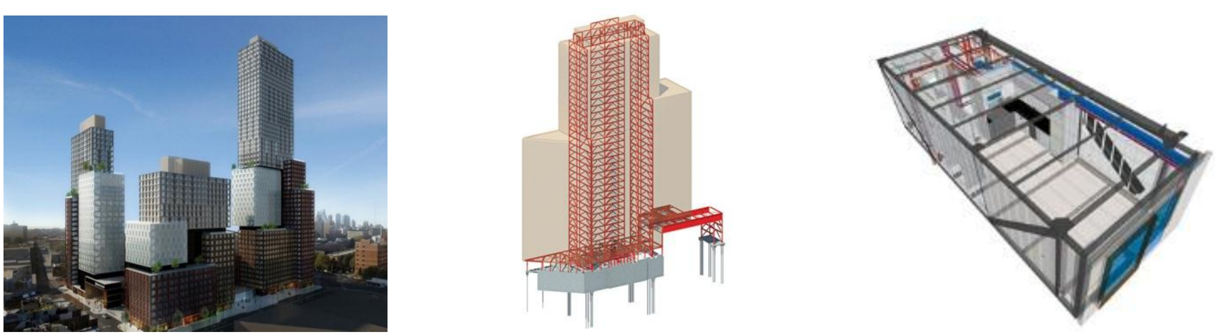
A primary motivation behind a shift towards manufacturing the building process is to reduce cost, time-to-build, and improve the quality of the project (Alwisy et al. 2012). A 2011 market report states that 37% of the AEC industry takes advantage of modular construction on a high volume (≥ 50%) of projects within their firms (McGraw-Hill 2011). It is projected by those same industry professionals to rise to 45% by the end of 2013. Schedule time saving of 35-66%, decrease in project overall budget by a min of 6% to 20%, improvement to off-site labor productivity by as much as 2.32%; these are the main driving factors (Eastman and Sacks 2008; McGraw-Hill 2011). Growing trends such as these, could be accounted for by present construction nearly always has an off-site component that plays a major role to some degree and to varying complexities of modularization (Nawari 2012).

a) Prefabricated Roof b) Water Closet Prefabrication c) Container Unit Decomposition

Figure 1: Examples of Physical and Virtual Modules

Other areas that promote modular construction that has advantages revolves around: reduction of need for workforce, the reduction of on-site carbon emissions, the improvement of construction schedule and product quality, economy of scale in manufacturing of multiple repeated units, speed of installation on-site, and improved quality and accuracy of the product (Lawson and Ogden 2008; Lu and Klorman 2010; Lawson et al. 2012)

Historic building construction typically factors in consideration by architects and engineers related to standard performance characters for the main disciplines on conditions related to the final build configuration. Off-site construction now requires not only consideration of the performance after construction but also consideration of production, transportation, and installation performance. This industrialization shift in the construction of the building requires special methods of production technology and particular design criteria to support these new processes, all of which now need to be accounted for in the design phase (Moghadam et al. 2012). An example of a high quality mid-rise to high-rise project in the U.S. depicted in Figure 2.



a) Architecture Rendering b) Structural Lateral System c) Modular Unit

Figure 2: $4.9 billion Atlantic Yards Project (Largest Modular Project in the US)

(Source: http://continuingeducation.construction.com/article.php?L=5&C=943)

Mass customization of modular units and the development of digital technology are the new emerging paradigms of the twenty-first century. Interrelationships between these two domains have already prompted a shift towards mass customization based on developments in the digital revolution (Huang and Krawczyk 2007). However, the modular industry today still faces challenges related to moving past traditional market social stigmas within the AEC industry (Jellen and Memari 2013). Major social, as well as technical, issues that inhibit adoption (based on a lack of understanding of the scope) encompass (Lu 2008):

- Understanding how to coordinate the system interactions
- Understand how modularization works;
- Not designing for modularization early enough
- The lack of knowledge about what is needed with complex modular construction

There is, however, a potential for closing this gap with another successful technology that is redefining processes through adoption in other areas of design and construction. This technology is Building Information Modeling (BIM). Relating BIM to modularization, McGraw-Hill Construction in conjunction to National Institute of Standards and Technology (NIST) listed the emergence of BIM technology as a major factor fueling the interest in modular construction and prefabrication (McGraw-Hill 2011).

Information driven technology, BIM being one of them, has the potential to continue advancing our understanding of how to perform design and construction on modular and prefabrication construction. Ikerd (2008) and Aldea et al. (2012) state that firms who use collaborative information technology can gain a significant competitive advantage by adopting new processes for the structural sector of the AEC Industry. As of now, current modeling techniques are limited especially for the relationships between the modular unit and any extra lateral system needed in taller structures. In essence, there is no special software for the design of modular buildings currently as compared to stick-built where there are a multitude of software and tools. However, such tools could be developed according to Ramaji and Memari (2013).

In looking towards tool development, an understanding of the process must be known or proper tools cannot be developed to meet the needs. The lack of understanding and having ill-defined processes that professionals can reference focusing on modular design and construction is still incomplete. However, BIM has started to change this through developing such processes. Defined processes can reduce the current variability that relates to system effectiveness and project teams willing to implement modularization on projects. This paper will layout and summarize process advancements where modular thinking needs to be conducted.

BIM IN MODULAR DESIGN AND CONSTRUCTION

Recently, new terminology and their meanings are becoming mainstream such as Building Information Modeling (BIM), Virtual Design and Construction (VDC) and Integrated Project Delivery (IPD). All of these are resulting in more and more engineering firms being asked to participate or are required to collaborate in model-based workflows (Rammant and Adriaenssens 2008). BIM can be thought of as a tool and as a process that generates, through multi-person and firm participants, the ability to convey design concepts and details in a clearer and more concise manner. Often this conveyance allows for earlier considerations of various topics. This “shift” proves essential in that design decisions cannot be afforded to be revisited later in a project, especially as projects become more complex as timelines are compressed (Middlebrooks and Hammond 2010). This has made numerous large-scale projects possible by breaking down communication barriers. In general, these types of tools and processes are in the process of transforming the way business is being conducted (Keil et al. 2001), particularly over the last several years in the building industry (Jacobi 2007) with unprecedented opportunities for expansion.

To support BIM adoption, Fallon and Palmer (2007) found that successful software adoption at the design stage can lead to a 10% cost savings on a project based on better: design efficiency, material selection, and coordination. Bayramoglu (2001) and Gallaher et al. (2004) additionally found through an extensive study on technology improvements, that there is a reduction in errors on the order of 20%, all possible through the use of enabling technologies that improved communication between all stakeholders. McGraw-Hill Construction's report (2012) expands this value to 37% across the lifecycle, which is a 10% increase from 2009 results. Furthermore, they concluded a 36% profit increase were found within firms that have adopted BIM, this is up 15% from 2009.

Relating BIM to the modular domain, Nawari (2012) identified countless advantages that can lead to significant impacts in off-site construction including: the support and increase in speed, sustainability, safety, constructability, quality and time of construction, and enhanced prefabrication yield. Additionally, Song and AbouRizk (2006) found that virtual systems can simulate the shop production environment at a realistic level. The associated realism with BIM can help simplify any simulation modeling misunderstandings and has the capability to help grasp complex systems' interactions more clearly. One of Lu and Korman's (2010) modular BIM case study projects showed that while it costs $44,000 to implement BIM technology into the firm, it saved a project $220,000 overall for a $44 million dollar project as compared to the same company who did not use BIM for modular.

In order to understand the technology and how it can play a role in the process, a discussion on the structural aspects of modular construction is needed. The section to follow provides a discussion of these highlights.

STRUCTURAL MODULARITY TO CONSIDER IN DESIGN

Based on the survey that Haas et al. (2000) conducted, the top building trades that are using prefabricated components most effectively involving structures are: structural assemblies (3rd), concrete (9th), and masonry (14th). These results are still valid in that McGraw-Hill (2011) found that in industry, mechanical systems are still the most prefabricated while architectural components and structural as a whole remains in send and third respectively. Structurally speaking, many items can be truly modular and/or simply just prefabricated based on current manufacturing methods (Badir et al. 2002; Hallowell and Toole 2009).

Modularized structural systems can come in different classes and it is necessary to know the types and configurations in order to make recommendations in the process. The main classes to differentiate items are 1) panelized systems and 2) 3D modular or volumetric systems (Jellen and Memari 2013). Panelized systems are flat assemblies that often focus on wall, roof, and floor systems, whereas 3D modular systems are volume spaces that are often made up of panels. A third system that can be considered prefabricated is structural elements/sub-assemblies. Ramaji and Memari (2013) categorize modular buildings in five typical configurations. Within each combination, however, there are unique attributes to each. Grouping prefabricated structural systems by type, Table 1 lists the most common as suggested by prominent literature.

Table 1: Types of Prefabrications

Elements	Panelized Systems	Typical Configurations
Concrete forms	Wall (bearing, lateral, infill curtain)	Stacking 3D modular system
Reinforcing cages	Roof	Hybrid Cored-Modular
Precast concrete	Floor	Hybrid Podium
Joists and trusses	Precast concrete	Framed Unit systems
Stairs		Open Building System

As Table 1 represents, many items we design for are in fact considered modular; it's just that the traditional engineer of record (EOR) does not account for the modular aspect in most cases. The more standardized, consistent and repetitious the dimensions are, the larger the number of components can be.

In order to design, engineers and other trades related to modular construction need common and specific/specialty knowledge about different criteria, behavior, modeling assumptions, decision factors and much more. This knowledge is particularly important when working with technology that needs this different information to function, thus the "I" (information) in BIM. Without it, then it's simply a 3D model for visual purposes only. Information needed in modular BIM is still unknown as it has limitedly been studied and deployed, particularly with no proven and efficient software to run simulations. Listed in Table 2 are key information classes that should be known to properly model behavior and to make decisions on modular designs. This listing is not comprehensive due to this domain being so new. As new technology is developed, this list will surely expand.

Table 2: Examples of Potential Information Knowledge Needed

Design and Performance Criteria	Behavior of the Structural Systems	Owner Criteria
• Safety • Redundancy • Robustness factors	• Individual module diaphragms • Whole building diaphragm • Continuity in vertical plane • Connection of units • Limit states	• Completion schedule • Cost • Material requirements • Aesthetic look
Modeling Considerations	**Manufacturing Domain**	**Optimization Studies**
• Load definitions • Module overlap • Element definition • Boundary conditions • Force-deformation relationships	• Factory space limitation • Available human resources • Factory working hours • Automation limitations • Available equipment	• Cost • Schedule • Benefits and challenges • Performance and function • Material Properties • Configurations

PROCESSES SUPPORTING MODULAR

The misunderstanding of current technology and lack of integrated and collaborative delivery methods is a concern. This is because they do not actively support efforts such as modular construction notions to make a real impact. Processes help all project team members to better understand other stakeholder's role(s). They also provide a foundation for defining workflows that support integrating computational modeling particularly between disciplines to convey and test design ideas (Lee et al. 2012).

Various efforts have been or are still being conducted to define proper processes. Current process models depict the big picture project workflows at different stages of the building lifecycle but at a low level of detail to define what could be modular. An example is with buildingSMART International's (Norway) examination of structural design of a system as a whole yet it focused on model generation in the design phase (buildingSMART International 2007). However, a few projects have placed more emphasis on identifying locations where technologies are needed. Lee et al. (2012) is developing an integrated model that describes the entire planning and design process for all major participants on energy efficient renovation projects. Additionally, Solnosky (2013) developed an Integrated Structural Process Model (ISPM) that identifies critical tasks at an integrated and structural level for structural planning, design, fabrication and construction of new projects implementing BIM and integrated concepts.

Efforts are now being centered in the research community improve to the process to support these new technologies including modular, prefabrication, and off-site construction. The following sub-sections look at the general structural processes based on Solnosky's (2013) Integrated Structural Process Model in relation to where prefabrication and modularization fits within the larger picture. The topic here is limited to concepts that could lead to heavily influencing modularization adoption.

Perhaps the two most prevalent and demanding design trades that modularity and prefabrication affect is the architectural and structural disciplines, a close third is MEP but there is more room later in the lifecycle for refinement. There is a close relationship between these two design processes due to architectural designs defining the geometry of the building elements where it then becomes a key input in structural designs (Porwal and Hewage 2011). An integrated interaction between various parties, particularly architectural and structural designers, in the early stages is beneficial as they then complement one another (Holzer et al. 2006). Looking at the relationships and functions of the architecture, the structure, and the true modular aspects, clear definitions emerge. Architecturally, spaces and layouts of components and modules are represented in three dimensions and must yield to city bylaws and national codes. Structurally, the modules and the supporting structure and lateral system requires that the designs meet building codes and meet performance requirements for smaller components such as walls, beams, and columns. Modular, in and of itself, takes these two notions and provides a set of rules needed for dividing the layout into units and specifies allowable module dimensions based on road regulations, acceptable dividing elements, and rules related to structural systems capabilities.

Planning and Early Design

Planning centers on the start of a project and looks at the owner's program and proceeds to define major requirements, which the design and construction team must meet. Following the program, major requirements and constraints that need to be met are then identified. Simultaneously, a project execution plan (PxP) needs to be decided upon. This leads to the development of initial requirements and their priorities from diverse perspectives such as spatial, functional and financial. Here is where the modular experience of the team needs to be evaluated to understand how to approach modular attributes. Additionally, the requirements and goals of the owner and teams need to be aligned and compared with what can be done from an off-site construction aspect. Next is the development of site, schedule, and cost constraints. The last section is the generation of the architectural vision that is developed while finalizing the building occupancy rating. Concurrently, project and modular risks to the goals need identified and proper planning needs to be undertaken.

Now that planning is essentially complete, next comes the early design or conceptualization design phase. No matter the name, the focus here is on selecting and testing schemes and ideas against early rules of thumb and best practice techniques to develop feasible alternatives. Early design transitions from planning with the determination of the design criteria for the different systems including modular at a large scale focus. Examples of these include: spatial impacts, performance, reliability and efficiency. Relationships between the systems need to be identified, including the modular characteristics and requirements. This task set looks to study modularization opportunities without going in-depth with calculations. Modular definitions and the creation of groups to facilitate sub-assemblies are identified. The key to prefabrication is to acquire feedback from specialty subcontractors. Feedback focuses on the ability to achieve tight tolerances, delivery times, availability of equipment to ship, the amount of repetition and uniqueness, and envelope sizing limitations.

The remaining portion of early design, essentially is to postulate and holistically evaluate alternative schemes for stick built and modular built aspects of the project, thus narrowing down to one solution. Possible material types and system configurations are identified and those not feasible are dropped. Major prefabrication details in terms of systems and sizes are isolated through early design routines and iterative parametric studies. The optimum implementation of modular units and assemblies can be achieved by designing one of two ways: 1) highly serviced and more expensive parts of the building and 2) more regular and repeating features. Both of these reinforce careful consideration to the architecture and spatial planning of the building. The studies on modules will be given to the owner to determine if they support these ideas and their associated details. A goal here could be to look for and try to include as many off-the-shelf components as possible. Design items to focus on at this point include:

- Access areas in the building design to maintain modules as needed
- Make the modules as complete as possible to speed construction and improve quality, safety, operations and maintenance
- Integration of air distribution systems as part of the structural system
- Exploit the high strength and stiffness to weight ratio
- Utilize wall and floor decking as an inherently stiff system to resist lateral loads
- Integrate slabs for better acoustic, fire and environmental performance between units

Once alternatives are chosen, constructability reviews, preliminary sequencing, and code reviews can be conducted to help select the best alternatives. These alternatives are then compared to the other systems to narrow down the ideas to the single best to be then fully designed. To conduct these concepts, Table 3 lists the major tasks and subtasks that impact modular ideas in planning and early design.

Later Design and Detailing

Having determined the type of structural system to be designed and the modular configurations in a larger scope, the design of these separate structural systems and their interactions can now be done. In traditional construction these phases are referred to as: Design Development (DD) and Construction Documentation (CD). An extension of these phases is detailing, which is really just a continuation of design but now at a smaller more detailed level. These phases can be looked at within two distinct view points, the module structure and the supporting secondary structure.

For the non-modular based structural systems, designing evolves the concept(s) from a holistic level into a single solution that is optimized at the member level. Systems' narrowing focuses around the configurations, orientations, and patterns within the lateral, foundation, and gravity systems. As this process refines the solution, the more detailed the checks and models become. Constructability, site logistics and planning for fabrication and construction can start to be formulated here to ensure the design meets the appropriate construction techniques. Major considerations regarding the site build portion of the structure that needs to be thoroughly looked at is listed as follows:

- Considerations for walls, enclosures, MEP penetrations, specialty equipment in the building, etc.
- Energy performance and, if appropriate, deconstruction and reuse of the pods
- Diaphragm action and redistribution of lateral loads
- The connectivity and adaptability to contain and support the modules
- Strength and serviceability needs to support modules without damage and to protect the structure against man-made and environmental conditions

- Coordination to ensure constructability, sustainability, and performance against building codes, standards and industry best practices are fulfilled

Table 3: Major Planning and Early Design Tasks that have Significant Modular Impact

Main Integrated Tasks	Subtasks with the Integrated	Modular Aspects of the Tasks
Develop the owner's program and objectives	Define the owner's needs and corresponding constraints	Owner recommendations on modular
Develop initial project requirements and their priorities	Consider priorities from diverse perspectives such as spatial, functional and financial	Align modular priorities between: • Owner, consultants, and trades Module size
Determine structural criteria requirements for the design: • Spatial impact • Performance • Reliability • Efficiency	In particular relating to the building code: • Systems requirements • When code provisions cannot be used	N/A (no specialty aspect)
Consider prefabrication of various component complexities	Acquire feedback from specialty subcontractors	Consider: • Delivery times and transportation • Specialty equipment
Conduct interactive rationalization between the systems	Layout the project massing based on different systems and how they dictate one another	Develop concepts around: • Overall layout arrangements • Building • Floor to floor dimensions • Column spacing • Symmetry effects • Module size and shipping
	Look at how the site and geographic conditions can drive a particular system selection	Consider selecting modular aspects: • Adjacent structures • Geotechnical findings • Geographic region • Architecture impact
	Consider the applicability for the structure to overcome special situations	• Concerns for isolation and damping • Special system needs • Multi-hazard resistance • Build-ability and load transfer
	Look at the parameters in determining what material is available and its associated limitations	Investigate the impact on the unit and supporting structure: • Material availability • Material resistance to load • Meeting project drivers • Limitations of the configurations and systems • Weight concerns
Conduct a constructability and project driver review		Module size Ability to control quality Off the shelf product used
Obtain input from a fabricator and determine if the ideas are feasible		Have vendor involvement

In the design of the modular units themselves, structurally there are two main ways of doing this. The first is through proprietary systems and the other is through customized systems. The first lends itself to more off-the-shelf products. As a result it can more quickly be built due to less fabrication and schedule constraints. Many of these are not done by the Engineer of Record (EOR) and instead are done by the specialty contractor (in this case the modular expert). The second way is through custom designed systems are unique to the project. These require a much deeper understanding of structural behaviors and limit states which results in the EOR producing these designs.

In either case, but more specifically the second, the goal is really generating a modular structure capable of resisting the loads acted on the module. These include site loading, long term sustained loads, fabrication loadings, and even transportation loading. The scale of the structure is considerably smaller at a unit level than at the supporting level with stick built. Because of the scale, the narrowing and refinement of the structure often is done more quickly as there is less per unit to determine and refine. The coordination here can be said to be even more serious than normal as tolerances and considerations on buildability in the factory with other systems is more constrained by the unit parameters. The design process is fairly standard with just different criteria and requirements. Typically it follows: analyze, design, coordinate, modify, and repeat till a final solution converges. Much of the design of the modules can actually be correlated to traditional design and construction in the detailing phase where the details are determined. Here with modular, detailing can be done on the module at the same time that the site built support structure is being done at a far less level of detail at the connections level. The main area to consider is coordinating the module interaction and the relationship to the supporting structure (if there is any).

Correlating the relationships between site built supporting structure and the modular units (structure included) there are many characteristics on how the two relate that need to be known. This area as a whole has been limitedly studied due to most historical modularization has had limited structural aspects to it or there was no need for supporting structures. The characteristics to consider all focus on the change in known behavior mechanism of the systems. This is a result in that they fundamentally behave and connect differently. The characteristics below focus on these relationships:

- Second-order effects due to sway stability of the group of modules
- Force transfer of horizontal loads to the stabilizing system
- Diaphragm action within the walls of the modules in how they relate to the building diaphragms
- Manufacturing tolerances and alignment of stick vs. modular components
- Robustness against accidental actions within the modular system during construction and during occupancy
- The influence of installation eccentricities on the additional forces and moments induced on the modules
- Modules corners in how they act together to transfer wind loads and to provide for alternative load paths

To summarize these two concurrent tracks, Table 4 lists the major tasks and subtasks that are in later design and detailing that focus on modular structures and supporting structure that have the most influence.

Table 4: Major Later Design and Detailing Tasks that have Significant Modular Impact

Main Integrated Tasks	Subtasks with the Integrated	Modular Aspects of the Tasks
Early and detailed site logistics		Consider: • Storage of modules • Location of cranes • Placement sequences
A quality control and assurance review	Perform on both the resultant designs and the models for accuracy	• Ensure modular model matches remaining site built structure
Coordination with other disciplines	• Areas heavily influence design decisions • Review for final errors • Conduct with the other disciplines	Coordinate how the modular system connects with other disciplines and fits together
A code and permit review is conducted to ensure designs meet expectations	Ensure: • Standard code provisions are met • Special provisions are met	Review any specialty areas related to modular philosophies
Determination of initial temporary supporting structure with construction methods	Determine: • What needs support • How to support • When to support	Determine: • If modules will need support during fabrication, transportation and during erection
Conduct a value analysis resulting in suggestions for value improvement	Fabricator input on component options	Input from the shop fabricators and foreman for best designs
Erection planning and engineering of the structure as a whole to ensure safe and stable construction	Ensure: • Pieces can safely be erected • Stability of the structure is maintained • Any special limitations are met	Consider: • Module weight, equipment capabilities, lifting points on module, erection loads and stress in the unit

Fabrication and Construction

The modular building lifecycle of the structure continues after detailing and begins with the assembly of the modules. There are really two types of assembly, preassembly (off-site fabrication) and on-site assembly (traditional site construction). These two can be thought of as merely an extension of one another. Off-site fabrication is often referred to in the industry as Modular Construction Manufacturing (MCM). Off-site fabrication is really where the benefit of modularization is at the forefront in promotions. Expanding fabrication’s definition, it is merely a transition phase from taking the developed system and component designs from the digital world to the physical world in a plant setting. While fabricated elements can be in several forms, only the engineered-to-order types are considered in this paper.

Fabrication inherently implies there is a manufacturing of components, elements, and assemblies to a certain level before they are shipped to the site for final assembly (construction). Within fabrication there are two primary core ideas, they are: planning the production in the factory and the other is the actual production of the modular unit. The production line for making the units can take three directions:

1) All hand assembly (human workforce)
2) Fully automated (machine workforce only)
3) A hybrid of 1 and 2.

Depending on the modular units and available automated machinery, the third option is most likely. Here smaller components are machine automated then hand assembled into larger units. The production line for modular units (in particular full units) can be divided into a number of substations for different activities and different systems. The framing structure, enclosure, MEP, and finishes are the most popular unit substations. Specific sets of shop drawings and/or 3D BIM models are required for each phase and station for accurate and efficient assembly.

Once the modular unit or assembly is finished within the factory, then the construction phase starts. A major advantage with modular construction is that it takes most of the production and time away from the construction site which is often the slow unproductive activities on a daily basis. On-site placement of modules reduces the high variability in how different structural types could be constructed. Construction starts with an adjustment to the structural schedule for any delays or conditions that appear onsite or issues that occurred at the factory and were not previously accounted for.

The first actual construction task is the erection of any supporting structure that will be used to support the module(s). Often times, these are lateral systems and possibly even floor/diaphragm systems. Also, foundations need to be constructed. Once constructed, the modular units can be set into place and attached/connected to other building support systems. Any temporary structure(s) may be used during this process depending on the project and the modular conditions. With any on-site tasks there is always the inspection process and potentially requests for information (RFI) conduction occurring. Now though, the RFIs are more on how modules interact with site built portions. After module(s) are set for a particular sequence, a critical process gateway will ask if all sequences are complete. If not complete, then a cyclic loop triggered where more modules or even back to fabrication is done depending on how large the project is. The process repeats until the entire structure is constructed as planned. Achieving this, the remaining tasks that follow generate and deliver the record (as-built) model to the owner for any future use they may want including operations and maintenance. Further detail in key tasks during fabrication and construction are listed in Table 5 in relation to modularization.

With hardware and software becoming more user friendly, BIM is moving into the field permitting direct usage of the models at the site. During this entire process, BIM and other advanced technologies can be implemented to speed and refine the process. Models can be used within construction to perform the following:

1) Performing infield clash detection in regards to alternatives being erected and ensuring modules are going to fit
2) Managing the construction process of what gets done each day and track progress
3) Perform structural simulations such as settlement or movement of the modules once set
4) Coordination between the trades
5) Layout the locations for modules with GPS and surveying equipment via model referencing.

Table 5: Major Fabrication and Construction Tasks that have Significant Modular Impacts

Main Integrated Tasks	Subtasks with the Integrated	Modular Aspects of the Tasks
Determine plant production schedule and method to conform with the construction schedule	Determination optimal shipments of materials to the plant and site	Module weight Module size DOT limitations
Finalize material and resource allocation for fabrication	Allow for time to be optimized while waste is minimized based on: • Materials, layouts, and finishes Input from the erection team on: • The fabrication of elements, components, and assemblies	N/A (no specialty aspect)
Fabrication of the individual elements and components	separated by: • hand (human) and automated machine	Determine sizes of elements capable of being hand manufactured
Construction of assemblies and complex components	How sub components are assembled into the larger units	Ensure proper trade coordination when multiple systems are assembled
Recording and shipping of pieces and assemblies to the field	Track: • Elements, components, assemblies, and modules	Module weight Module size DOT limitations
In-field clash detection	Account for onsite conditions as well as for conflicts with design intent	Focus area on: • System connectivity • Modular to site built items
Manage the construction process		N/A (no specialty aspect)
Layout of the structure	Each section can be laid out with: • Appropriate tools, equipment and models	Items to layout and coordinate: • Penetrations • Connections to utilities • Connections to other systems • Corner points • Heights
The erection of any temporary supports, the structure and modules	Layout in the proper sequence the: • Structural elements • Components • Assemblies	N/A (no specialty aspect)
Inspection for errors	Appropriate tools, equipment and models	N/A (no specialty aspect)
Generation of the as-built documents	Ensure actual built conditions are modeled properly	Account for all modular components and if / how they can be serviced

MOVING FORWARD WITH PROCESSES AND SOFTWARE

The processes discussed herein support open unbounded integration between the trades such that the structural system can be as efficient as possible. Throughout this process, modular highlights and traditional methods of modular design and construction were integrated in. While the process supports modularization, detailed modular processes on the design is conducted and how technology is used is still limited. Moving forward, more detailed studies are needed to improve the processes such that it will promote and clarify modular procedures.

Support for Further Studies

New detailed processes would need to be constructed as they are critical to understanding what the proper techniques and methodologies are that directly relate to developing new modular software. Further, more detailed maps with corresponding information exchanges, model uses, and discipline interaction identification are needed at the critical phases where the software could be employed. These areas need looked at, at different project phases as a process often changes as the design becomes clearer and more evolved. Such processes with information exchanges identified are part of a study by the authors with the goal to develop a modular BIM platform. Additional support the processes may give are in helping to understand how users may interact with the software, when they would use it, and what they need to conduct work in the software. Additionally, early in the process, designs are more approximate, as such less information is attainable. This infers that the software may take different forms or menus for different stages of design.

To properly make BIM software capable of supporting designers and constructors, knowledge of information usage is needed. Modular information was touched on earlier yet these identified instances are merely a few of what the program needs to know for the different stages of the lifecycle. Information that is used, stored, and generated has to be defined to ensure the software generates it, accepts it, and can store it. This could relate to an extended creation of a Level of Development (LOD) requirements defined by the NBIMS for modularization. The current LOD standard being researched, with intent to be in the next NBIMS, does not look at modular construction as they are focusing on conventional systems.

SUMMARY AND CONCLUDING REMARKS

The process to plan, design and construct a building is a complex endeavor that takes many skilled participants. Structurally speaking, the process has a natural evolution in the design but there remain barriers to adopt integrated practices and larger scale modularization concepts. Described in this paper is an integrated process that deploys BIM based technology to support collaboration. Locations where modularization should be considered and how it fits within an integrated process were identified. Modular concepts and schemes must be considered early before the form of the building is finalized or else the opportunities quickly become limited. From here, close collaboration is needed between the structural systems within the module and those secondary supporting systems to ensure stability, integrity, and functionality of the structural system is upheld. With the size and function between the two being different often the module design progresses faster and detailing of members and connections can be done earlier. Fabrication and construction are similar to current practices but now more work is shifted to a factory that can be automated and/or manned by human workforce.

A BIM based process for modular design has more advantages than simply guiding a firm or project team. When properly constructed, it allows programmers to follow the process to develop interoperable software capable of linking software together. This is critical for modular construction as no good mainstream tools exist currently and is the direction of a current study by the authors.

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Residential Vertical Expansion of Existing Commercial Buildings Using Modular Construction Methods

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Abstract: Off-site construction methods may offer advantages over site-intensive construction methods for certain types of vertical expansions, such as those that could add valuable residential units to an existing commercial building. Evaluating the feasibility of a vertical expansion is, in itself, involved. When considering the use of modular construction there are additional items to be reviewed during the conception stage. Vertical expansions can be design intensive depending on the condition of the existing building and the availability of design documentation. Feasibility 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.

1. Introduction

Modular Construction is ideal for the construction of buildings with repetitive floor plan elements. Residential structures such as apartment buildings, student housing and workforce housing tend to be ideal candidates for modularization. The projects that are highly compatible with modular construction methods tend to be those that would significantly benefit from off-site construction, construction schedule time-savings, and reductions in community disturbance or business operations.

Renovation projects, particularly those planned for congested urban areas, can potentially take full advantage of these benefits. Initially, by choosing to renovate a building versus constructing a new one, owners can preserve the historic nature of their building and its relationship with the surrounding community, as well as take advantage of the existing embodied energy, avoid expensive foundation and site activities, and eliminate the need to purchase new land.

Renovation through vertical expansion is an approach that can be used to add roof-top apartments to buildings that are able to accept expansion. Vertical expansion, if feasible for a given existing building, can provide the financial benefits gained from rental or sale of the new units as well as be a part of a more comprehensive roof renovation plan that would not only add more square footage to the building but can simultaneously replace aging roof components and improve the energy performance of the roof system.

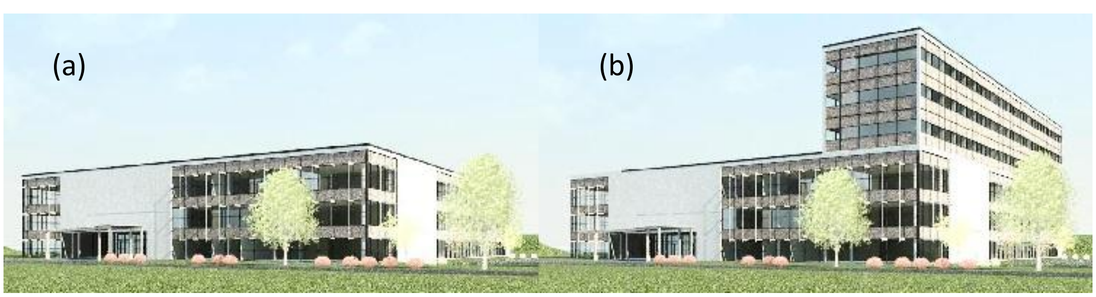

Figure 1. (a) Rendering of an existing commercial building (b) Vertically expanded building.

The modularization of an expansion can introduce the benefits of off-site construction, such as lower wages, high quality components and just-in-time delivery schemes. The benefits of modular construction can have value to a building owner who desires to accomplish renovations quickly, while maintaining the operation of an existing business. The Steel Construction Institute (SCI) suggests the following advantages modular construction may have if applied to an expansion project (Lawson 2008):

- New facilities are added cost-effectively
- Construction is rapid, which minimizes costs and disruption
- High-quality can be achieved by off-site manufacturing
- Delivery of modules can be timed to suit local conditions
- Light-steel constructed modules may not over-load an existing building
- In some projects it is not necessary for the occupants to move out during renovation

1.1 Objective

The objective of this paper is to explain the relevant typical design considerations pertinent to a modular vertical expansion in the U.S. The paper begins with a brief description of how members of the European Union have been using roof-top expansions to add space to the top of existing buildings. Following is a summarization and discussion of important items that should be considered when evaluating the feasibility of a modular vertical expansion. The considerations are broken into non-structural and structural categories.

1.2 Roof-top Extensions

Modular construction, along with light-steel framing and panel construction, is used by members of the European Union (EU) to add roof-top extensions to existing buildings, in particular, older masonry and concrete apartment buildings that were constructed between 1950 and 1970 (W/E Consultants 11/07). Figure 2 shows an example of a concrete building, in Denmark, extended with CFS modules to create communal space.

Figure 2. Communal space added to the roof of a concrete building in Denmark (SCI 2001)

Lawson points out (Lawson 2008) that many buildings, of this construction type, were initially built to house the post-world war II homecoming. A large stockpile of these buildings exist in the EU. Lawson goes on to say that many of the buildings are aging and are currently due for either renovation or demolition. He also points out that modular construction, when used for renovations to this type of building is generally used to accomplish the following:

- Expand building horizontally or vertically

- Add bathroom, balcony or stair modules
- Upgrade façade to improve aesthetics or building energy performance

1.1.1 Renovation of Buildings Using Steel Technologies (ROBUST)

In order to address the problem of the aging buildings research was conducted to determine renovation alternatives. Two notable research projects that, in part, investigated the benefits and challenges of using modular construction for roof-top extensions were reviewed for this paper.

ROBUST, one of the research projects, was conducted between 2007-2010 by a consortium of representatives from the European steel industry ("ROBUST - Renovation of Buildings Using Steel Technologies" 2013). The project focus was on the use of Cold-Formed Steel (CFS) construction methods in renovations. CFS Modules were reviewed, as an option, and information regarding their use in renovation is presented in the resulting third work package (WP3), which investigates the use of steel-intensive technologies for building extensions and conversions.

In WP3 roof-top extension design considerations are reviewed. WP3 also contains research regarding the use of portal moment frames to stabilize rooftop extensions. Although this is more relevant to framed light-steel extensions, there is still important information contained in the document pertaining to roof-top extension connections to existing masonry and concrete that could be relevant to modular extension connections as well. Two publications, which were part of WP3, point out some important design issues. The first publication points out constructability, safety and technical issues with general roof-top extensions (Lawson et al. 2013) and the second points out some specific issue with using modular construction for roof-top extensions (Lawson 2008). Below are a few important points identified by the authors of the reports:

1) *Motivations for extending buildings*

   a. Create more space
   b. Change of use
   c. Energy efficiency improvements
   d. Upgrades to new regulations
   e. New lift, stairs or balcony required
   f. Conservation of historic property
   g. Deterioration of existing building

2) *Constructability*

   a. Will the project be economical?
   b. What are the township and zoning regulations and what are the aesthetics and visual integration requirements?
   c. What are the characteristics of the building. Is it suitable for extension?
   d. What are the technical issues in regards to structure, thermal insulation and fire safety?
   e. Will the extension infringe on the neighbors natural light access?
   f. Are there historic building restrictions?
   g. Will modular construction methods be able to be successfully used?
   h. Can strong points be identified in the existing structure, for module attachment, to ensure stability?
   i. Is the cladding of new structure compatible with that of the existing structure?
   j. Does light-weight façade materials need to be attached by sub-frames to the modular units or to the existing building?

k. Will the modular units have adequate bearing?
l. Will the foundation system have adequate excess capacity, if needed?

3) *Interfaces that require special attention*

a. New structure/old structure interface
b. New cladding/old cladding interface
c. Expansion joints

4) *Safety and access issues*

a. New egress routes, additional occupant load to existing egress routes
b. Change of fire resistance ratings of building elements such as doors or roof due to the addition of the roof-top extension
c. Fire load characteristics of the new envelope must reduce the risk of fire propagation
d. New requirements for fire-fighting access brought on by increase in building height.
e. Addition of elevator with only one additional level

2. Non-Structural Considerations Associated with Modular Vertical Expansions

2.1 Economic Considerations

Projects that involve a high level of off-site manufacturing (OSM) are generally more cost-effective with larger projects. Fixed overhead factory costs and transportation costs are large in comparison to the overall budget in smaller projects, but conversely, smaller projects can be economical if they are repeated several times. The economics of OSM in smaller project may be improved in the future by the integration of numerically controlled machinery and integrated CAD/CAM software (Lawson and Ogden 2008).

Modularization of a project usually involves a break-even point. This is the point (usually measured in square footage or units produced) where it becomes economical to choose modular construction over a competing site-intensive construction method. One New York City modular manufacturer of corner-post structural steel modules estimates their break-even point around 20,000 ft^2 (O'Hara 2013). In other words, the manufacturers experience shows that in order to achieve economy, the project size should be larger than 20,000 ft^2. Manufacturers of all wood or CFS modules may have a lower break-even point. ASCE points out that typically corner post bearing modules are more costly to manufacture than an all light-steel product (Lawson et al. 2012).

The primary benefit of using modular construction is time savings. The time savings can provide the benefits of reduced interest charges from outstanding loan balances, early rental income and also less disruption to the existing business (Lawson et al. 2012). When assessing the economics of a modular projects, these benefits as well as others are often weighed against the production costs of the modules. Other less tangible benefits can include fewer call backs due to higher quality product and gains from material efficiency.

Local labor rates can affect the economy of a modular project. The Building Industry Association of Philadelphia shows that considerable cost savings can be achieved through modularization in locales where the labor rate is high (Black 2010). Labor rates in Philadelphia, for example, are 39% higher than the national average and construction costs are 18% higher than the national average. The report shows that, due to reductions in labor costs achieved by using off-site construction, a modular single-family row home (one example only) constructed in the city can cost 20% less than an identical home constructed by on-site wood-framed construction.

2.2 Regulatory Considerations

Local zoning code and building code regulations have significant effect on the feasibility and cost-effectiveness of a vertical expansion. According to the ROBUST report (Lawson et al. 2013), the following zoning issues can have influence on the design.

- Local regulations may impose limitations on aesthetics, height, shape of roofs, as well as type of use.
- Height is also connected to the natural lighting issue. The geometrical arrangement of the new building has to preserve natural light for the neighbors.
- The building can be registered as a historical site. In this case, the project has to take into account the constraints on the appearance of the façades and the roof.

In addition to the zoning regulations, the building code has a large influence on a design. The International Building Code (IBC) is the governing document adopted by a large percentage of municipalities across the U.S. The 2009 IBC (International Code Council 2009) has many regulations that could significantly affect the feasibility or heavily influence the choice of building materials for a specific project.

Most vertical expansions would be categorized as an addition per the IBC definition. They would follow the regulations either in IBC Chapter 34 Existing Structures, or the most recently adopted version of the International Existing Buildings Code (IEBC). Chapter 34 requires that any addition causing greater than a 5% stress increase to elements within the gravity load system or 10% increase to elements part of the lateral force resisting system be altered to resist the increased load. Another relevant point in chapter 34 is section 3409, which states that the provisions of the IBC are not mandatory for historic buildings judged by the building official to not constitute a distinct life safety hazard.

Allowable building heights and areas prescribed in chapter 5 affect the choice of materials used for the expansion. Structural steel and CFS modules can be used in non-combustible construction applications, whereas wood framed modules are combustible and are restricted to the requirements for Type V and Type III construction.

Apartments are semi-permanent dwellings and are categorized as an R-2 use group according to section 310. Table 503 allows for a maximum building height of 50’ (max. three stories) with Type 5A construction and 40’ (max. two stories). Type III construction allows for a maximum height of 65’ (max. four stories) and 55’ (max. four stories), respectively, for Type A and B construction with the provision of a two-hour rated exterior wall according to table 601. Section 504.2 allows for an increase of one story and 20’ if an automatic sprinkler system is installed, but at the same time restricts the total increase to 60’ and four stories.

The IBC allows combustible construction to be set on a non-combustible Type 1A podium, maximum one story, with a 3-hour fire resistive barrier between the two (with special restriction on podium occupancy and other prescriptive requirements). In this manner, the amount of allowable stories and building height for wood construction can be increased by the podium height.

The IBC maximum building height restrictions will typically limit the use of wood-framed modules to vertical expansion no greater than four stories and 60’ unless special provisions are followed or local exceptions pertain. According to Cheung (Cheung 2010), some locales such as Portland, Tacoma and Seattle allow for the construction of 5 and 6 story wood framed buildings (with some restriction). The 2006 Seattle building code has allowed, in the past, for two-story non-combustible podiums beneath five stories of combustible wood framing (Cheung 2010). In general, building height regulations with podium construction consideration can affect material selection for modules and also will determine whether the construction type of the existing building is adequate for expansion.

Fire protection requirements of the IBC should be considered early on in the design process or feasibility analysis. Initially, the addition of even one story of residential occupancy brings a requirement for an automatic sprinkler system in accordance to NFPA 13 or 13R if under four stories (Section 903). In addition, according to Section 905, Class I or III standpipes are required for buildings that have any floor level greater than 30' above fire department vehicle access height. Lastly, buildings having an occupied floor greater than 75' are considered high-rise according the IBC and are subject to the requirements of section 403. Increasing the height or changing the construction type of the building can require a higher degree of fire-protection for the whole building. This can greatly affect the feasibility or cost-effectiveness of a vertical expansion.

Separation of occupancies and dwelling units is another component of fire protection that must be considered. Both non-separated and separated occupancy classifications can be considered for an expansion if the occupancies in the expanded building differ. Depending on the particular project, one classification may offer advantages over the other. If the building is evaluated as non-separated, then the whole building is subject to the most restrictive occupancy related to height and area according to table 503. If the building is considered separated, then a horizontal assembly would be required between the proposed expansion and the existing building according to table 508.4. Each occupancy will then follow the height and area restrictions pertaining to their individual use groups and the construction type of the building. The exception being that a particular use group cannot be located on a story higher than its allowable amount of stories or height according to table 503 unless section 509 special provisions is followed and a podium design is constructed as discussed earlier. This may allow for more overall stories to be constructed but may not be relevant if the developer is considering wood-framed units on the top stories.

In addition to the building separation requirements, the separation of the residential units should be considered. This can be a deciding factor in module selection. Depending on the IBC requirements, a structural steel module, may end up costing less because the fire resistive detailing is easier to implement than other module types. Group R-2 occupancies are required by section 420 to have fire partitions, per section 709, separating the units on a floor, and horizontal assemblies, per section 712, providing the story to story separation.

Accessibility and egress should be given consideration during feasibility analysis. Initially, access must be provided to the new floors, by either stair or elevator. In addition to access, the egress must be provided per chapter 10. Additions must meet the IBC requirements for new construction and therefore must have accessible egress according to section 1007. If the accessible floor is above four stories, then an elevator is automatically required, with some exceptions.

Section 1107 has requirements for accessible dwellings. When residential units are added to the top of a building, it is likely that section 1107 will require that at least the bottom floor of the expansion have Type A or Type B accessible dwelling units unless the building being expanded already has adequate accessible units on lower floors. In this case, some of the general exception in section 1107.7 may apply. In any regards, consideration should be given to the IBC accessibility and egress requirement because it may turn out that adding just one floor of residential units to the existing building can require the installation of an elevator or lift, which can be cost prohibitive to smaller projects.

2.3 Consideration of Air Rights

The high cost and scarcity of land in dense cities along with the existence of sprawling low-height transportation systems and short buildings in urban areas make vertical development in dense cities a reasonable alternative for developers to consider. Air-rights provide incentive and a framework to develop vertically. Air rights describe the vertical property rights of a landowner. According to Goldschmidt (Goldschmidt 1964) the landowner owns as much of the space above the ground as he can occupy or use in connection with the land. This of course has limitations set by aviation regulations. The first air rights construction project was in New York over the New York Central Terminal where a street, apartment buildings and an office building were constructed over the railroad track.

Air rights can be transferrable rights in which the land owner can sell the rights to a another party to develop the space above their property. The space usually involves a set horizontal division at some agreed upon elevation. New York City has provisions in the zoning code to define air rights within the city. From the definition of development rights, the air rights are associated with the maximum allowable building area set by zoning. If the building is smaller than the maximum allowable, by zoning code, then the unused portion of this amount can be considered developable and transferable ("NYC Zoning - Glossary" 2014). Additional Air rights can also be obtained through lot mergers or transfers of development rights from neighbors.

3. Structural Considerations Associated with Modular Vertical Expansions

3.1 General Concerns

The primary objective for the structural engineer employed to design or evaluate the potential of a vertical expansion is to assess the structural capacity of the existing building system and determine how many stories can be added to the existing structure and what, if any, modifications are required to the existing system.

In general, the structural engineer will accomplish this by conducting an investigation and developing an assessment of the condition of the existing structure. The engineer will conduct structural analysis to determine the capacity and reserve capacity of the structural system and use the analysis to make prudent recommendation regarding the maximum amount of stories that might be added and the appropriate structural systems that might be used for the addition. Vertical expansion can be grouped in three categories:

- *Category I* - This type of expansion was previously planned for when the existing building was first designed. The original plan set is readily available and foundation and structural systems have been designed to support a designated amount of additional stories. Minimal structural analysis and investigation is necessary in order to proceed with design.
- *Category II* – In this case, the structure has not been originally designed with the intent of future vertical expansion. The original plan-set or as-built drawings are available and reliable. Only minor investigation of existing structural elements is necessary to verify accuracy of drawings and condition of the structure. Structural analysis is required to assess the feasibility of the addition.
- *Category III*– In this case, the structure has not been originally designed with the intent of future vertical expansion. No drawings are available and significant structural investigation and analysis is necessary to assess the condition and capacity of the existing structural system.

The level of difficulty, in evaluating a vertical expansion will often increase, respectively, from a "Category I" to a "Category III" expansion. The availability and trustworthiness of the original design documents can greatly affect the amount of initial structural investigation that is required for analysis, thereby affecting the cost of evaluation. If a building has already been designed for a future vertical expansion, very little investigation and analysis may be required unless building codes have significantly changed between original design and newly proposed addition. If no design documents are available a full building structural investigation is often necessary, which most likely will be costly and time consuming.

Many of the buildings being considered for vertical expansion are historic and should be reviewed carefully because the building codes, material strengths, occupancy and building construction methods are likely to be different than todays standards. Thornton (Thornton et al. 1991a) lists the areas below that should be researched when evaluating the feasibility of the vertical expansion of a building:

- Review as-built drawings, compare drawings to field observations and measurements of the existing structure
- Comparison of the analysis and design methods in use at the original time of design to present practice
- Comparison of the requirements of the prevailing codes and standards in effect at the time of the original design to the present requirements
- Comparison of code provisions for live load reduction at the time of the original design to the present requirements
- Review of the changes in functional use within the building

In general, Gustafson suggests (Gustafson 2007) that the building materials of the period be considered. He points out that, in particular, steel design and composition has had many changes over the years and that AISC Iron and Steel Beams, Design Guide 15 and Appendix 5 of the AISC Specifications for Structural Steel Buildings have good reference information for evaluating existing structural steel framing.

Schwinger mentions (Schwinger 2007) that the building should be carefully evaluated for any damage and emphasizes the importance of a thorough building examination. He points out the following items to look for:

- Framing damage
- Corrosion
- Signs of modification to structure or the addition of heavy mechanical equipment that may have been conducted or installed without engineering review
- Unusual deflection
- Foundation settlement
- Cracks in slabs

Structural design methods have matured over recent decades and have led to more efficient use of structural building materials. A better understanding of live loads and lateral loads have led to more accurate and often times smaller design loading over the years. Often older building were designed much more conservatively and have significant structural capacity (Thornton et al. 1991a).

Thornton points out (Thornton et al. 1991b) some ways that the changes in building code and design methodology have made it possible to design a cost-effective vertical expansion for the B. Altman building in New York city. The building was constructed in the early 1900's and the following changes in methodology and code were taken advantage of:

- Allowable steel stress at the time was 16 ksi, and in 1991 the allowable stress was 0.66fy=0.6*33ksi=22ksi, which gained the designers 35% more steel strength.
- 22 kips per floor structural capacity was gained through changes in occupancy loads.
- The application of live load reduction reduced design live loads for columns and foundations up to 60% in some location.
- Heavy roof cinder was removed and a lighter concrete floor deck was used. This provide extra structural reserve capacity.

In addition to the techniques used for the B. Altman building expansion, engineers will strive to use the lightest possible structural elements in their designs to reduce stress on the existing structural system. An eight-story vertical additions was added to an existing office building in Philadelphia, PA. The structural engineer specified an innovative light-weight composite joist floor system and a bearing steel wall panel assemble to increase the amount of level able to be added to the building (Squitiere and Vacca 2013).

3.2 Weight of the Modules

Modular construction can offer a light-weight alternative to structural steel framing in some settings. The three most common modules used for multi-story modular construction are show in Figure 3. Figure 3a shows a corner post bearing module or open sided module. Corner post bearing modules are typically constructed with HSS corner and intermediate columns, CFS non-bearing in-fill walls, structural steel perimeter framing and either light steel or concrete floor systems. Loads are transferred primarily through the HSS columns. These modules are typically used in applications where wider spaces (Lawson 2007) are required or situations that require higher strength structural steel components (Lawson and Richards 2010). Corner-post bearing modules are typically stable for no more than 2-stories and require additional bracing from diaphragm action or braced core.

Figures 3b and 3c show wall bearing modules constructed from all CFS or all wood, respectively. These modules are used for cellular structures up to eight stories. Wall bearing modules are traditionally stand-alone and typically transfer both vertical and horizontal loading through continuous wall bearing and diaphragm action within the wall system (Lawson and Richards 2010).

The weights of each of the modules are shown below in Table 1. The weights reflect typical module construction considering only the framing components and gypsum board. Structural steel construction is listed in the table as a point of comparison to site intensive construction methods.

Table 1. Weight of typical modules used in multi-story modular construction.

Construction Type	Weight (lb/ft2)
Corner-Post Bearing	57.5
CFS Wall Bearing	36.8
Wood Wall Bearing	37.7
Structural Steel Framing	61.2

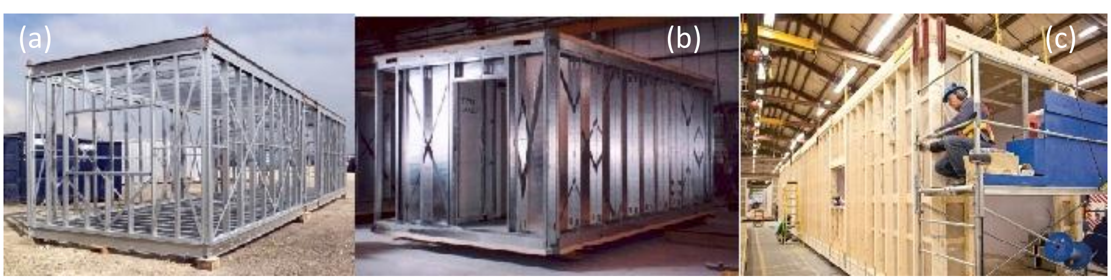

Figure 3. (a) Corner-post bearing module (image by Lawson and Ogden, 2008), (b) CFS wall bearing module (image by Lawson and Ogden, 2008) (c) Wood wall bearing module (image by Modular Building Institute)

3.3 Transfer Mechanisms and Structural Remediation

Both gravity and lateral loads must be transferred from the proposed expansion to the existing building and the existing structural components strengthened if they do not possess adequate capacity. Often the structural system proposed for a new expansion is not the same as that of the original building. Often large transfer beams or trusses can be required to transfer loads. In the case of the Philadelphia office building renovation, mentioned earlier, the engineer specified custom trusses constructed from HSS steel members to transfer the loads to a concrete column grid spaced at 27', below the expansion. Large steel tie-downs constructed of plate steel and rod were fastened to the existing columns to resist the large uplift forces imposed by the new expansion.

The university of Plymouth used modular construction to add 28 roof-top bedrooms to an existing four-story steel-framed building (SCI 2001). The extended building is shown in Figure 5. The engineer specified a grillage of structural steel to transfer the loading from the proposed expansion to the existing structure.

Figure 4. Modular residential expansion of existing university building

If the structural system or component within the structural system does not have adequate capacity, then remediation is required to resist the new loads. Schwinger points out (Schwinger 2007) that there are generally two options for the remediation of a floor system. Either new framing could be added to distribute the increased loading or the existing framing could be strengthened. He suggests, that often it is more economical and easier to strengthen the existing construction. Schwinger also discusses that column strength is typically dictated by the slenderness of the column and if added capacity is required, he recommends stiffening the column weak axis with plate steel in an efficient manner. Lastly, he recommends welding new steel to existing steel if possible, because it is easier and requires less precision than field drilling bolt holes.

3.4 Structural Design of Modules

Structural design of modules is typically accomplished by the modular manufacturer and reviewed by a third party structural engineer or designed by a structural engineer and review by the manufacturer. The external loads to a modular building are derived in the same manner as any other site-constructed building. Loads can be determined from provisions in ASCE/SEI 7 or prescribed by local building code and zoning regulation.

Chapter 16 of the IBC regulates the structural design criteria for most construction projects in the U.S. Some criteria, such as load combinations, are specified directly in the text but most are referenced from reliable design codes and sometimes modified partly by language within the IBC. Table 3-2 lists design codes referenced by the 2009 IBC that are applicable to modular design.

Table 2. IBC referenced codes applicable to modular design.

Structural Material	Referenced Standard
Structural Steel	AISC 360-05
Cold-Formed Steel	
Composite Slabs:	ASCE 3
Non-Composite Floors:	ANSI/SDI-NC1.0
Framing Members:	AISI 100,200,210,211,212,214-07
Lateral Design:	AISI 213-07
Wood	
Framing Members:	AF&PA NDS-05
Lateral Design:	AF&PA SDPWS-08
Concrete	ACI 318-08

Modules must be structurally designed for different stages of construction. Smith points out (Smith 2010) that a module must be hoisted onto a truck for shipping, transported to a building site, hoisted off a truck, maneuvered around the site, and finally placed into service. Smith goes on to say that often times dynamic loads placed on the prefabricated element are often the largest that the element will experience in its lifetime and that at times the overdesign of the structural elements for this stage can be a deterrent to using modular construction for a project. The following is a list of items that require design by an architect or structural engineer:

- Structural design of the gravity system
- Structural design of the lateral force resisting system
- Stability of structure under lateral loading
- Connections
- Cladding
- Interface with other modules or building elements
- Robustness in taller buildings
- Fire-safety
- Acoustic Performance
- Durability
- Airtightness and thermal performance

The module is the basic element of a modular building and consists of beams, columns, braces and stressed skin structural elements. Modules are typically categorized as either a wall bearing module in which loads are transferred through the side walls, a corner-post bearing module in which loads are distributed horizontally through edge beams and transmitted vertically through corner or intermediate columns and lastly non-load bearing module commonly called a pod.

The selection of module construction type is generally governed by the required building construction type, economy of design, structural capacity requirements and the availability of modular manufacturers. Lawson summarizes the limits of each module type and the general load resistance strategy as discussed in the following paragraphs (Lawson and Richards 2010).

Wall bearing modules constructed of CFS or wood framing are used for structures between four and eight stories in height. The compression resistance of the wall elements usually limits the story height. Some variation of a corner-post bearing modules is used in most cases for structures of greater height. In this case, the compression resistance of the corner-post governs the design. Square HSS sections are used commonly because of their high resistance to buckling. Lateral loads, such as wind or seismic are resisted by one of three methods:

- Diaphragm action of boards or bracing within walls of the modules; appropriate for four to six story buildings
- Separate braced structure using hot-rolled steel members located in lifts and stair area or in end gables
- Reinforced concrete or steel-plated core; suitable for taller buildings

In taller modular buildings structural integrity is a design consideration. Robustness is provided by ties between the modules (Lawson 2007). The ties help distribute the load to other modules in the event of a module within the system being destroyed. The interconnection and load sharing between modules help prevent a total building collapse.

Module to module connections typically involve a bolted connection and steel plates. The connections can be made at the corners of the modules where structural steel is typically present. Figure 5 shows an example of a typical CFS steel module to module connection. The detail can be repeated at the top and bottom and the modules can be connected both vertically and horizontally with the same detail.

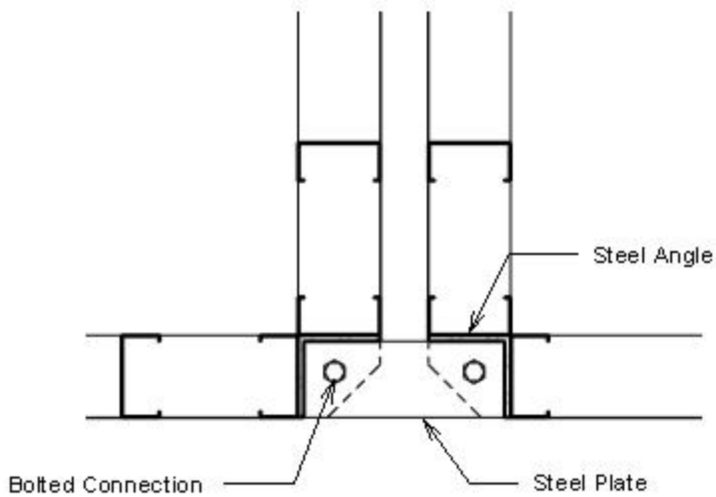

Figure 5. Typical CFS module to module connection

4. Discussion

Figure 6 presents a list of suggested steps to follow when considering a vertical expansion. A thorough review of building codes and zoning regulations should be conducted along with a detailed evaluation of the existing building in all cases. The construction type of the module should be carefully selected and the construction type of the existing building be evaluated to verify allowable heights and areas per IBC table 503. The most economical construction type is likely to be different for each project and the use of wood-framed modules will be restricted to lower expansions in most cases.

Wood framing can be an economical choice for vertical expansion if allowed. Wood-framed and CFS modules are comparable in weight and both are lighter than structural steel framing and corner-post bearing module construction. It is possible that the break-even point for wood-framed is lower than that of the corner-post bearing modules, due to the industry familiarity with the material. If this is true, then wood would be the ideal material for smaller vertical expansions involving less square-footage.

All CFS modules could be a logical choice in cases were non-combustible construction is required along with light-weight construction. However it appears that all CFS module construction is not popular in the U.S. Of the manufacturers reviewed in Pennsylvania only corner-post bearing modules were currently being used for multi-story modular construction. It is possible that the strict U.S. building code provisions make it economical to use this type of construction for multi-story projects.

The heavier weight of the corner-post bearing modules and the large break-even point make it questionable whether this type of modular construction would be the more appropriate for vertical expansion. However the use of some structural steel in an expansion is unavoidable. Structural steel will be needed in most cases were large openings are required in the floor plan and most likely will be used in the transfer mechanism as well.

Non-structural requirement such as the addition of elevators of a sprinkler system is likely to control the feasibility in smaller expansions. These costs can make it impossible to bring economy to a project.

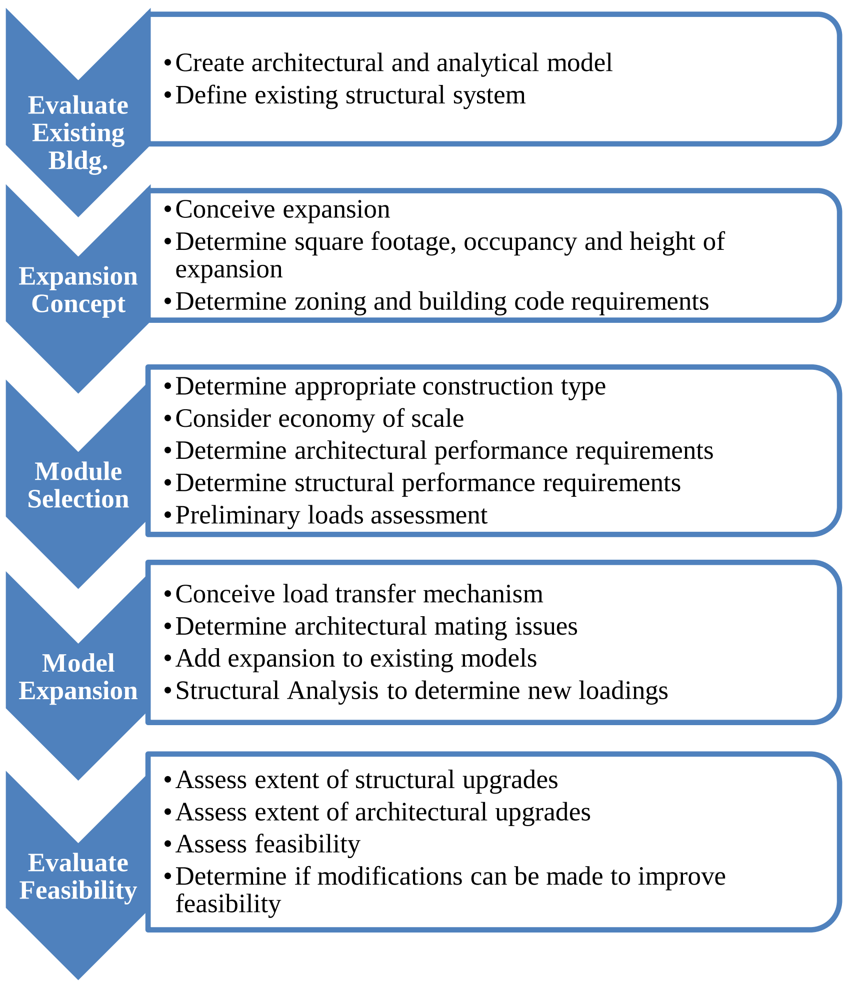

Figure 6. Feasibility analysis of a modular vertical expansion.

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Integrated BIM Platform for Multi-Story Modular Building Industry

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ABSTRACT

Modular construction is known for its economic advantages and high construction quality because of the factory construction environment. Despite the simplicity of the construction of modular single-family dwellings that brings about speedy erection at the job site, the same thing cannot be stated for multi-story modular buildings, especially in design phase. Considering complexities in this industry, more integrated project management is required. Integrated project delivery needs an integrated information management system. Building Information Modeling (BIM) has been used during the past decade to address this need. In this system, different disciplines use an identical BIM model as an input for their analysis and a platform to share their results. Constant information exchanges between BIM models and specialized analysis and design software has to be reliable to have a flawless integrated BIM model. National BIM Standard (NBIMS) is established to address this need and has been used in many different types of construction so far. Using NBIMS for standardization of information exchanges in modular building industry will be very helpful for integrated application of BIM application in modular building projects. In this paper major components of the NBIMS that include Information Delivery Manual (IDM)/Model View Definition (MVD), Industry Foundation Class (IFC), and International Framework for Dictionary (IFD) will be discussed. Next, the methodology for extending the NBIMS will be discussed. Then, for more clarification, the efforts for extending NBIMS in structural analysis/design and precast/prestressed construction areas are reviewed. At the end, the processes for information exchange standardization in modular building industry are discussed

***Keywords**:* Modular Buildings, Building Information Modeling (BIM), Information Exchanges, Information Delivery Manual (IDM), Model View Definition (MVD), Industry Foundation Classes (IFC), International Framework Dictionary (IFD), National BIM Standard (NBIMS).

INTRODUCTION

Ever since engineers started using computers for design purposes in 1970s, interoperability was an issue. It started with the translation of geometry, and later expanded to encompass lifecycle information translations. There are two types of information translation: 1) syntactic translation that is the original idea of information translation, where the information is copied from one format to another format; and 2) Mapping information that involves mapping from one type of model to another type with varying semantic; an example is translation of architectural model to structural design model (Eastman 2012).

Advanced features of Building Information Modeling (BIM) have changed the contribution of Information Technology (IT) in the construction industry. This change has evolved from a simple 3D modeling of the construction geometry to an integrated semantic product and process model. Introduction of Industry Foundation Classes (IFC) in 1994 started various efforts to develop an open model standard to address the interoperability issues of the BIM data exchanges in industry (Laasco & Kiviniemi 2012).

Vries (2005) defines a standard in construction as an approved specification of a limited set of solutions to actual or potential matching problems, prepared for the benefits of the party or parties involved, balancing their needs, and intended and expected to be used repeatedly or continuously, during a certain period, by a substantial number of target parties. There are many advantages in using an open standard for interoperability instead of direct translation, one being decreasing the number of required translators. As depicted in Figure 1, by developing an open standard, it's not required to develop a translator between two individual units; we have to just develop a single translator between each unit and the open standard. Other issues with direct translation that can be addressed using an open standard format include handling software changes, access to the proprietary file formats, responsibility in errors in translation and its testing (Laasco & Kiviniemi 2012; Bloor & Owen 1995; Gielingh 2008).

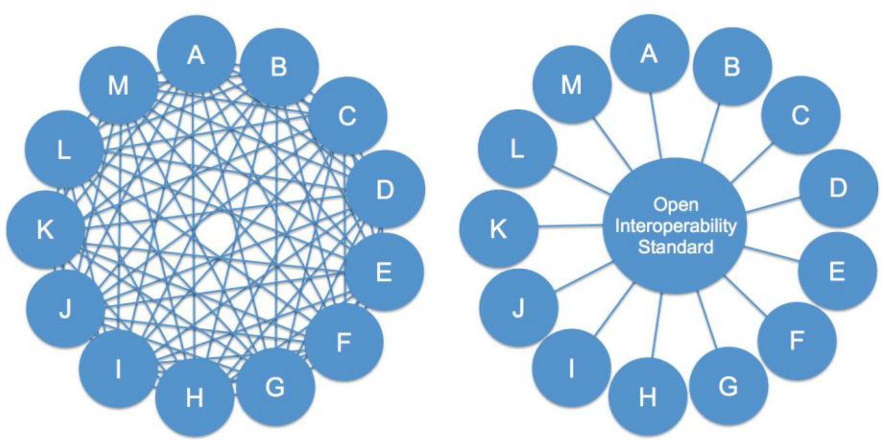

Figure 1: Direct Translators vs. Open Interoperability Standard (Courtesy of: Laasco & Kiviniemi 2012, Bloor & Owen 1995:18, and Gielingh 2008)

There are two different methodologies for data exchanges in IT standards: structuralist (also known as explicit) and minimalistic. The structuralist approach is more comprehensive and complete. The processes of developing the structuralist approach is top down, i.e., first start with high level model, and then add more detail for different parts to complete the model. The minimalist approach is simpler and as a result could be adopted by the user community more easily. The minimalist process is bottom up, i.e., start with a small amount of information and then before adoption, it would be improved based on the experiments, testing, and iterative improvement. Once developed, tested, and adopted, the model would contain more information than what is required (Behrman 2002).

NATIONAL BIM STANDARD

National BIM Standard (NBIMS) was established to standardize semantic and ontologies of information exchanges to support business contexts (Nawari and Sgambelluri 2010). The objective of NBIMS is achieving an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information, created or gathered, about that facility in a format useable throughout its lifecycle by all (NBIMS 2012).

As depicted in Figure 2, NBIMS has three major parts: 1) Information Delivery Manual (IDM), 2) International Framework for Dictionary (IFD), and 3) Industry Foundation Class (IFC) file format. IDM is a standard for the processes of the work, IFD is a standard for the terminology that is used in the processes, and IFC is a standard format for data management and information exchanges. In the following sections, each of these parts is defined in more detail.

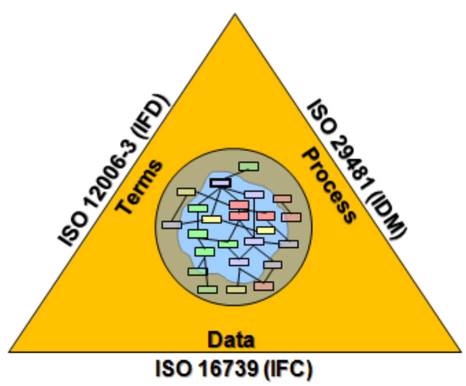

Figure 2, Holistic Diagram of the NBIMS (Courtesy of: buildingsmart-tech.org)

Information Delivery Manual/Model View Definition

IDMs and MVDs are to specify the information exchange requirements and relate these exchange requirements to the IFC file format. They explain the exchange scenario in a human readable format, as well as in a computer interpretable way for software vendors to implement the standard (NBIMS 2012).

An IDM involves identification and documentation of information exchange processes and requirements. These documents are typically expressed in human-readable form (Nawari and Sgambelluri 2010). IDM supports the integrated construction processes by serving the technical implementation needs of the software vendors and provides role—based process workflow for the end user (Laasco & Kiviniemi 2012). IDM is an integrated reference for processes and data required by BIM and specifies where a process fits; why it is relevant; who creates, consumes, and benefits from the information; what is the information; and how should the software solution support this information (Wix 2007; Laasco & Kiviniemi 2012).

An MVD is conceptually the process that integrates Exchange Requirements (ER) coming from one or many IDM processes to the most logical Model Views that will be supported by software applications. Implementation of these components will specify structure and format for data to be exchanged using a specific version of the IFC file format. In other words, it standardizes the way that the information for a certain Model View has to be organized, and then helps to show how the information has to be digitally exchanged using the IFC file format (Nawari and Sgambelluri 2010, NBIMS 2012).

Industry Foundation Class

The IFC file format was developed by International Alliance for Interoperability (IAI) to address the interoperability problems of BIM software. Now it is the standard format of the NBIMS. Using the standard for information management and exchanges can guarantee the sustainable information modeling in the project and prevent missing information during exchanges. IFC is a format for the representation of the object, their attributes, relationships, and inheritance (Nawari and Sgambelluri 2010; Laakso and Kiviniemi 2012).

The IFC files take advantages of both structuralist and minimalistic approaches by using a layered model (Tarandi 1998). As depicted in Figure 3, the structure of the IFC files is divided in four layers, including domain, interoperability, core, and resource. The layers have a restrictive hierarchy and the information in each layer has to be independent of the upper levels. The resource layer holds the resource schema that contains basic definitions intended for describing objects in the higher layers. The core layer consists of the Kernel and extension modules. The Kernel determines the model structure and decomposition, providing basic concepts regarding objects, relationships, type definitions, attributes and roles. Core extensions are specializations of classes defined in the Kernel. The interoperability layer provides the interface for domain models, thus providing an exchange mechanism for enabling interoperability across domains. The domain layer contains domain models for processes in specific AEC domains or types of applications, such as architecture, structural engineering, and HVAC, among others (IAI 1999a; IAI 1999b; IAI 2000, Laasco & Kiviniemi 2012).

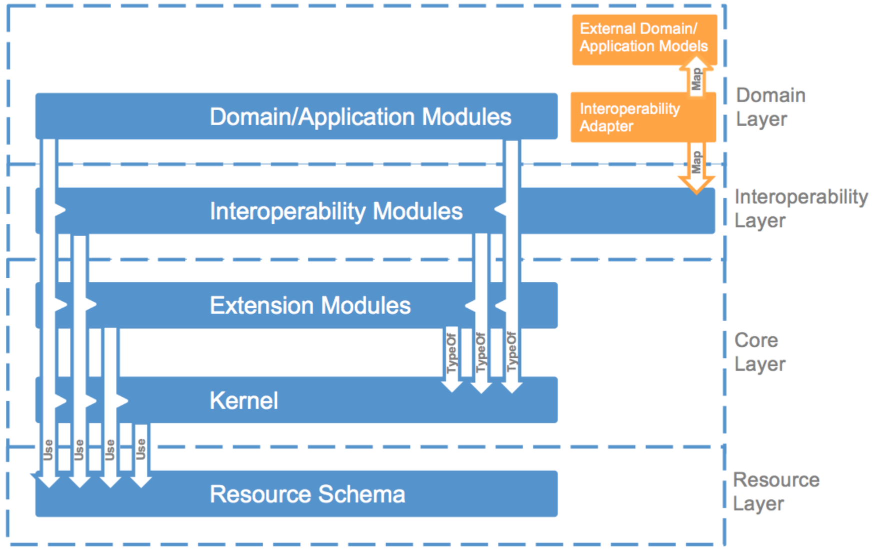

Figure 3, IFC data model structure (Courtesy of: Laasco & Kiviniemi 2012, IAI 1999b, and IAI 2000)

International Framework Dictionary

For any free flow of information, three requirements need to be addressed: a format for information exchanges, a process model, and a standardized description of what the information you exchange actually is. The last requirement has been addressed in the NBIMS by developing the IFD library, which in simple term is a standard for a terminology database (NBIMS 2012; IFD-library.org).

IFD is an open library, where concepts and terms are semantically defined and make it possible to assign a Globally Unique ID (GUID) to each part of the information in the IFC format. As a result, an exact discretion of a component can be correctly understood by the receiving application, as long as the correct GUID is given. For example, the architect can describe the column in a language other than English, and then the structural engineer in the United States will be able to understand the exact description of that column. While textual based information like names and descriptions are exchanged between actors, the underlying GUID is used by the computers. IFD provides a mechanism to develop a dictionary to connect the information from existing database to data model, (NBIMS 2012; Bell and Bejorkhaug 2006; Laasco & Kiviniemi 2012).

Contents within the Data Dictionary can be categorized in two different parts: 1) Subject (Term): something that can be represented by a name, and be distinguished and recognized from other concepts 2) Characteristics (Properties): concepts their meaning cannot be provided except the description and cannot be defined using other concepts; these concepts include: Behavior, Environmental influence, Function, Measure, Property, and Unit. Figure 4 illustrates how a subject (window) can be described using different characteristics and how the IFD library could be used to define different Model Views (NBIMS 2012; IFD-library.org).

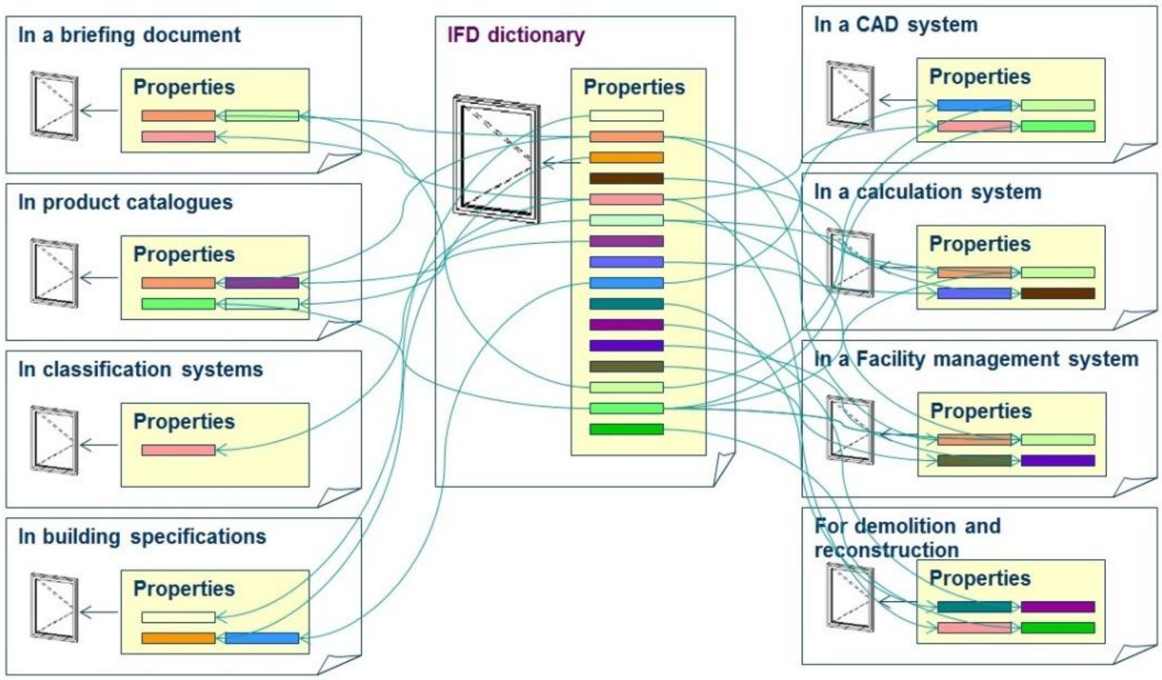

Figure 4, IFD application in BIM models (Courtesy of: IFD-Library.org and Lars Bjørkhaug-Catenda AS)

NBIMS EXTENSION PROCESSES

The NBIMS along with its open standard file format (IFC) is extendable for information modeling and exchanges of any type of construction. For this extension, there are three steps that need to be followed. In the following, these steps are explained.

Developing the Information Delivery Manual (IDM) is the first step. IDM is the user-interfacing phase of NBIMS exchange standard development. First, a lifecycle process map of the BIM model has to be defined. In this step the disciplines that are using the BIM model will be recognized. Then the information exchanges between these disciplines at different phases of the work will be identified. Each of these information packages that are being exchanged is one Exchange Model (EM) (Eastman et al. 2010). Examples of process map and EM definitions are depicted in Figure 5 and Figure 6, respectively, which are developed for precast/prestressed concrete construction (Aram et al. 2010; buildingSMARTAlliance 2011; Venugopal et al. 2012; Panushev et al. 2010).

Afterwards, the Exchange Models would be described. The information included in each of the EMs has to be recognized and defined clearly. The specification of the required information in each of Exchange Models is called Exchange Requirement (ER). An example of EM specification is depicted in Figure 7 (Panushev et al. 2010). The set of the process maps and described EMs is called Information Delivery Manual (IDM).

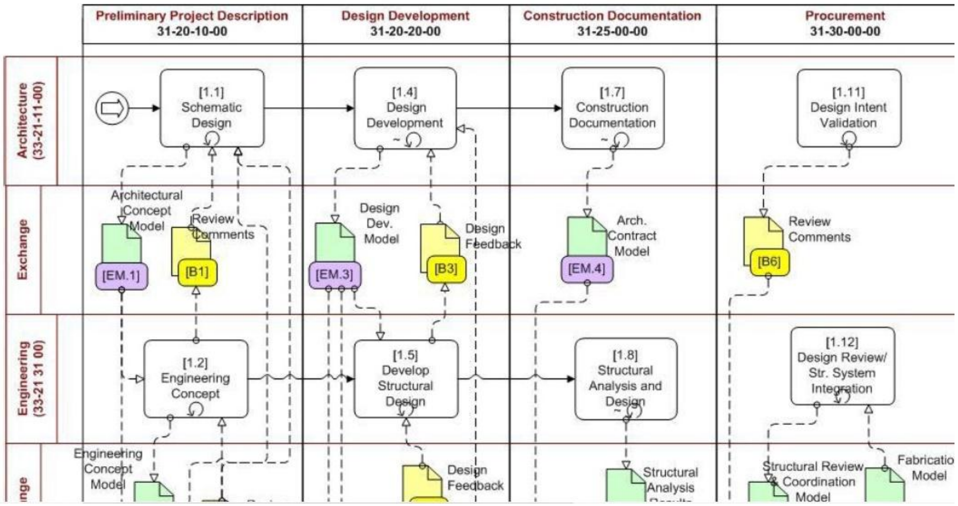

Figure 5: An example of process map (Courtesy of: Panushev et al. 2010)

Project Stage	31-20-10-00 Preliminary Project Description
Exchange Disciplines	(33-21-11-00) Architecture (33-21 31 00) Engineering (33-25 41 11 11) Building Product Manufacturing
Description	Architectural concept model consists of concept layout of precast pieces into simple assemblies, without surface or structural detailing. Building model includes massing models, structural and other grid controls, building program and space layout and use, expected thermal and acoustic functions, if known, It might involve major architectural finishes, structural system selection, structural grid and site analysis.
Related Exchange Models	A_EM.1, P_EM.1, S_EM.1

Figure 6: An example of EM (Courtesy of Aram et al. 2010)

Information Group	Information Items	Attribute Set	Attributes		P_EM.1	P_EM.2	P_EM.3
Foundations							
	Grade Beam, Pier Cap, Spread Footing, Slab on Grade, Stem Wall, Retaining Wall, Drilled Pier, Cassion, Pile, Pile Cap	Shape	Geometry	Required?	R	R	R
				Deformations?	A	A	D
				Function?	V	F	E
				Level of	L	M	H
				Accuracy?	P	P	C
			Dimensional Tolerance	Required?	O	O	R
		Type	Structural Type (CIP	Required?	R	R	R
		Supplier	GC/Contractor/Fabricator	Required?	O	O	O
		Material	Material type	Required?	R	R	R
			Quantity	Required?	O	O	R
		Assembly relations	Part of structural system	Required?			R
		Nested relations	Contains	Required?			O
			Contains connection	Required?			O
		Connection relations	.. to Precast	Required?			O
			.. to CIP	Required?			O
			.. to Steel	Required?			O
		Meta Data	Author, Version, Date	Required?			O
			Approval Status, Date	Required?			O

Figure 7: An example for EM specification (Courtesy of: Panushev et al. 2010)

Model Views Definition (MVDs) is the second step. As Nawari & Sgambelluri (2010) define, the Model View Definition (MVD) is the software developer interface of exchange. In this step, the functional specification of the IDM will be translated to a human-readable format that later could be used to store information in a digital format. The MVD is developed using the NBIMS' IFD library. If there is a concept that is not addressed in the IFD library, the developer can define a new concept; but he/she has to use the IFD library concepts as much as possible. In this step, the defined information exchanges in IDM will be organized in IFC specification hierarchy schema to make it possible to map the required information to the IFC predefined concepts. An example of a Model View Definition (MVD) is shown in Figure 8 (Hietanen and Final 2006).

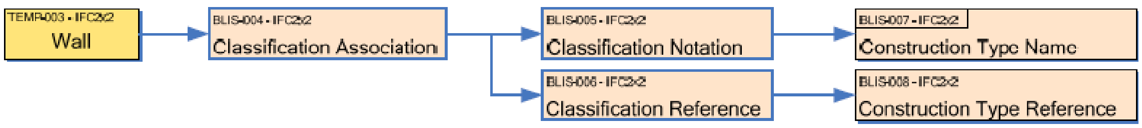

Figure 8: An example of MVD (Courtesy of: Hietanen and Final 2006)

Binding the developed MVD to IFC file format and its implementation is the third step. After preparing the MVDs, each of the concepts in the MVDs will be mapped to their associated IFC format entities. The mapping between MVDs and IFC format is called IFC binding. An example of connection component assignment is depicted in Figure 9. If there is lack of proper entity in the IFC file format, the developers can submit a proposal to the buildingSmart to add the new entities in the next version of the IFC file format.

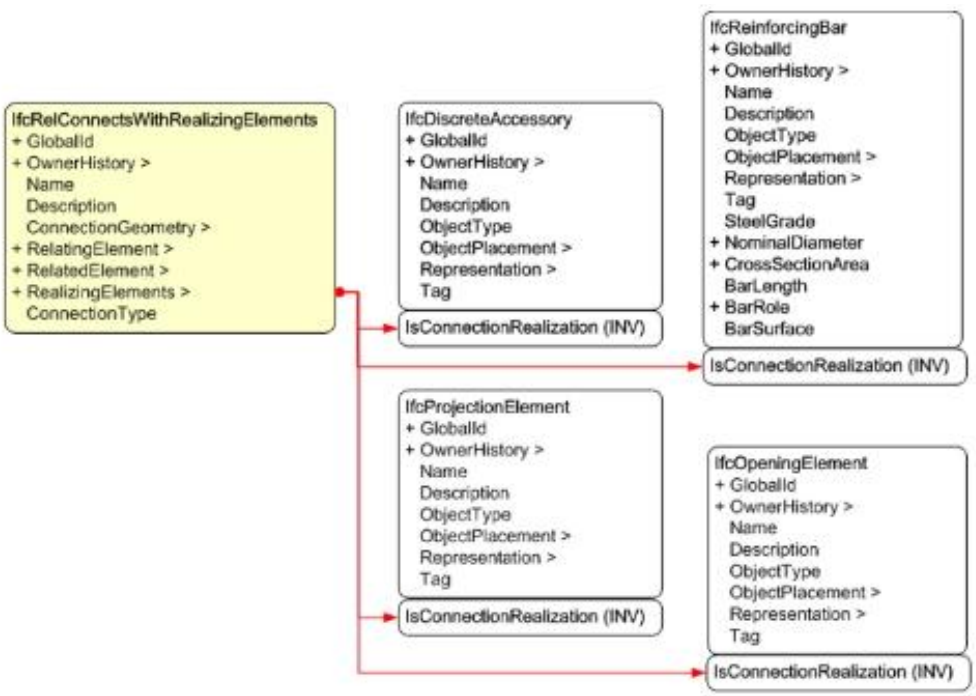

Figure 9: IFC binding example (Courtesy of: Panushev et al. 2010)

The whole developed documents including IDM, MVDs, and IFC bindings have to be sent to NBIMS as a proposal for evaluation. Once accepted, it will be added to the standard and the software vendors would have to adopt and implement the developed MVDs, concepts and entities to be qualified for the buildingSmart IFC certificate. Accomplishing these activities will address the interoperability problem in the area to which we are extending the NBIMS.

MAJOR EFFORTS RELATED TO STRUCTURAL ASPECTS

Many efforts have been done so far to extend the NBIMS to address interoperability issues in different areas. Since software developers are responsible for practical implementations of the standard, the Building Lifecycle Interoperable Software (BLIS) Group was founded in 1999 to fill the gap between publication of the standard and its implementation in software. In 2006, BLIS introduced MVDs as an official element for IFC standardization to show how data exchanges are applied between different types of applications; and by this means benefits the implementers of IFC software (Laasco & Kiviniemi 2012). IFC extension proposals have to be sent to BLIS for evaluation. Figure 10 summarizes the list of the efforts that has been done for NBIMS extension. Not all of these efforts have been completed or evaluated by BLIS; the status column in Figure 10 shows the status of each effort (IFC Solution Factory 2014) that could be Idea, Draft, Proposal, Candidate, or Official, respectively. For more clarification some of these efforts will be discussed in more detail in the sections that follows:

Name	Status	Reference No.	Name	Status	Reference No.
Basic HandOver to Facility Management	Draft	GSC-001	Extended coordination view	Idea	ISG-001
Architectural Design to Building Energy Analysis	Candidate	GSA-003	Extensibility	Idea	VBL-003
Architectural Design to Circulation/Security Analysis	Proposal	GSA-002	Indoor climate simulation to HVAC design	Proposal	HUT_HVAC-001
Architectural Design to Quantity Takeoff for Cost Estimating	Candidate	GSA-004	Landscape design to road design	Idea	CRC_CI-002
Architectural Design to Spatial Program Validation	Candidate	GSA-001	Masonry Structural Design to Structural Analysis	Draft	UF-DCP-001
Concept Design BIM 2010	Official	GSA-005	Precast Concrete Exchanges	Candiate	PCI-001
Design to Code Compliance Checking (ICC 2006)	Proposal	ICC-001	Road design to landscape design	Idea	CRC_CI-001
Early Concept Design to Analysis	Draft	GSA-006	Space Requirements and Targets to Thermal Simulation	Draft	HUT_HVAC-002
Nordic Energy Analysis (subset of CDB-2010)	Candidate	NOW-001	Structural design to structural analysis	Proposal	VBL-001
Architectural design to landscape design	Idea	CRC_CI-003	Structural Design to Structural Detailing (ATC-75)	Draft	ATC-001
Architectural design to structural design	Draft	VBL-002	Wood Structural Design to Structural Analysis	Draft	UF-DCP-002
Architectural design to thermal simulation	Proposal	VBL-007	Architectural design to quantity take-off - level 1	Idea	VBL-004
Architectural Programming to Architectural Design	Draft	BSI-001	Architectural design to quantity take-off - level 2	Draft	GSC-002
Curtain Wall Design to Energy Analysis	Draft	UNSW-001	Architectural design to quantity take-off - level 3	Idea	VBL-006

Figure 10: IFC Solution Factory MVDs (Courtesy of: IFC Solutions Factory)

Structural Design to Structural Detailing (ATC-75):

This project was developed by the Applied Technology Council (ATC) to address the interoperability issue of structural element information between BIM software or between BIM and structural analysis/design software. The methodology that ATC used in this project was the same as that discussed in this article. First, the structural engineering business processes map has been developed. As depicted in Figure 11 (ATC-75 2010), the structural engineers interact with three types of models consisting of: 1) the architectural model, 2) the structural model, and 3) the construction model. The whole processes of the structural design have been divided in four stages consisting of: 1) defining the structural systems, 2) development of the structural model, 3) performing structural analyses for verification, and 4) extracting structural drawings and specifications. Next, the Exchange Requirements (ER) were recognized and based on that, the MVD has been developed and bound to the IFC format (ATC-75 2010).

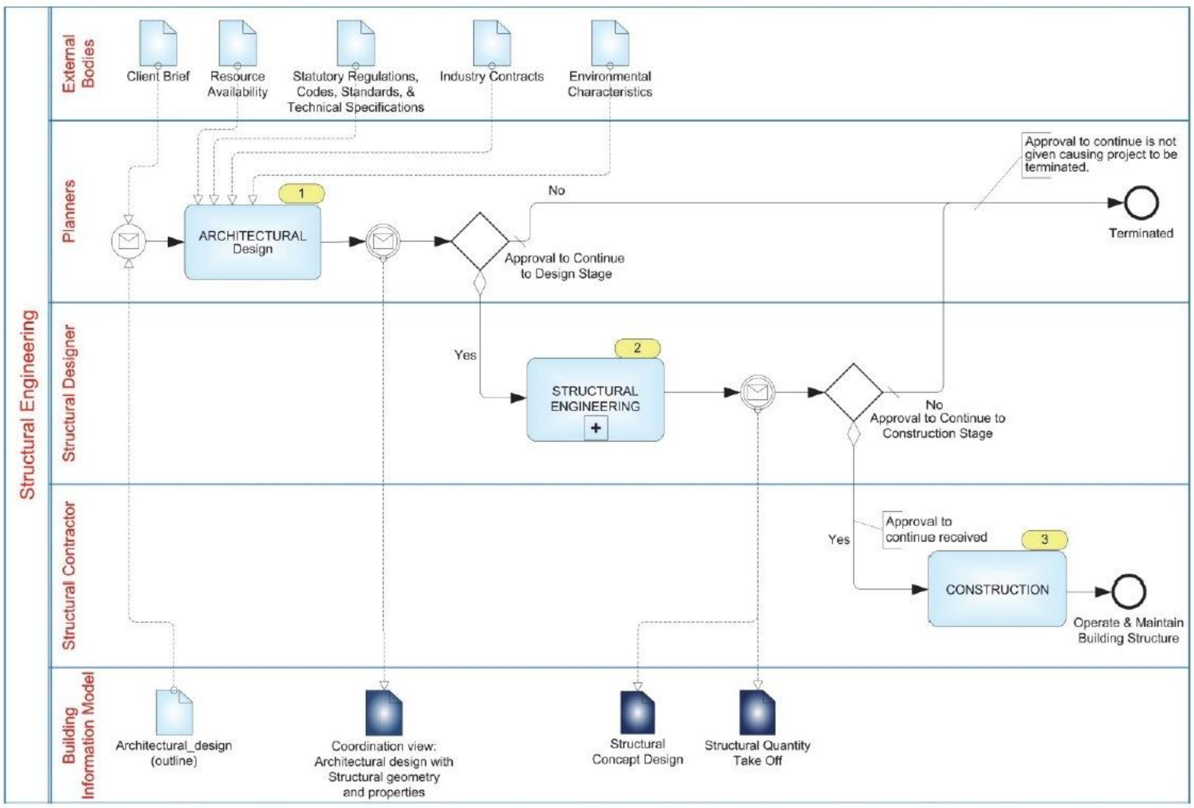

Figure 11: Structural engineering business processes map (Courtesy of: ATC-75 2010)

In this project, a benchmarking test has been done on a variety of BIM and structural design software types to systematically quantify the state of interoperability in a methodical and comprehensive format. This was also done to rate the success of information transfer from one software to another. The criteria for these tests included the following: 1) the accuracy of geometric coordinate transfer, 2) material properties transfer, 3) curved and shaped geometric transfer, and 4) sloped geometric transfer. An identical simple model has been developed for the benchmarking tests. One benchmarking test has been done before developing the IDM, MVD, and IFC binding and one done after. The software vendors modified their software based on feedbacks from the project and the first benchmarking test. The comparison of two benchmarking tests showed a significant improvement in the correct information exchanges among these software. For more clarification, the result of the second benchmarking test on Bentley Structural v8 is shown in Figure 12 (ATC-75 2010).

		DESTINATION									
		CAD / BIM SOFTWARE					STRUCTURAL SOFTWARE				VIEWER
	Software / Version	Bentley Structural v. 8i	AutoCAD MEP 2011 v.E.49.0.0	Revit 2011 20100326_1700	Digital Project v1, r8	Tekla Structures v. 16.0	Sap 2000 11.0.8	Etabs 9.1.6	RISA-3D 7.0.2	Ram Struct System 11.2.1	DDS IfcViewer 6.4
Columns	Geometry	No	No	No	No	No	IFC2x3 Unsupported	IFC2x3 Unsupported	Importer unavailable	Importer unavailable	yes
	Properties	No	No	No	No	No					No
	Sloping	N/A	N/A	N/A	N/A	N/A					N/A
Beams	Geometry	Yes	Yes	Yes	Yes	Yes					Yes
	Properties	No	No	No	No	No					No
	Curved	No	No	No	No	No					No
	Sloping	Yes	Yes	Yes	Yes	Yes					Yes
Braces	Geometry	Yes	Yes	Yes	Yes	Yes					Yes
	Properties	No	No	No	No	No					No
Walls	Geometry	Yes	Yes	No	Yes	Yes					Yes
	Properties	No	No	No	No	No					No
	Curved	Yes	Yes	No	Yes	Yes					Yes
	Sloping	Yes	Yes	Yes	Yes	Yes					Yes
			NA								
Slabs	Geometry	Yes	Yes	Yes	Yes	Yes					Yes
	Properties	No	No	No	No	No					No
	Sloping	Yes	Yes	Yes	Yes	Yes					Yes
Remarks					DP can not display element properties from IFC files. Body name is inherited from Bentley element name.	No import errors. Must import as reference model.					

Figure 12: Second benchmarking test on Bentley Structural v8 (Courtesy of: ATC-75 2010)

Precast/Prestressed Concrete Constructions

This research was done to address the interoperability issues in the precast/prestressed concrete industry. This research also followed the same methodology as discussed previously. First, the IDM was developed for the planning, design, documentation, construction and fabrication phases and their information exchanges (Panushev et al. 2010). Next, five different Model Views were defined and bound to the IFC file format. These five MVDs are supporting the following five use cases:

- Clash detection among different disciplines like MEP, structural or electrical -- In this model view, the boundaries of the elements are important.
- Structural analysis and design purposes -- This model view is in the form of nodes and axes and 3D geometry is not addressed, but the loads and the weight of the elements are concerned.
- Precast fabrication purposes -- In this model view, the boundaries of the precast parts and the hollow cores are addressed.
- Parent assembly representation -- This is developed for the times that is needed to specify the components that the parent assembly is composed of. In this model view, the geometry of the parent assembly is derived from the geometry of individual components
- Production and delivery sequencing -- Geometry is not concerned in this model view, but items like piece counting and erection sequencing is important.

STANDARDIZATION IN MODULAR BUILDING CONSTRUCTION

Proper information exchange and integration of different project phases are the two fundamental needs of the construction industry. Modular building industry is still at relatively early stages of its development, therefore there is no specific code or standard for the modules and the processes of this this type of construction; as a result, integration level of the information in this industry is relatively low (McGraw-Hill 2011). Standardization of information exchanges can significantly increase the information integrity level of the projects in this industry. In the following, the steps that need to be followed to achieve this goal are summarized:

Product Architecture Model (PAM) development: There are many different innovative systems in the modular industry and for developing a standard, these different systems have to recognized, categorized, and documented. In the PAM, different options for the assemblies and subassemblies have to be recognized based on the conventional modular systems; and then aspects such as functionality, aesthetic, geometry, energy efficiency, and sustainability have to be mapped to these options; then, attributes like scopes, limitations, and relations needs to be assigned to the assemblies and subassemblies to come up with the Product Architecture Model.

IDM/MVD development: The processes of the modular building projects are different from the site-built constructions; for example, modular building projects have two additional stages that are manufacturing and transportation. In addition, the design considerations of modular buildings are different as well. Therefore, a special process map along with exchange requirements required to be developed to standardize the information exchanges in this industry. Furthermore, different MVDs need to be defined to ease using the BIM model for different disciplines like structural engineer, architect, manufacturer, logistic manager, etc.

Updating the IFD: Modular buildings contain a lot of assemblies and subassemblies. Each of these assemblies is a concept. A lot of these concepts are new and are not addressed in the concepts developed for site-built constructions (especially assemblies at higher levels); these concepts have to be defined clearly to prevent any confusion. For example, it should be clear what subassemblies are pointed out when we say the module’s light gage steel wall; does it mean the wall including the corner posts of the module; does it mean the wall including the sheathing on the walls. Clear definition of the new concepts will significantly increase the interoperability in this industry.

IFC Binding of the developed MVDs: In order to ease information exchanges between different disciplines and make auto model view generations possible, the developed MVDs needs to be bound to the IFC file. Since there are new concepts defined for the modular assemblies and subassemblies in the IFD, new classes in the IFC file format need to be developed for storing new concepts’ information in the IFC file. For example, if the structural engineer needs the equivalent stiffness and resistance of the walls of modules, an entity needs to be defined in the IFC class of the module’s wall concept to store the values of these parameters.

SUMMARY AND CONCLUSION

In this article, the National BIM Standard (NBIMS) has been reviewed. NBIMS has been established to address information exchange issues in AEC industry. It has three main parts including: Information Delivery Manual (IDM)/Model View Definition (MVD), Industry Foundation Class, and International Framework for Dictionary. IDM/MVD specifies the information exchange requirements and model views; IFC is a file format for digital storing and information exchange purposes; and IFD is like a dictionary for defining concepts from different disciplines into a universally understood language. Next, the methodology for extending the NBIMS for a certain area of the AEC industry was discussed. This extension has three main steps including IDM, MVD and IFC file format binding. Then, efforts and the methodology for extending NBIMS in different construction areas were discussed. One of these efforts is Applied Technology Council's (ATC) research for addressing interoperability issues in structural design to structural detailing processes. The other one is the research for extending NBIMS issue in Precast/Prestressed Concrete Constructions. At last, the steps that this research is seeking to extend the NBIMS for modular building industry are discussed. These steps are: Development of Product Architecture Model (PAM), IDM/MVD development, Updating the IFD, and IFC Binding of the developed MVDs.

NBIMS is still in its infancy. There are many different ongoing researches and projects that are trying to extend it for different types of construction and their different disciplines; and still many more efforts needs to be done. Regarding the framework of the NBIMS, it does not just address the interoperability issues, but it also standardizes the information flow and the construction processes. Standardization of information flow and processes defines the responsibility of different disciplines to each other clearly; and this helps to prevent constant challenges of different disciplines for receiving their required information in a proper format and roper time. It has to be noted that by improvement of the technology, the processes may be changed or some new attributes be added to the product, so the IDMs and MVDs has to be updated constantly for the upcoming changes based the feedbacks from the industry.

On the other hand, the software vendors can play a very important role in practical implementation of different aspects of the NBIMS; the software vendors provide tools for leveraging NBIMS in the projects. So, they have to adopt and implement the extension of the NBIMS to make it possible to use the NBIMS extensions in the projects. Therefore, their participation in the extension projects can speed up the NBIMS evolution and its adoption in the industry; in addition, it will guarantee the feasibility of the full implementation of the NBIMS extensions.

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SECTION 3:

Architectural / Structural Design and Guidelines

SC

87 DIKEMAN
FULL PROJECT INFORMATION

Location of Project:	Brooklyn, NY
Phase:	Construction
Type of Project:	Modular, Residential
Client/Owner/Developer:	RH Associates LLC
Total Square Footage:	3,020 sf
Project Cost:	NA
Name of Service Provider:	SHoP Construction Services LLC
Location of Firm:	New York, NY

SC Principals:
Jonathan Mallie

SHoP Architects Design Team:
Christopher Lee

SC Project Management, Engineering & VDC Team:
Alexis G. Lenza, Erik Churchill, Russell Davies, Soheil Mohammadi, John C. Gulliford, Andres Utting, Matt Kovaleski

Project Team

Design-Builder:	SC
Fabricator:	Island International Exterior Fabricators
Architect/AOR:	SHoP Architects
Structural Engineer:	AVRO Consult Engineering, P.C.
MEP/FP Engineer:	Engineering Solutions
Geotechnical Engineer:	GZA
Civil Engineer:	DS Engineering Services P.C.

PROJECT ABSTRACT

The demand for modular buildings ranges from storm-resistant sea-front homes, to low-rise residential and/or mixed use buildings, to hotels, luxury residential and commercial towers. We regard each project as unique, and through evaluation of critical factors such as —architectural, structural, mechanical, electrical, plumbing and fire protection systems, along with logistics, schedule and cost, determines project-tailored prefabricated building solutions for their clients.

As a result of our approach, a highly-engineered component-based system is developed which achieves the goals of maximizing production efficiency while minimizing on-site construction, without sacrificing opportunities for programmatic versatility and architectural expression. In order to minimize the cost of design, the component system and related building details are formed as part of an integrated engineering, detailing and 'just-in-time' manufacturing system based on a flexible approach to plant production. By reducing the amount of complex decisions and the number of nonconforming conditions, the flexible plant production system reduces the number of unique components which must be created and managed, delivering inherent compatibility with digitally-driven manufacturing techniques. The dimensional envelope of each building module is managed utilizing precision fixturing, which enhances product precision in the plant and tolerance management in the field.

The 87 Dikeman Street Project in Red Hook, Brooklyn is a four story ground up construction of a 2-family residence, consistent with the R5 underlying zoning, including a 40 ft height limitation on the site. The site is a vacant lot situated between two existing 2-3 story residential buildings.

The design proposal includes a 3-bedroom, 2.5 bath primary unit on the upper 3 floors and a 1-bedroom, and 1 bath secondary unit on the 1st floor. The project, which is designed to be fabricated and erected using modular construction techniques, comprises 4 modules that will be stacked and mated together on-site. The modules sit on a foundation of concrete mini-piles to allow for all living spaces and all mechanical and electrical equipment to be raised above an elevated base flood plain elevation established by FEMA.

Led by SC and Island International Exterior Fabricators (teamed as Design-Builder & Modular Fabricator), the 87 Dikeman Street Project team includes SHoP Architects (Design Architect and AOR), AVRO Consult Engineering (Structural Engineer), GZA (Geotechnical Engineer), Engineering Solutions (MEP/FP Engineer), and DS Engineering Services (Civil Engineer).

Structural Systems and Design Considerations for Low-Rise Generational Specific Housing Buildings

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ABSTRACT

Each day, approximately 10,000 people from the "baby boomer" generation turn 65 years old. Coupled with the expected population growth the DC-Baltimore region, there is a need for both traditional housing, and generational specific housing--but a stagnant economy has made supplying more housing a complicated endeavor. While low building costs have always been a priority, a hyper competitive marketplace has forced developers to differentiate their properties by adding environmentally friendly and sustainable building features, more amenities, and other building characteristics that don't necessarily contribute to cost efficiency. The onus is placed on the design team to select the most efficient structural system to mitigate the impact of more costly building features. For housing projects less than 10 stories in height, the most efficient structural system is not always obvious, particularly with so many viable options available. The aim of this paper is to explore the design considerations and nuances for generational specific housing, and to present several of the structural systems used for both multi-family and generational specific housing buildings.

DEFINING THE TERMS OF SENIOR LIVING

The term Senior Living generally applies to housing specifically targeted for people aged 55 years and older where the housing facility provides some level of assistance with daily life activities. The types of housing vary from Independent Living, where the emphasis is on a a transition to a low-maintenance lifestyle, to Assisted Living, which serves the need for both basic housing and medical care. Senior Living facilities can vary from individual apartments and free-standing homes to multi-story buildings with hundreds of occupants. The terms related to Senior Living vary as widely as the types of available facilities and can mean different things to different people and it is important to differentiate the technical facts from colloquial speech. Below is a brief glossary of terms related to Senior Living:

Independent Living (IL): IL housing is for seniors aged 55 years and older that includes anything from multi-unit apartments to detached houses. Residents live independently; however, there is an emphasis on recreational activities and amenities. IL facilities often include recreation centers where seniors can connect with peers and participate in arts&crafts, take classes, watch movies etc. Some also include amenities for sports and physical activities such as swimming, tennis, or golf. IL is commonly referred to as a Retirement Home or an Active Adult community. Recent years have seen denser, urban, transit oriented IL developments, and often times catering to more financially secure seniors seeking a more urban setting.

From a building design perspective, IL varies very little from traditional multi-generational mixed-use developments with an emphasis on mobility, ease of living, opportunities for social interaction, and increasing demand on proximity to mass transit and an urban lifestyle.

Assisted Living (AL): Assisted Living is housing for seniors with the need for some assistance with day-to-day activities but not around the clock care. AL housing typically includes private living quarters, meals, on-call assistance, and housekeeping. Residents can exercise as much independence as they want with the knowledge that personal care and support services are available if they need them. AL is generally regarded as a step below skilled nursing.

AL housing is the link between IL to housing with continual nursing care and typically has smaller unit sizes, basic kitchens and is located on the floors below the IL units in the building.

Nursing Care: Nursing Care (NC) facilities are for residents that require 24 hour nursing care and assistance with continuous assistance with activities of daily living. Nursing homes are typically licensed by the state of residence and cater to those with special needs such as Alzheimer (AZ) patients. Nursing facilities are also referred to as Skilled Nursing Facilities (SNF) or Convalescent Homes.

The design of nursing/SNF/AZ housing is centered on the ability to administer nursing care to the occupant. Nursing care units are generally located on the lowest levels of a mixed-use building to provide the easiest access for both care givers and residents.

Building Amenities: Features of the building that add to the comfort of the tenants such as convenience stores, coffee shops, fitness centers, pools, community rooms, etc.

Mixed-Use Development: Mixed-use developments are buildings that typically blend combinations of residential, commercial, cultural, institutional, or industrial uses. These developments aim to take maximum advantage of building code requirements (number of stories, fire rating and separation of uses etc.) while providing a place for tenants to work, dine, shop etc. in addition to a place to live.

IMPACT OF FAIR HOUSING ON SENIOR LIVING

In April 1968 the United States Congress passed the federal Fair Housing Act (FHA) with support from President Lyndon B. Johnson. The original purpose of the Fair Housing Act as to protect buyers and renters from discrimination based on race, color, religion, sex, or national origin. Although not directly aimed at seniors, the Fair Housing Act laid the groundwork for future legislation that made it easier for seniors to find housing without age discrimination.

The influence of the FHA was extended in 1988 when provisions were added to protect persons with disabilities and familial status. The Fair Housing Act is enforced by the US Department of Housing and Urban Development (HUD) and its subsidiary branches (Office of Fair Housing and Equal Opportunity and the Office of General Counsel), making it one of United States' largest federal civil rights agencies.

The Americans with Disabilities Act (ADA), a federal law passed in 1990, further impacted the design of Senior Living facilities by prohibiting discrimination in public accommodations (lobbies, rental offices, terraces etc) based on disability, however it does not apply to individual apartments.

The FHA's nondiscrimination requirements apply to all dwellings such as houses, condominiums, and apartments and are understood to apply to all Independent Living, Assisted Living facilities in the United States.

NATIONAL POPULATION TRENDS

According to the US Census Bureau (Vincent & Velkoff, 2010), the United States is projected to experience a rapid growth in its older population. The baby boomer generation, generally regarded as those born between 1946 and 1964, begin crossing into this age category in the early 2000's and have a major impact on this trend. The Bureau estimates that by 2050 there will be over 88 million Americans aged 65 and older which is more than double the estimated amount of 40 million in 2010. Nearly 1 in 5 Americans are projected to be over the age of 65 by 2030.

The impact of this population shift will be important to both public and private interest groups. In addition to the impact on federal programs such as Medicare and Social Security, private sector decision-makers including senior living real estate developers will play a pivotal role in shaping the living environment of America's aging population.

POPULATION TRENDS IN MARYLAND AND SUBURBAN DC

Based on statistics from the US Administration on Aging (USAoA), the western states (from Texas through Washington state) saw the greatest percentage increase in persons aged 65 and older between 2000 and 2011. The exception is the Mid-

Atlantic region including Maryland and Virginia which saw an increase of 20% to 28% of people 65 years and older. Interestingly, the vast majority of people 65 years and older lived in metropolitan areas in 2011 (81%), adding emphasis to the idea that people seeking IL housing are looking increasingly in urban areas with a mix of nearby transit and amenities.

While Maryland has a below average percentage of overall population above age 65, the US Census data from 2000 supports the notion that the majority of elder citizens live in urban areas or counties surrounding Baltimore and Washington DC.

% Total of MD Population age 60+, 2000

1. Baltimore County: 17.52%
2. Montgomery County: 16.31%
3. Baltimore City: 13.85%
4. Prince George's County: 11.31%

State Average: 4.12%

The trend of a population increase of older citizens is projected to continue in Maryland's most populated jurisdictions.

Projected % Change of MD Population age 60+, 2000 - 2030

1. Prince George's County: 155%
2. Montgomery County: 129%
3. Baltimore County: 63%
4. Baltimore City: 25%

State Average: 111%

The data are clear in that the number of older Marylanders is increasing rapidly. It is expected that the percentage of aged 60+ will be 25% statewide by 2030, while the number of people over the age of 85 is expected to rise by almost 200% by 2030.

While the population projections seem to point to an inordinate number of seniors seeking generation specific housing in the coming decades, it's important to note that only a small percentage of seniors actually seek senior-specific housing. According to Building Design + Construction (Fabris, 2013), only 5% - 8% of seniors opt for this type of housing.

While the senior housing market felt the same pains as the rest of the housing market during the recession, the positive demographic trends point to a bright future for the market. Advances in health and technology may keep seniors in the current living situation under the care of family or friends as opposed to seeking to take the major step of moving to a senior-only facility. So despite what seems to be an overabundance of baby boomers heading toward their 60's, the proverbial sweet spot for a transition to the senior living lifestyle, perhaps it is not guaranteed that the same percentages of seniors will make the transition. Status quo may not be sufficient any longer. Developers of senior housing must stay ahead of the demand and provide state-of-the-art facilities with unique features that appeal to today's seniors, and those features are predicated on location, amenities, and quality.

RESPONSE BY THE REAL ESTATE INDUSTRY

The trend toward an aging population in the United States is not lost on the Real Estate development community as developers are looking to capitalize on the opportunity with acquisitions of existing properties and development of new ones. The Senior Housing market felt the same bruises as the real estate industry as a whole through the recession. The last few years have seen a major turnaround in activity and that trend looks to continue. According to CoStar Group, public REITs have invested $54 billion in cash for properties in the last 12 months. Of the 25 most active REITs, one in five was a health care related entity (including both senior housing and medical office) accounting for over one-third of total spending. The result is that prices for the most desirable properties are being driven upwards and the market is becoming more competitive (Heschmeyer, 2013). Low interest rates are also a driver for acqusitions and refinancing that can be a source of capital for renovations and expansions for senior housing operators.

According to a report from Marcus & Millichap's National Senior Housings Group, the senior housing sector is moving toward efficiency and consolidation. Senior housing operators with few properties are looking to sell to well-capped buyers who are scouring the country for the right deals, especially value-add opportunities. CoStar notes that the sales volume of senior multi-family properties increased by 35% to $1.59 billion in the first half of 2013. From a design perspective, it puts even more emphasis producing a building with the right mix of modern amenities in a desirable location.

URBAN AND MIXED USE SENIOR HOUSING

In the past decade and in particular since the recession, developments in the DC and Baltimore metro areas are focused on density, accessibility to mass transit, and walkability. John McIlwain of the Urban Land Institute illustrates this point further in his report “Housing in America: The Next Decade” (2010) where he predicts a period of reurbanization, growth of major cities, and a decline in suburban homeownership.

Young professionals and families with young children are not the only workforce sector that is beginning to favor the city over the suburbs. While some seniors may be tethered to their homes due to underwater mortgages, others that are free to move are bucking the trend of flocking to the Sun Belt and are choosing to move closer to the cities where they live in order to stay closer to their children and grandchildren. Seniors, in particular empty-nesters that seek a maintenance free yet active and social lifestyle, are attracted to multi-family senior housing developments in urban settings. Some, including Mel Gamzon, President of the Senior Housing Global Advisors, say that "Multi-family mixed-use interegenerational housing is the future of the industry. There are huge opportunities in intergenerational housing models." (Ecker, 2013).

Senior Housing, IL in particular, has always been community and socially oriented but that may not be enough to beckon the 'newer' seniors, in particular the active 55-62 age bracket, from their homes. These active seniors seek opportunities for fitness, wellness, and preventative health maintenance not just in close proximity to where they live but in the same building.

WHAT TENANTS WANT – A SENIOR LIVING WISH LIST

The current real estate climate suggests that Senior Housing is a safe investment, a fact illustrated by the torrid pace that REITs are soaking up properties. The population trends suggest that demand for senior housing will only increase, perhaps significantly, in coming decades. Does this mean that senior housing is a sure thing, and that 'if you build it, they will come"? Peter Fabris from BD+C cautions against this line of thinking not only for developers but for A/E design professionals. He notes that today's seniors "have a definite mindset of what they want" from their retirement housing. What exactly do these potential occupants want? And which ones impact the design and construction of the facility? According to Fabris:

1. Unique or Distinctive Amenities – Building amenities can be the difference between a marginally successful 90% occupied building and a wildly successful 98% occupied one. Not every property is blessed with attractive natural features. Those properties lacking an attractive natural setting rely on interior common spaces for an edge. Not just dining rooms and card tables but wood working, arts and crafts, spas, and wellness centers.
2. Design That Overcomes Preconceptions – The design, both of the interior living spaces and the facade, must overcome the stark and clinical look of the facilities of old. If a standard market-rate multi-family development incorporates high-end finishes and articulation that enables it to add value to the community, then a senior development should be no different.
3. Diversity in Unit Mix Flexibility of Spaces – Seniors prefer to age in place and are naturally reluctant to move to apartments as their health situation changes. Room size and layout should reflect the flexibility that seniors with ever-changing health situations need. This is especially important for developments with Memory Care (or AZ) units to accommodate those with cognitive

disabilities. These spaces require very specific design features including those for physical safety and personal security.

4. Sustainability – Like the public at-large, seniors want to know and understand how their housing affects the environment. Sustainability efforts may not be on the forefront of the project however sustainable designs are increasingly part of the day-to-day fabric of design and should be marketed as such.

BUILDING CODE ANALYSIS

The International Building Code (IBC) is the primary driver of how large a building can be. This paper focuses on Occupancy Groups R-2 and R-4, which are defined in IBC Section 310.
Used in conjunction with the requirements of Chapter 6, Table 503 in IBC establishes the allowable building areas and heights based on Occupancy Group and Type of Construction.
The zone highlighted in Image 3 shows the large range of allowable building heights and areas for Occupancy Groups R-2 and R-4. When the height of a building exceeds about ten stories, the choices in structural systems become very limited—generally speaking, the options are either cast-in-place concrete or structural steel, with the ultimate choice strongly influenced by the geographical location of the project. But when the building height is less than ten stories, the most appropriate and cost effective structural system is more opaque. This paper will explore four distinct structural systems suitable for mid-rise housing buildings: Stick-Framed Wood (Type 3 Construction), The Infinity System, Non-Proprietary Deck-on-Studs, and Hambro.

STICK-FRAMED WOOD (TYPE 3 CONSTRUCTION)

Type 3 construction has been used in the Southeast United States for some time, and recently has been widely adopted in the mid-Atlantic region, particularly the Washington, DC metropolitan area. Type 3 wood construction is most clearly distinguished from the more conventional Type 5 wood construction in two ways: the allowable building height and the construction of the exterior walls.

The primary advantage of Type 3 construction is that it affords developers the opportunity to build a five-story building, while still taking advantage of the low-costs associated with wood construction. Section 504.2 in IBC permits an increase in the allowable heights outlined in Table 503 provided that an adequate sprinkler system is installed—the result being a five story, wood-framed , Type 3A building with a total allowable building height of 85 feet.

However, the nuances of Type 3 construction—particularly the requirements that the exterior walls must be constructed of noncombustible materials, and that the exterior bearing walls must have a two-hour fire rating—partially offset the cost savings generally associated with wood stick framed construction.

Stick-framed Type 3 buildings are generally framed with open-web wood trusses or engineered i-joists supported on wood stud bearing walls—the exterior walls are constructed with FRT lumber while the interior walls are constructed with non-treated lumber. Although not common, cold formed steel studs are also an option for the exterior walls. It must be noted that steel studs will not shrink, while the interior wood walls will shrink—the result is a sloped floor that could be problematic if not accounted for during the design process.

Type 3 buildings are typically light and the design of the lateral force resisting system is governed by wind loads. The lateral forces on the building are generally resisted with structural-panel wood shear walls or CMU shear walls—or a combination of both. Unit demising walls are the best options for shear walls as they are long, uninterrupted, and have enough dead load to mitigate the formation of net uplift at the ends of the walls. It is good practice to avoid using interior bearing walls as shear walls as these walls are subject to damage by tenants, and are typically interrupted with openings.

The additional height of Type 3 buildings can pose a challenge with respect to the lateral system when compared to Type 5 buildings—lateral resistance is rarely an issue for the latter. When designing the lateral force resisting system, one of the goals is to minimize the need for atypical wall constructions by using the minimum sheathing required to meet the needs of the architect. The fire rating requirements for demising walls mandate that at least one layer of 5/8" gypsum wall board (GWB) sheathing be provided on each side of the wall. It is common that GWB alone is insufficient to meet the shear requirements of the wall—in this case, a layer of OSB may be added to the wall construction. This atypical wall construction not only creates atypical units with reduced area, but also can be a coordination problem during construction. When OSB is required at the lower level shear walls, mobilizing the shear capacity of the interior bearing walls may ultimately be the better option.

While the design of the building superstructure is relatively straightforward, the details associated with Type 3 construction present unique challenges—namely, separating the floor framing from the rated and non-combustible building envelope. The details shown in Figures 1 and 2 illustrate two ways to handle exterior bearing wall conditions, the major difference compared to Type 5 construction being the use of ledgers in lieu of traditional platform framing. There are a myriad of options available for supporting the floors from the exterior walls—Images 6 and 7 are just two of many—with the ultimate direction often driven by the preference of the contractor.

Some contractors prefer to keep the same wall construction around the perimeter of the building—i.e., maintaining the two hour rating for all exterior walls. However, it is worth noting that a very small percentage of the exterior wall may actually qualify as a "bearing wall" (a bearing wall is defined by IBC as a wall that supports no more than 100 pounds per linear foot in addition to it's own weight). Locating the first truss close to the exterior wall can limit the amount of load accumulation in that wall, thus rendering the wall "non-bearing", and non-bearing exterior walls in Type 3 construction only require a 1 hour rating.

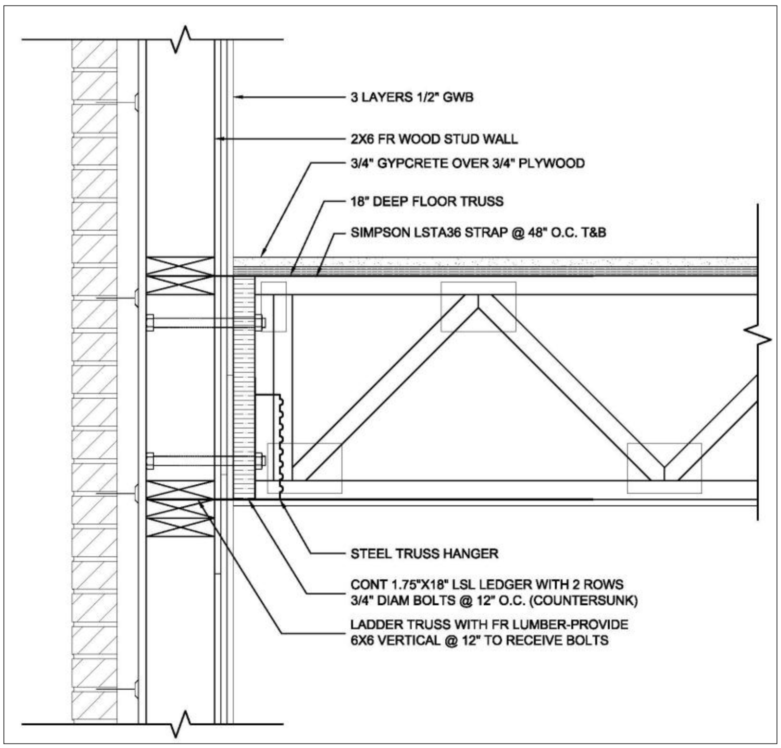

Figure 1: Type 3 Detail at Exterior Bearing Wall

Shrinkage of the frame is a concern for any wood structure, but this concern is exacerbated in Type 3 construction because of the additional building height. The total accumulated shrinkage can approach 2", so engineers and architects have to be conscious of this matter when detailing exterior wall openings, particularly for buildings with brick facades (the brick will expand while the wood frame will shrink which can result in gaps in the building facade). Engineers can mitigate the amount of shrinkage in the exterior frame by limiting the number of plates in the walls; however, doing so may require balloon framing for interior walls to minimize the amount of floor tilt due to differential shrinkage.

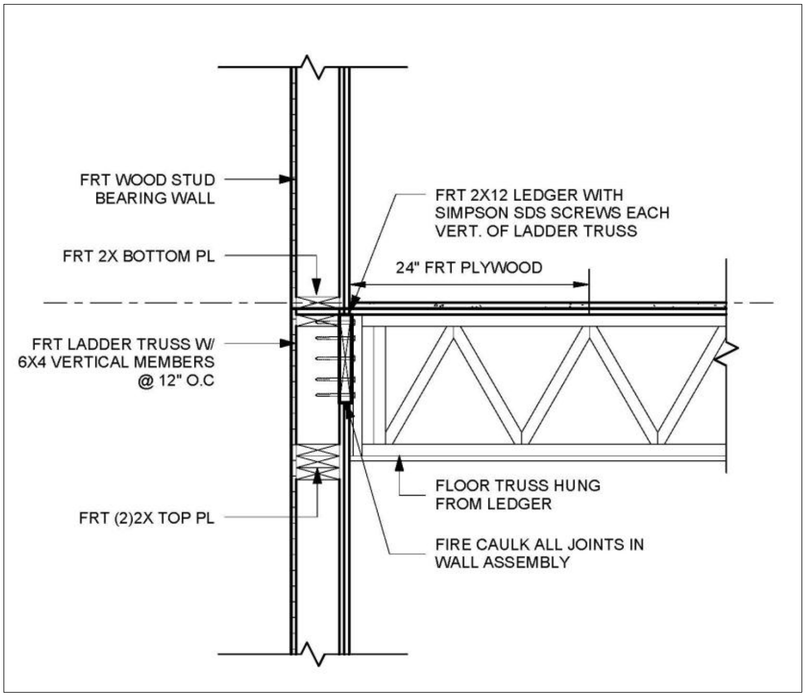

Figure 2: Type 3 Detail at Exterior Bearing Wall

THE INFINITY SYSTEM

The Infinity System is a Type 1 or Type 2 proprietary structural system widely used for all types of housing projects that uses the Epicore floor system. The Epicore floor system employs proprietary metal deck produced by Epic Metals to support a concrete slab with typical span ranges on the order of 20 feet for a 6 inch deep slab. The floors are typically supported on metal stud bearing walls that are pre-engineered and prefabricated. The Infinity System offers a turnkey solution to developers—Infinity Structures will design, fabricate, and install the system, although the onus is generally placed on the structural engineer of record to design the floor slabs. The turnkey nature of the Infinity System offers obvious benefits to developers and the costs of the system are generally competitive with a cast-in-place concrete structure for buildings up to about 9 stories.

The height of an Infinity building is limited by the capacity of the bearing walls, which are typically 6 inches wide. The Infinity system is very heavy compared to Type 3 or Type 5 wood buildings and the accumulation of the higher loads at the bottom of the building result in closely-spaced, heavy gage steel studs. It is imperative that the bearing walls align vertically throughout the building—offset bearing walls create load transfer conditions which usually require structural steel framing and significantly reduce the efficiency of the system. Infinity is particularly well suited to modular-type buildings with repetitive floor plans.

It is important to note that the floors require temporary shoring until the concrete slab has cured. While not a major design consideration, the shoring does present problems for the contractor with respect to sequencing the work as the shoring is an impediment to the installation of the building mechanical systems.

Strapped metal stud shear walls can be used to brace Infinity buildings against lateral loads, but are generally only effective up to 4 or 5 stories—beyond these heights, cast-in-place concrete shear walls or structural steel braced frames are generally advisable (note that while CMU walls are also an option, their low seismic response modification coefficient render them largely ineffective for taller buildings). The weight of Infinity buildings results in much higher seismic forces compared to wood structures—the result being a more complicated lateral design and analysis. The lateral system is one of the most important aspects of an Infinity building and must be investigated early by the structural engineer—the costs of structural steel braced frames and cast-in-place concrete shear walls are generally not included in preliminary cost estimates for the Infinity system, but must be considered by the developer when comparing different options for the structural system.

For mixed-use projects, the housing component is commonly located on a cast-in-place concrete podium constructed over street level retail or parking. Heavy bearing wall systems like Infinity have a significant impact on the cost of the podium structure. As the residential building approaches the practical limits of the system, a tighter column spacing for the podium—or a post-tensioned podium—is required to support the loads of the residential construction. Tighter column spacing has a significant impact on the use of the building below the podium, and thus is another component of the structure that must be investigated early in the design process by the structural engineer.

NONPROPRIETARY DECK-ON-STUDS

Nonproprietary deck-on-studs systems are an alternative to the Infinity system. These systems employ conventional, "off the shelf" metal deck to support a concrete floor slab. Non-proprietary systems can offer more flexibility with regard to deck and slab thickness combinations—standard dovetail deck with 6" of concrete can be used with temporary shoring to provide a virtually identical system to Infinity, or a thicker slab with heavy gage conventional ribbed deck can be used to avoid the need for temporary shoring.

The generic nature of this system has the obvious benefit of encouraging competition among builders, but requires more effort from the structural engineer to design the system components. It is worth noting that there are companies that will install these systems in a turnkey fashion (i.e. design, fabricate, and install the system components) similar to Infinity, but there are generally slight differences in their relative scope of services, which makes direct cost comparisons a cumbersome endeavor.

Outside of the generic nature of the system components and the responsibilities of the structural engineer, the nonproprietary deck-on-studs systems are virtually identical to Infinity from an engineering perspective. These systems have the same issues with respect to the design of the lateral force resisting system, are best suited for modular-type buildings, and have the same impacts on the design of a podium structure for mixed-use buildings.

HAMBRO

Hambro is a proprietary structural system that uses composite steel joists and a thin concrete slab supported on either metal stud bearing walls or a structural steel frame. Hambro is able to achieve longer spans compared to Infinity or other thin-slab systems and provides relatively superior acoustic performance. When Hambro floors are supported on a structural steel frame, the practical height restrictions mentioned for systems supported on bearing walls are virtually eliminated.

Hambro’s longer spans are achieved at the cost of a much deeper structure. Assuming static ceiling height requirements relative to system comparisons, a deeper structure results in a taller building, leading to increased building skin costs, potentially larger lateral forces, etc. The open-web nature of Hambro joists allows the building systems to pass through the floor plenum, eliminating much of the need for dropped ceilings and providing more flexibility with respect to field coordination.

Although the Hambro system is lighter than Infinity or or other thin-slab systems, it is still much heavier than wood-framed structures and the impacts on the transfer structure for mixed-use projects must be considered. Furthermore, the relative weight of the system also requires careful consideration of the lateral system to determine how the building will be braced against lateral forces.

Even more so than Infinity and other deck-on-studs systems, the Hambro system is sensitive to the repetition of floor plans between levels—variations in bearing wall or column locations can result in transfer conditions which can be very costly, and nonorthogonal building shapes and wall configurations require different joists lengths which can significantly impact the efficiency of the system. Decks, balconies, terraces, and other areas that require a drop on the floor elevation can also be problematic in a Hambro building and should be carefully considered by the design team early in the design process—these areas can result in latent costs that may not be captured in preliminary price estimates.

IMPACT OF MULTIGENERATIONAL SENIOR HOUSING ON STRUCTURAL DESIGN

The successful model for the future of senior housing appears to be defined. It's urban and dense. It has cutting-edge amenities that would be attractive to people of all ages not just seniors. It enables occupants to enjoy a fulfilled, healthy, and social lifestyle sometimes without walking outside the building, or at most a short walk to a nearby Town Center. With competition for urban land becoming increasingly fierce, and the options for senior housing increasing by the month, the question is then: can the modern senior housing development be built affordably?

Below is a list of some of the design challenges for mixed-use multi-generational senior living:

Alignment of Bearing Walls: The typical layout of a low rise multi-family building includes vertically stacked unit demising walls on all levels. The design is incredibly efficient since the load path is continuous to the bottom of the residential levels and has no need for expensive transfer framing. A secondary benefit to stacked demising walls is that the bearing walls can be used as shear walls to resist lateral loads from wind and earthquake. The load(s) from the floor framing effectively weigh-down the walls down therefore eliminating the need for expensive hold-down hardware at the ends of the walls.

The demising walls at multi-generational buildings do not align vertically since the distribution of units changes every couple of levels. Typically these buildings have AZ/Memory Care units on the lower levels, AL units in the middle levels, and IL on the upper levels. Each of these unit types have different widths and layouts, forcing the floor framing to span from corridor wall to exterior wall. The spans in this direction are typically longer, requiring stronger and more expensive floor framing. There is added cost for framing around the window and door opening since they are in a load bearing wall, and the benefit of the shear walls no longer applies.

Accessibility of Balconies: Balconies are somewhat of a standard for multi-family housing units especially those that can take advantage of favorable views or weather. The same can be said for balconies at IL units. AL units are also trending toward larger units with 9 foot ceilings, walk-in closets, and balconies. AZ/Memory Care units have little to no functional need for balconies aside from keeping a uniform appearance on the façade as the floors above.

This condition can be problematic for the structure for a few reasons. If the floor joists run corridor to exterior wall as described above, then the walls surrounding the balconies often become bearing walls. The load(s) from those bearing walls require expensive transfer framing or the introduction of posts/columns in to the space when the building transitions from floors with balconies (AL) to floors without balconies (AZ). This is a condition that is somewhat unique to multi-generational housing serving seniors of different needs groups.

Coordination with Structured Parking: Suburban multi-family developments are able to take advantage of the availability of land by proving surface parking for the tenants and visitors. Urban multi-family developments often times do not have this luxury due to relative scarcity of land. In most cases the building is constructed tight to property lines on three sides. Couple this with the need for parking for mixed-use tenants and the result is structured parking. Most structured parking is located below the retail/amenity level of the building, and in the DC suburbs it's typically located below grade. In most cases the building from the foundation level to the retail-to-residential transition (aka the "transfer podium") is constructed with cast in place concrete. The challenge then becomes coordinating column locations that work both for the parking level below the retail, for the retail spaces at the 1st Floor, and for the edge of the housing building above. Although not an uncommon issue, it is one that is unique to mixed-use developments that have multiple uses stacked one on top of the other.

CONCLUSION

As the need for housing—generational specific housing in particular—continues to increase, it will become crucial for building designers to understand the various needs and wants of the building's occupants. Ensuring that these needs are accommodated can have significant impacts on the structure of the building, making proper selection of the structural system paramount. Therefore, having a firm understanding of all of the systems available for the project is the first step in ensuring that the needs of the project are satisfied.

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2012 Wood Frame Construction Manual

Presented by:
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Project Engineer

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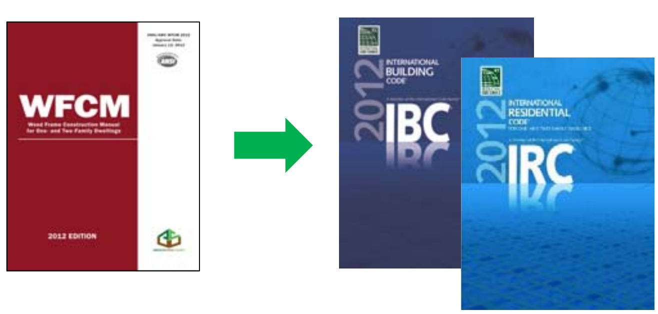
Outline

- ❖ Code references
- ❖ Chapter-by-chapter discussion
  - Changes to 2012 version
- ❖ Building Green with WFCM

www.awc.org 3

WFCM and IRC/IBC

- ❖ 2001 WFCM → 2003, 2006, 2009 IRC/IBC
- ❖ 2012 WFCM → 2012 IRC/IBC



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WFCM

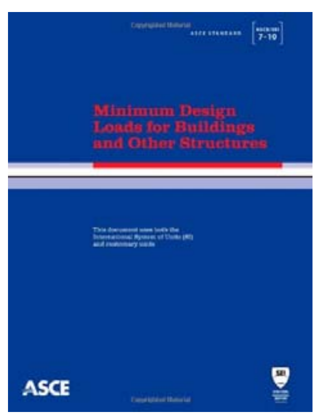
- ❖ **Chapter 1: General**
- ❖ **Chapter 2: Engineered**
- ❖ **Chapter 3: Prescriptive**
- ❖ **General outline Chapters 2-3**
  - Connections
  - Floor systems
  - Wall systems
  - Roof systems

5

Chapter 1: General

- ❖ **Mean roof height $\leq$ 33 ft**
- ❖ **$\leq$ 3 stories**
- ❖ **Building length/width $\leq$ 80 ft**
- ❖ **Loads – ASCE 7-10**
  - 0-70 psf ground snow load
  - 110-195 mph wind speed
    - 700 yr. return, 3-sec gust, Exp. B, C, D
  - Seismic Design Categories
    - A, B, C, D_0, D_1, D_2

NEW!



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Chapter 1: General

❖Not covered

- Ancillary structures
  - Decks
  - Balconies
  - Carports
  - Porches

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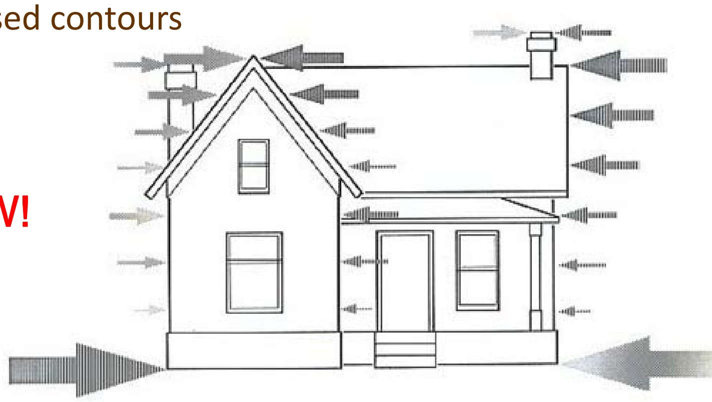
ASCE 7-10 Seismic Loads

❖Risk-based maps

- Reduced along New Madrid and Charleston, SC
- Revised contours

NEW!



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ASCE 7-10 Wind Speed Maps

- Speeds are for ultimate event
- Maps for Risk Categories (I, II, III and IV)
- Importance Factor included in maps
- www.atcouncil.org/windspeed

NEW!

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ASCE 7 Wind Speeds

Table 1. Wind Speed Conversion

ASCE 7-05 Basic Wind Speeds based on 50 yr. return period 3 second gust (mph)							
85	90	100	110	120	130	140	150
Equivalent ASCE 7-10 Basic Wind Speeds based on 700 yr. return period 3 second gust (mph)							
110	116	129	142	155	168	181	194

http://www.awc.org/pdf/ASCE7-10WindChanges.pdf

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ASCE 7 Exposure Categories

B ***Suburban, use as DEFAULT unless others apply***
>60% to 80% of all buildings are in this category

C ***Open country, 1500 ft creates this category***

D ***Water, <u>including on hurricane coast!</u>***

Change in ASCE 7-10

It's about Flow Characteristics vs. Surface Roughness

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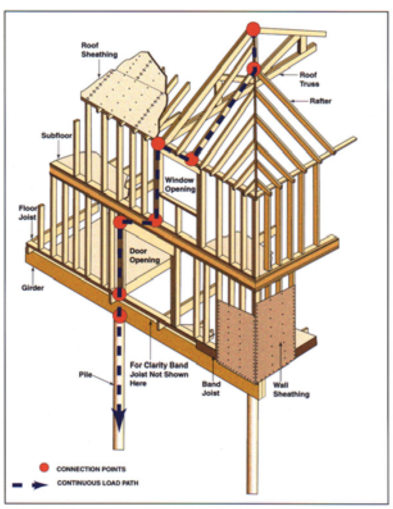
Chapter 2: Engineered



Source: FEMA

❖ **Loads and load path**
- Continuous
- Continuity created by connections
- Always ends in supporting soil

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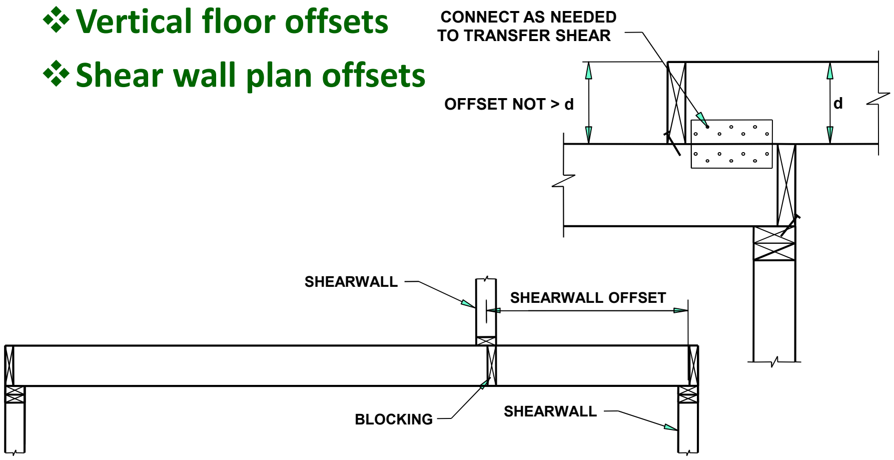
Chapter 2: Engineered

- Vertical floor offsets
- Shear wall plan offsets



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Chapter 3: Prescriptive

- Specific resistance requirements
- Wind Loads – Exposure B & C
- Other limitations

FLOOR SYSTEMS		
Lumber Joists	Joist Span	26'
	Joist Spacing	24" o.c.
	Cantilevers - Supporting loadbearing walls[1]	d
	Setbacks - Loadbearing walls[1]	d
Floor Diaphragm	Vertical Floor Offset	d_f
	Floor Diaphragm Aspect Ratio	Tables 3.16B and 3.16C
	Floor Diaphragm Openings	Lesser of 12' or 50% of Building Dimension

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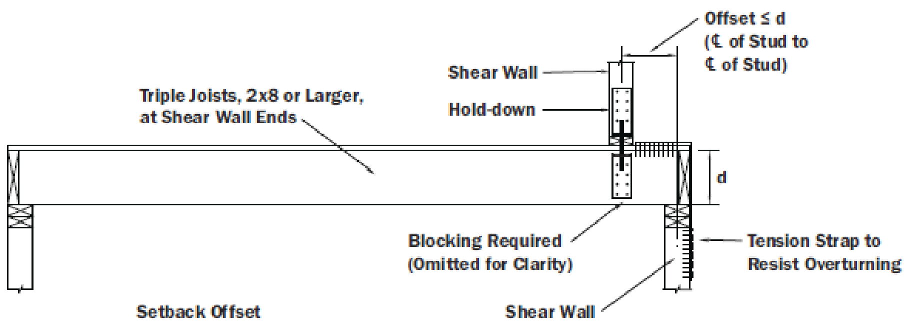
Chapter 3: Prescriptive

❖ Shear wall offset



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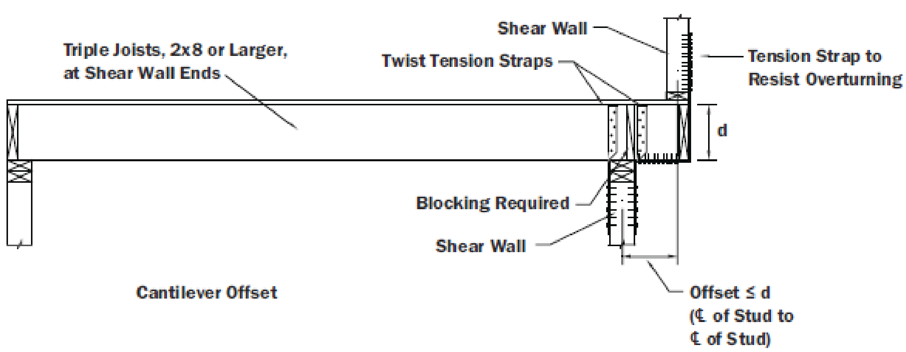
Chapter 3: Prescriptive

❖ Shear wall offset



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Chapter 3: Prescriptive

❖ Wind Uplift and Shear

Table 3.4B Shear Walls Resisting Uplift and Shear[1] **Exposure B**
(Prescriptive Alternative to Table 3.4)

700-yr. Wind Speed 3-second gust (mph)				110	115	120	130	140	150	160	170	180	195
Wood Structural Panel Shear Wall Requirements		Top & Bottom of Panel Nailing Requirements		Maximum Roof Span (ft) [2,3]									
Sheathing Thickness	Shear Wall Nailing	Rows of Nails	Nail Spacing (in)										
7/16" OSB or 15/32" plywood with species of plies having G≥0.49	8d Common Nails @ 4" panel edge spacing and 12" field edge spacing	1 [4]	4	-	-	-	-	-	-	-	-	-	-
			3	36	32	24	12	-	-	-	-	-	-
		2 [5]	6	36	32	24	12	-	-	-	-	-	-
			4	36	36	36	36	36	32	28	20	16	12
			3	36	36	36	36	36	36	36	36	32	24

NEW!

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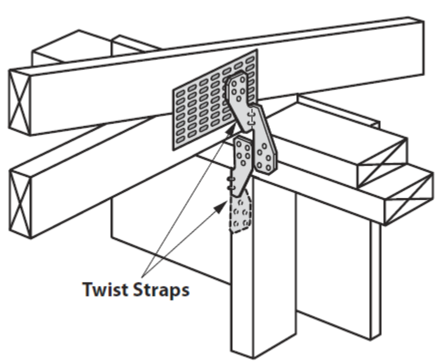
Chapter 3: Prescriptive

❖ Uplift connectors – prevent eccentricity



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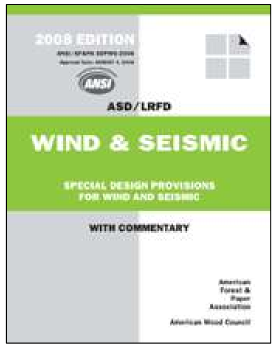
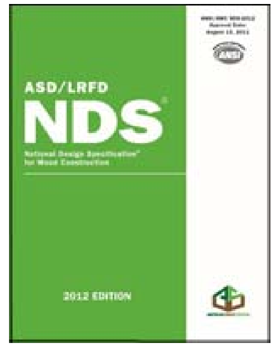
Chapter 3: Prescriptive

- **Shear walls, diaphragms, and shear connections**
  - ASCE 7-10 and 2008 SDPWS and 2012 NDS
  - 10' eave-to-ridge height
  - 10' wall heights





REVISED!

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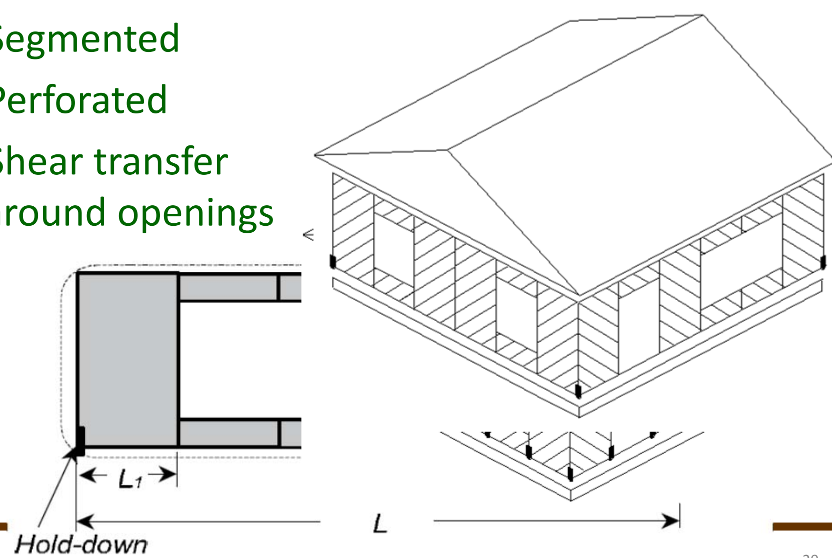
Shear Wall Methods

- Segmented
- Perforated
- Shear transfer around openings



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Chapter 3: Prescriptive

❖ Shear wall capacity adjustments

Table 3.17D Shear Wall Assembly Allowable Unit Shear Capacities, Maximum Shear Wall Segment Aspect Ratios, and Sheathing Type Adjustments

Exterior Wall Sheathing / Interior Wall Sheathing	Nails and Spacing Requirements	ASD Unit Shear Capacity of Wall Assembly (plf)		Maximum Shear Wall Segment Aspect Ratio		Sheathing Type Adjustment Factor	
		Wind	Seismic	Wind	Seismic	Wind	Seismic
3/8", 7/16", and 15/32" Wood Structural Panels (Blocked), maximum stud spacing 16" on center	8d common nails - 6" edge spacing						
No Sheathing or Non-Rated Sheathing		336	239	3.5:1	2:1[4]	1.30	1.00
1/2" Gypsum Wallboard (Unblocked)[2]	5d cooler nails - 7" edge spacing	436	239	3.5:1	2:1[4]	1.00	1.00
3/8", 7/16", and 15/32" Wood Structural Panels (Blocked)	8d common nails - 6" edge spacing	672	478	3.5:1	2:1[4]	0.65	0.50

Chapter 3: Prescriptive

❖ Exterior wall studs to resist wind

Table 3.20B3 Maximum Exterior Loadbearing[1] and Non-Loadbearing Stud Lengths for Common Lumber Species Resisting Interior Zone Wind Loads - Stud Deflection Limit = H/360

(Fully Sheathed with a Minimum of 3/8" Wood Structural Panels)[a]

Exposure B
H/360
3/8" WSP

700-yr. Wind Speed 3-second gust (mph)			110			115			120			130			140		
Stud Spacing (in.)	Species	Grade	2x4	2x6	2x8	2x4	2x6	2x8	2x4	2x6	2x8	2x4	2x6	2x8	2x4	2x6	2x8
			Maximum Allowable Stud Length (ft-in.)[1]														
	DFL	SS	13 - 7	20-0+	20-0+	13 - 2	20-0+	20-0+	12 - 9	19 - 9	20-0+	12 - 1	18 - 8	20-0+	11 - 5	17 - 9	20-0+
	DFL	No.1	13 - 0	20-0+	20-0+	12 - 8	19 - 7	20-0+	12 - 3	19 - 0	20-0+	11 - 7	18 - 0	20-0+	11 - 0	17 - 1	20-0+
	DFL	No.2	12 - 9	19 - 9	20-0+	12 - 5	19 - 2	20-0+	12 - 0	18 - 7	20-0+	11 - 4	17 - 7	20-0+	10 - 9	16 - 8	20-0+
	DFL	No.3/Stud	12 - 2	18 - 10	20-0+	11 - 10	18 - 3	20-0+	11 - 6	17 - 9	20-0+	10 - 10	16 - 9	20-0+	10 - 4	15 - 11	20-0+
	DFL	Standard	12 - 2	-	-	11 - 10	-	-	11 - 6	-	-	10 - 10	-	-	10 - 4	-	-

REVISED!

Chapter 3: Prescriptive

❖ **Header tables**

Table 3.22E2 Laterally Supported (Raised) Header Spans for Exterior Loadbearing Walls

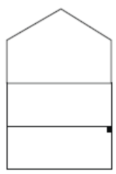
(Supporting a Roof, Ceiling, and Two Clear Span Floors)

Dead Load Assumptions: Roof/Ceiling Assembly = 20 psf, Floor Assembly = 10psf, Wall Assembly = 121plf

Raised Exterior

NEW!

Headers Supporting	Size	Roof Live Load 20 psf, 12	24	36	Ground Snow Load 30 psf, 12	24	36	50 psf, 12	24	36	70 psf, 12	24	36
		Maximum Header/Girder Spans (ft-in.) for Common Lumber Species[1,3] (Building Width (ft))											
Roof, Ceiling, and Two Clear Span Floors	1-2x6	2 - 4	1 - 10	1 - 6	2 - 4	1 - 10	1 - 6	2 - 4	1 - 10	1 - 6	2 - 3	1 - 9	1 - 6
	1-2x8	3 - 0	2 - 3	1 - 11	3 - 0	2 - 3	1 - 11	3 - 0	2 - 3	1 - 11	2 - 11	2 - 3	1 - 11
	1-2x10	3 - 8	2 - 9	2 - 4	3 - 8	2 - 9	2 - 4	3 - 8	2 - 9	2 - 4	3 - 6	2 - 9	2 - 4
	1-2x12	4 - 3	3 - 3	2 - 9	4 - 3	3 - 3	2 - 9	4 - 3	3 - 3	2 - 9	4 - 1	3 - 2	2 - 8
	2-2x4	2 - 5	1 - 10	1 - 5	2 - 5	1 - 10	1 - 5	2 - 5	1 - 10	1 - 5	2 - 4	1 - 9	1 - 5
	2-2x6	3 - 6	2 - 8	2 - 3	3 - 6	2 - 8	2 - 3	3 - 6	2 - 8	2 - 3	3 - 5	2 - 7	2 - 2
	2-2x8	4 - 5	3 - 5	2 - 10	4 - 5	3 - 5	2 - 10	4 - 5	3 - 5	2 - 10	4 - 3	3 - 4	2 - 10
	2-2x10	5 - 5	4 - 2	3 - 6	5 - 5	4 - 2	3 - 6	5 - 5	4 - 2	3 - 6	5 - 3	4 - 1	3 - 5
	2-2x12	6 - 3	4 - 9	4 - 0	6 - 3	4 - 9	4 - 0	6 - 3	4 - 9	4 - 0	6 - 1	4 - 8	4 - 0
	3-2x8	5 - 7	4 - 3	3 - 7	5 - 7	4 - 3	3 - 7	5 - 7	4 - 3	3 - 7	5 - 4	4 - 2	3 - 6
	3-2x10	6 - 9	5 - 2	4 - 4	6 - 9	5 - 2	4 - 4	6 - 9	5 - 2	4 - 4	6 - 7	5 - 1	4 - 3
	3-2x12	7 - 10	6 - 0	5 - 0	7 - 10	6 - 0	5 - 0	7 - 10	6 - 0	5 - 0	7 - 7	5 - 10	5 - 0
	4-2x8	6 - 5	4 - 11	4 - 1	6 - 5	4 - 11	4 - 1	6 - 5	4 - 11	4 - 1	6 - 2	4 - 9	4 - 0
	4-2x10	7 - 10	6 - 0	5 - 0	7 - 10	6 - 0	5 - 0	7 - 10	6 - 0	5 - 0	7 - 7	5 - 10	4 - 11
	4-2x12	9 - 1	6 - 11	5 - 10	9 - 1	6 - 11	5 - 10	9 - 1	6 - 11	5 - 10	8 - 9	6 - 9	5 - 9



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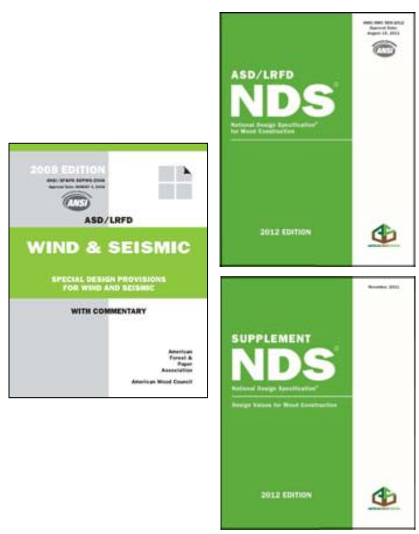
WFCM Supplement

❖ **References**

- 2012 NDS
  - Connection design values
- 2012 NDS Supplement
  - Lumber design values
  - Glulam design values
- 2008 SDPWS
  - Shear wall capacities
  - Diaphragm capacities

REVISED!



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WFCM Commentary

- ❖ **Background**
- ❖ **Example calculations**

REVISED!

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Building Green with WFCM

❖ **WFCM can help earn credits in ICC 700 – NGBS**

- Tools for advanced framing design (3 points)
  - Single top plates allowable under Chapter 2
  - Two-stud corners can be designed under Chapter 2
  - Single-ply/glulam headers in Table 3.22
  - 24” o.c. stud spacing available in tables in Ch. 2 and 3
- Performance-based structural design used to optimize lateral force resisting systems (3 points)
  - Design in accordance with Chapter 2

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Building Green with WFCM

❖WFCM can help earn points in LEEDv4 Homes

- MRc2 – Material-Efficient Framing
  - Implement one of the following in exterior walls and common walls (1 point):
    - Single top plate on walls
    - Place window and door headers in the rim joist
    - Raised single-ply headers not more than 2” thick in a 2x4 wall or 4” thick in a 2x6 wall, in accordance with 2012 IRC
    - SIPs for walls

WFCM (applies to: Single top plate on walls; Place window and door headers in the rim joist)

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Building Green with WFCM

❖WFCM can help earn points in LEEDv4 Homes

- MRc2 – Material-Efficient Framing
  - Implement any two for all interior and exterior walls (0.5 point):
    - Size headers for actual loads
    - Use two-stud corners or California corners
    - Use ladder blocking or drywall clips
  - Implement any of the following (0.5 point each):
    - Interior wall stud spacing >16” o.c.
    - Floor joist spacing >16” o.c. or SIPs
    - Roof rafter spacing >16” o.c. or SIPs

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WFCM Changes

- White paper

What's Changed?

- http://www.awc.org/pdf/2012-WFCM-Changes-Web.pdf

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Questions?

American Wood Council

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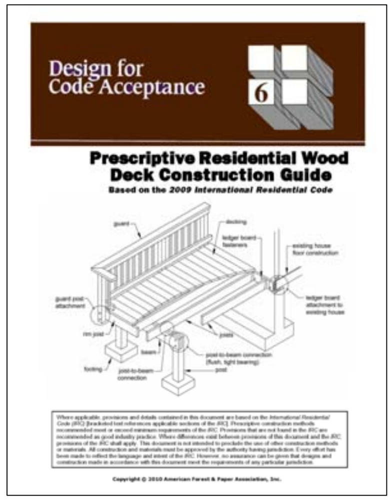
AMERICAN WOOD COUNCIL

Prescriptive Residential Wood Deck Construction Guide



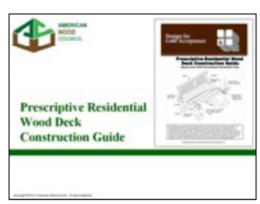
Free Downloads

DCA6 Deck Guide

http://www.awc.org/publications/DCA/DCA6/DCA6-09.pdf

DCA6 Presentation

http://www.awc.org/helpoutreach/ecourses/



Why is this Important?

News reports on deck collapse
Compiled by Dr. Frank Woeste

- 66 reports from 1996-2007
  - 500+ injuries
  - 17 deaths
- Example:
  - Chicago, IL - June 2003
    - 13 dead
    - 40+ injured

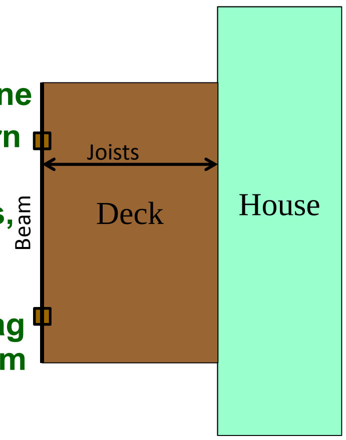
"Except for hurricanes and tornadoes, more injuries may be connected to deck failures than all other wood building components and loading cases combined!"
Dr. Frank Woeste, P.E.

Minimum Requirements

- Single level residential decks only
- Hot tubs outside scope
- Does not apply for snow loads, snow drift loads, or sliding snow loads that exceed 40 psf
- Does not address wind or seismic design issues
- Decks shall not be used or occupied until final inspection and approval is obtained
- Alternate methods and materials approved by the building official

Deck Design Example 1

- Deck height = 2'-0"
- 8' x 12' deck surface
- Structural members: southern pine
- Decking: 5/4 radius edge southern pine decking
- Determine sizes for joists, beams, hangers, footings, stringers, and treads
- Determine fastener spacing for lag screws in southern pine house rim board



Decking

- Dimension lumber (2″ nominal)
- Span rated decking
  - ALSC decking policy
- Attachment
  - 2-8d commons
  - 2-#8 screws
- Spacing 1/8″
- Perpendicular or 45°
- Bear on 3 joists minimum
- Substitution
  - Approved by building official

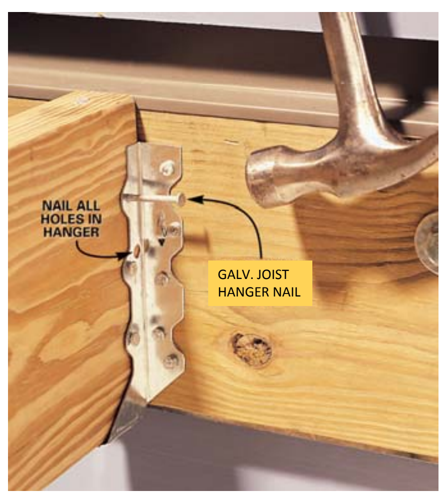
Minimum Requirements

❖ **Fasteners**
- Nails – ASTM F 1667
  - Threaded nails as stated in this document include helical (spiral) and annular (ring-shank) nails.
- Screws – ANSI/ASME B18.6.1
- Bolts/Lags – ANSI/ASME B18.2.1

❖ **½" bolts and lag screws prescribed extensively**
- Edge distance and spacing based on diameter
- Need to adjust for larger or smaller fasteners

Minimum Requirements

❖ **Corrosion Resistance 2009 IRC R317.3**
- Screws, bolts, nails
  - Hot-dipped galvanized
  - Stainless
  - Silicon bronze
  - Copper
- Hangers and anchors
  - Galvanized
  - Stainless
- Saltwater exposure
  - Stainless
- Other fasteners/hardware
  - Approved by building official
- Flashing
  - Nominal 0.019" min.



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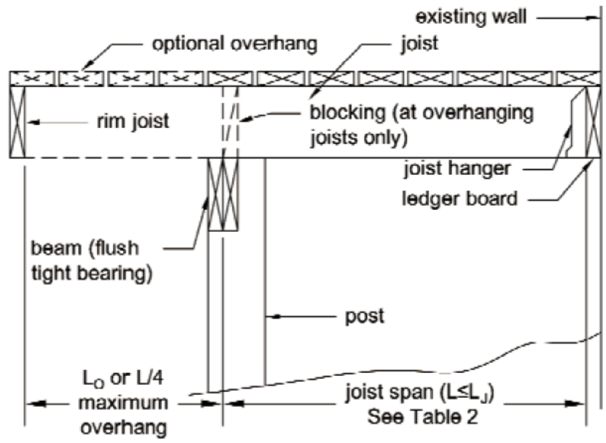
Joists

Figure 1A: Joist Span – Deck Attached at House and Bearing Over Beam



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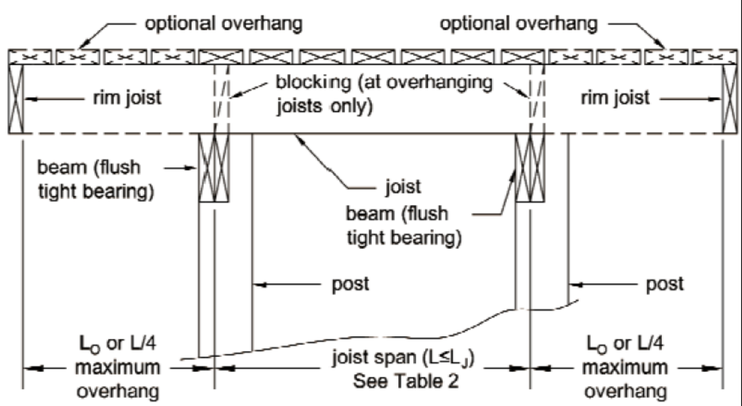
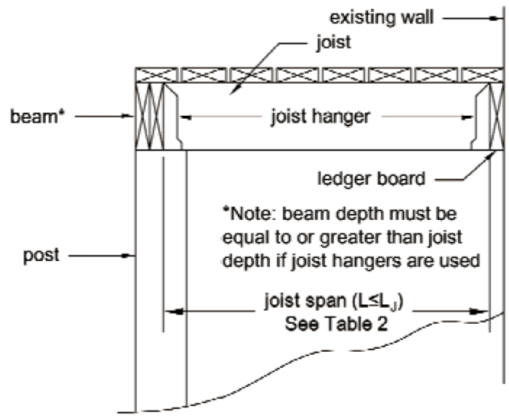
Joists

Figure 2: Joist Span – Free Standing Deck



Joists

Figure 1B: Joist Span – Joists Attached at House and to Side of Beam



Deck Design Example 1

❖ Joist Size for 8′ span dimension (w/out overhang)

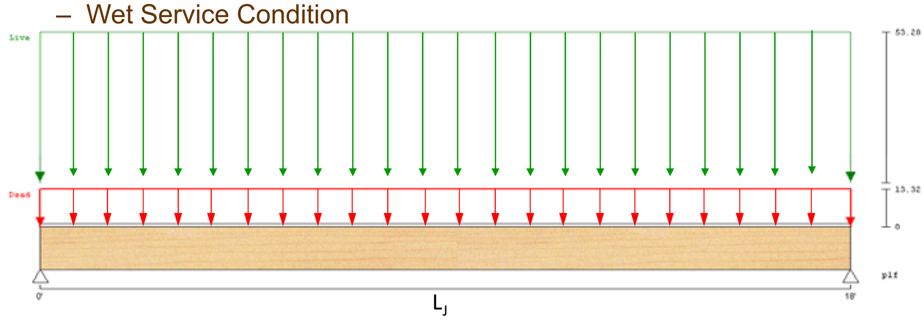
- DCA 6 Table 2
- 2x6 @ 16″ o.c.

Table 2. Maximum Joist Spans and Overhangs

		Joist Spacing (o.c.)[1]					
		Allowable Span[2] (L_J)			Allowable Overhang[3] (L_O)		
Species	**Size**	**12"**	**16"**	**24"**	**12"**	**16"**	**24"**
Southern Pine	2x6	9' - 11"	9' - 0"	7' - 7"	1' - 3"	1' - 4"	1' - 6"
	2x8	13' - 1"	11' - 10"	9' - 8"	2' - 1"	2' - 3"	2' - 5"
	2x10	16' - 2"	14' - 0"	11' - 5"	3' - 4"	3' - 6"	2' - 10"
	2x12	18' - 0"	16' - 6"	13' - 6"	4' - 6"	4' - 2"	3' - 4"

Joists

- **Span table development – without overhangs**
  - 40 psf uniform live load
  - 10 psf uniform dead load
  - No. 2 Grade
  - L/360 Deflection Limits
  - Wet Service Condition



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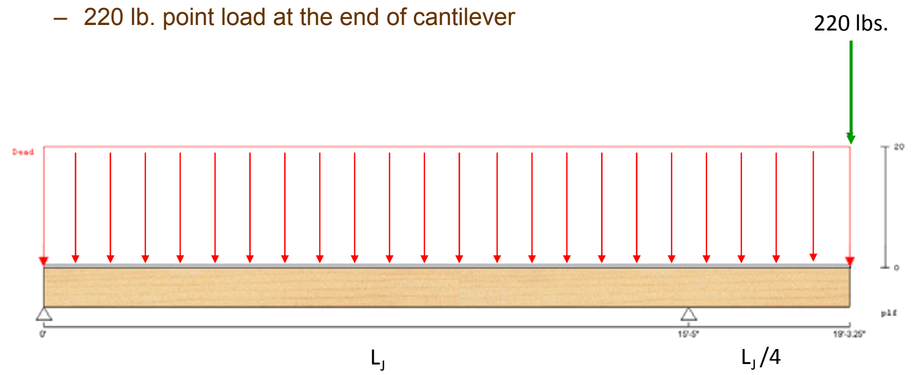
Joists

- **Span table development – with overhangs**
  - L/180 cantilever deflection limit
  - 220 lb. point load at the end of cantilever



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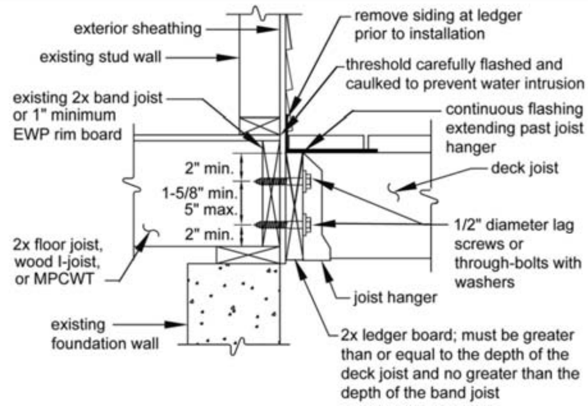
Ledger Requirements [R502.2.1]

- Ledger board depth > deck joist depth
- Ledger board depth < rim joist depth
- Flashing with drip edge
  - Corrosion resistant

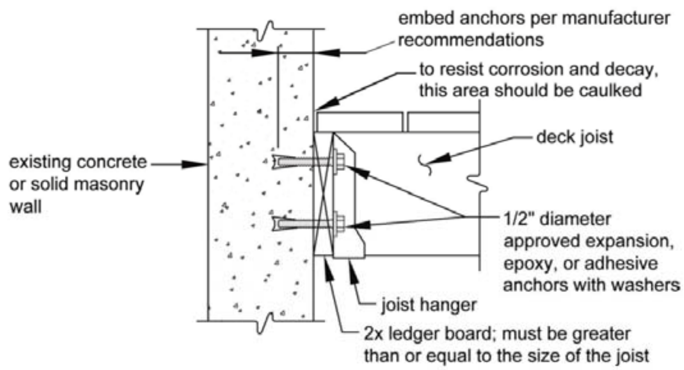
Figure 14. General Attachment of Ledger Board to Band Joist or Rim Board



Ledger Requirements

- **Ledger board to foundation wall**
  - Concrete or solid masonry
  - ½″ approved anchors

Figure 15. Attachment of Ledger Board to Foundation Wall (Concrete or Solid Masonry)



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Ledger Requirements

- **I-joists**
  - 1″ or thicker EWP band joist
    - OSB
    - SCL including LVL
  - <1″ band joist
    - Free standing deck
    - Full plan submission
- **Trusses**
  - 2x4 ribbon
    - No deck attachment
  - Requirements
    - Standard details
    - Free-standing deck
    - Full plan submission
    - SBCA tech note www.sbcindustry.com

Figure 13A. Wood I-Joist Profile

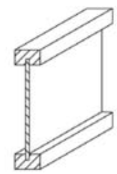
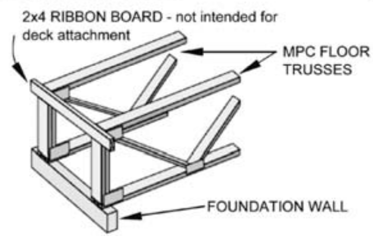


Figure 13B. Metal Plate Connected (MPC) Wood Floor Trusses with a 2x4 Lumber "Ribbon" at the Ends of the Trusses



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Prohibited Ledger Attachment

- **Exterior veneers**
  - Brick
  - Masonry
  - Stone
- **Requires free-standing deck**

Figure 17. No Attachment to or Through Exterior Veneers (Brick, Masonry, Stone)

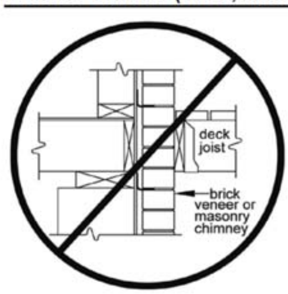


Photo courtesy of John Bouldin. All rights reserved.

Prohibited Ledger Attachment

- Cantilevered floors
- Bay windows
- Requires free-standing deck

Figure 18. No Attachment to House Overhang

Deck Design Example 1

❖ Ledger Fastener Spacing

- Assume 2x10 southern pine house rim board
- Assume 2x8 southern pine ledger
- DCA 6 Table 5
- ½″ϕ lag screws @ 18″ o.c.

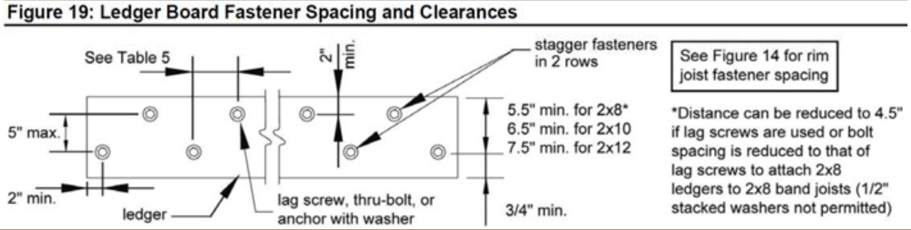
Table 5. Fastener Spacing for a Southern Pine, Douglas Fir-Larch, or Hem-Fir Deck Ledger and a 2-inch Nominal Solid-Sawn Spruce-Pine-Fir[7,9] Band Joist or EWP Rim Board[6]
(Deck Live Load = 40 psf, Deck Dead Load = 10 psf)[3,6]

Joist Span	Rim Board or Band Joist	6'-0" and less	6'-1" to 8'-0"	8'-1" to 10'-0"	10'-1" to 12'-0"	12'-1" to 14'-0"	14'-1" to 16'-0"	16'-1" to 18'-0"
Connection Details	On-Center Spacing of Fasteners[4,5]							
½" diameter lag screw with 15/32" maximum sheathing[1]	1" EWP[6]	24"	18"	14"	12"	10"	9"	8"
	1-1/8" EWP[6]	28"	21"	16"	14"	12"	10"	9"
	1-½" Lumber[7,9]	30"	23"	18"	15"	13"	11"	10"

Ledger Board Fasteners

- **Placement**
  - 2″ min. for top row
  - 2″ min. from ends
  - Staggered in 2 rows
  - Bottom row depends on ledger depth
  - 5″ max. between rows
- **Bolts**
  - ½″ diameter with washers
- **Expansion/Adhesive Anchors**
  - ½″ diameter with washers
  - Concrete or solid masonry
  - Hollow masonry with grouted cells
  - Embedment length per manufacturer

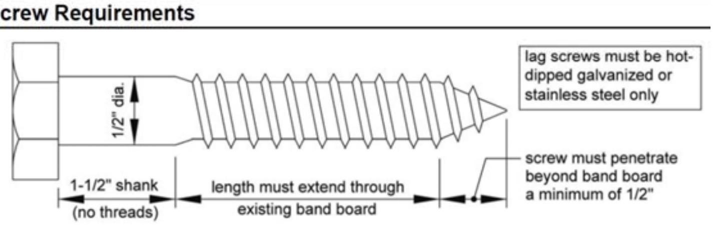
Figure 19: Ledger Board Fastener Spacing and Clearances



Ledger Board Fasteners

- **Lag Screws**
  - ½″ diameter with washers
  - Threads in band board
  - Extend ½″ beyond band board
- **Lag Screw Installation**
  - Pilot holes
    - ½″ diameter in ledger
    - $^{5}/_{16}$″ diameter in band board
  - Insert by turning
  - Do not hammer
  - Soap or lubricant
  - Snug but not over-tightened

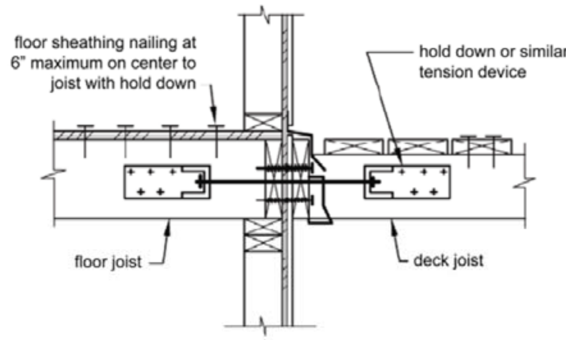
Figure 20: Lag Screw Requirements



Deck Stability

- **Attachment to House – Deck Supported by Ledger**
  - Lateral attachment to house floor system
  - *2009 IRC*
  - 2 locations per deck
  - 1500 lb capacity

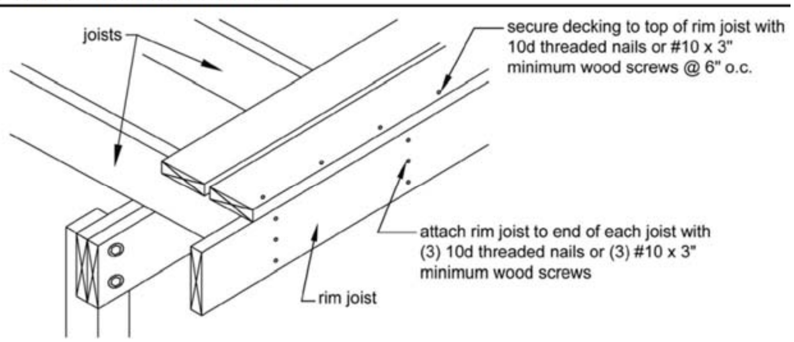
Figure 23A. Example of a Lateral Load Device for a Deck Attached to a House with a Ledger



Rim Joist Requirements

- **Decking attachment**
  - #10 x 3″ min. wood screws @ 6″ o.c.
  - 10d threaded nails @ 6″ o.c.
- **Joist attachment**
  - (3) #10 x 3″ min. wood screws
  - (3) 10d threaded nails

Figure 11. Rim Joist Connection Details



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Joist-to-Beam Connections

- **Options**
  - Toe-nails
  - Hurricane clip
  - Joist hanger

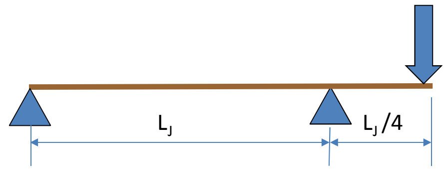
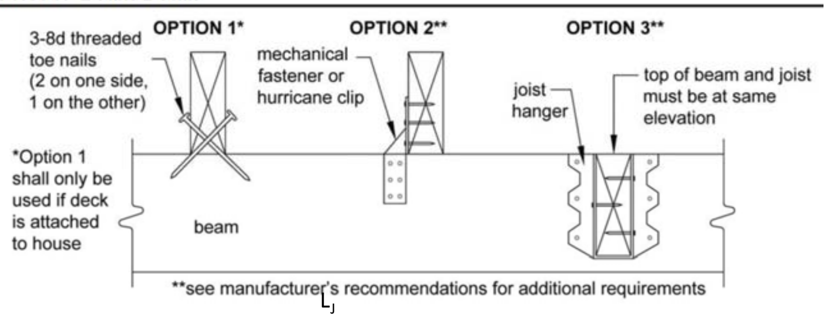


Figure 6: Joist-to-Beam Detail



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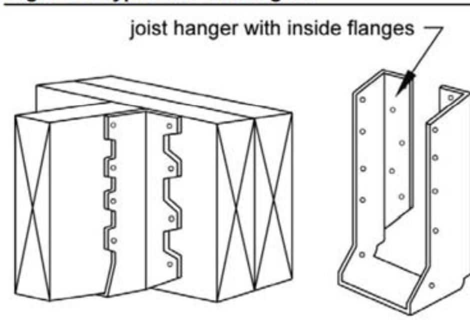
Joist-to-Beam Connections

- **Joist Hangers**
  - Capacity per Table 3A
  - Galvanized
  - No clips/brackets

Table 3A: Joist Hanger Vertical Capacity

Joist Size	Minimum Capacity, lbs
2x6	400
2x8	500
2x10	600
2x12	700

Figure 7: Typical Joist Hangers



- **Joist Hanger Size**
  - DCA 6 Table 3A
  - For 2x6
  - 400 lb joist hanger

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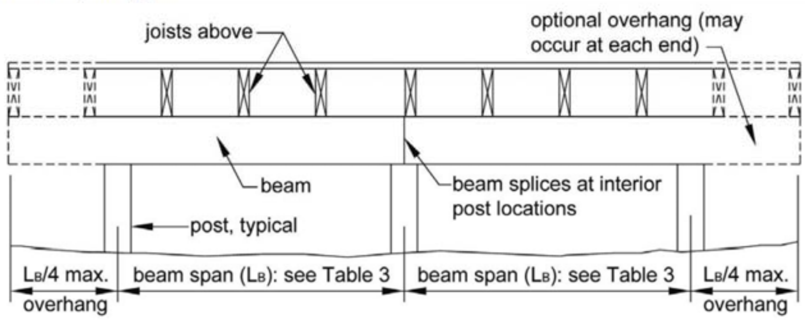
Beams

- **Spans**
  - L/4 maximum overhang
  - Splice over posts
  - Joists cannot be attached to opposite sides of the same beam

Figure 3: Beam Span Types



Deck Design Example 1

- **Beam Size for 12′ span dimension**
  - DCA 6 Table 3
  - For 8′ joist span
  - Try 2-2x8: spans 7′-7″
  - L_B/4 = 7′-7″ /4 = 1′-10¾″
  - 7′-7″ + 1′-10¾″ + 1′-10¾″ = 11′-4½″ < 12′ **NG**

- Try 3-2x8: spans 9′-6″
- L_B/4 = 9′-6″ /4 = 2′-4½″
- 9′-6″ + 2′-4½″ + 2′-4½″ = 14’-3” > 12” **OK**
- Use 8′ span with 2′ overhangs at each end

*2-2x10 also works

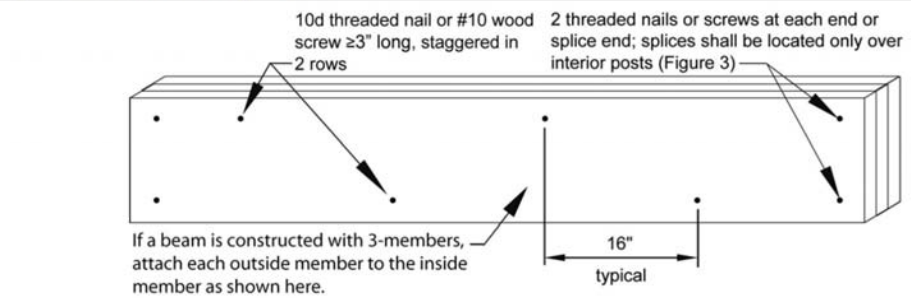
Table 3. Deck Beam Spans (L_B)[1] for Joists Framing from One Side Only

Species	Size[4]	Joist Spans (L) Less Than or Equal to: 6'	8'	10'	12'	14'	16'	18'
Southern Pine	2-2x6	6' - 11"	5' - 11"	5' - 4"	4' - 10"	4' - 6"	4' - 3"	4' - 0"
	2-2x8	8' - 9"	7' - 7"	6' - 9"	6' - 2"	5' - 9"	5' - 4"	5' - 0"
	2-2x10	10' - 4"	9' - 0"	8' - 0"	7' - 4"	6' - 9"	6' - 4"	6' - 0"
	2-2x12	12' - 2"	10' - 7"	9' - 5"	8' - 7"	8' - 0"	7' - 6"	7' - 0"
	3-2x6	8' - 2"	7' - 5"	6' - 8"	6' - 1"	5' - 8"	5' - 3"	5' - 0"
	3-2x8	10' - 10"	9' - 6"	8' - 6"	7' - 9"	7' - 2"	6' - 8"	6' - 4"
	3-2x10	13' - 0"	11' - 3"	10' - 0"	9' - 2"	8' - 6"	7' - 11"	7' - 6"
	3-2x12	15' - 3"	13' - 3"	11' - 10"	10' - 9"	10' - 0"	9' - 4"	8' - 10"

Beams

- **Assembly**
  - For built-up beams
  - 10d threaded or #10 wood screws
  - 16″ o.c. staggered

Figure 4. Beam Assembly Details



Post Requirements

- **6x6 or larger**
- **Max. 14′ height**
- **Centered on footings**
- **Cut ends field treated**
  - Copper naphthenate
  - [R402.1.2]
- **Post-to-Beam**
  - Notch
    - 3x or 4x beam
    - 2-ply beam
    - Two ½″ ϕ bolts w/ washers
  - Post cap
    - 3-ply beams

Figure 8. Post-to-Beam Attachment Requirements

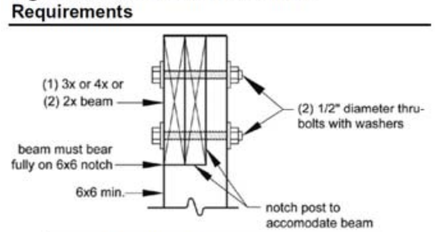
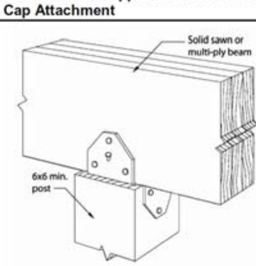


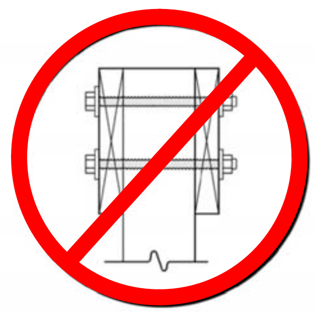
Figure 10. Alternate Approved Post-to-Beam Post Cap Attachment



Post Requirements

- **Prohibited connection**
  - Beam to side of post
  - Ensures wood-to-wood bearing
  - Avoids potential issues with non-compliant fasteners
  - Bolts in wet service environments have reduced capacity

Figure 9. Prohibited Post-to-Beam Attachment Condition



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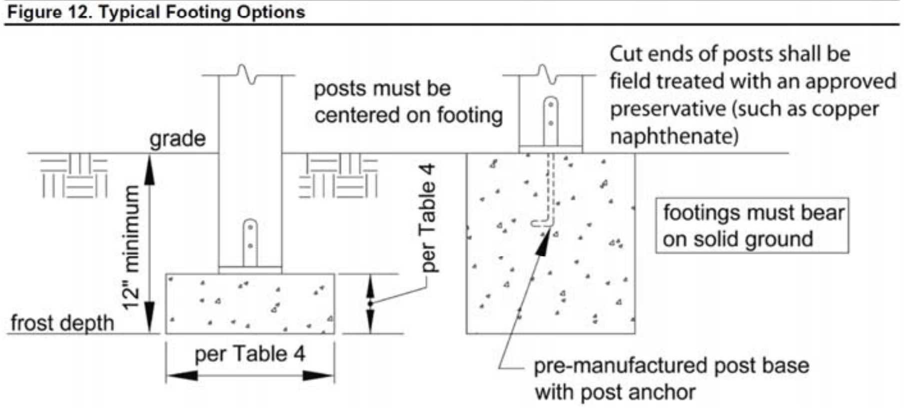
Footings [R403]

- **Depth ≥ 12" or frost line**
- **Soil 1,500 psf bearing capacity**

Figure 12. Typical Footing Options



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Deck Design Example 1

- **Footing Size**
  - DCA 6 Table 4
  - Thickness = 7″
  - Square = 16″
  - Round ϕ = 18″
  - Below frost line

Table 4. Footing Sizes[1]

Beam Span, L_B	Joist Span L_J	Round Footing Diameter	Square Footing	Footing Thickness[2]
6'	<10'	15"	14"	6"
	<14'	18"	16"	7"
	<18'	20"	18"	8"
8'	<10'	18"	16"	7"
	<14'	21"	18"	8"
	<18'	24"	21"	10"

Footing Design

DCA 6 Commentary

Post load: $R = 50\left(\frac{L_J}{2} + \frac{L_J}{4}\right)\left(\frac{L_B}{2} + \frac{L_B}{4}\right)$

Square footing: $B = 12\sqrt{\frac{R}{1500}}$

Round footing: $D = 12\sqrt{\frac{4R}{1500\pi}}$

Footing thickness: T ≥ P; $T = \frac{D - 5.5}{2}$

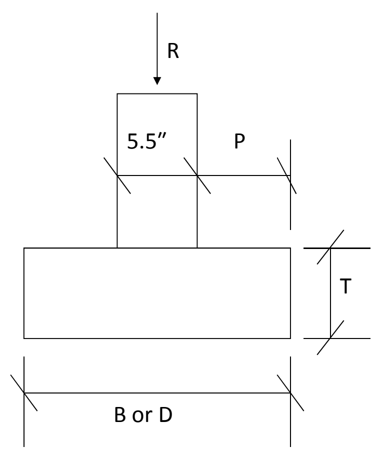

Figure C12. Footing dimensions and variables.

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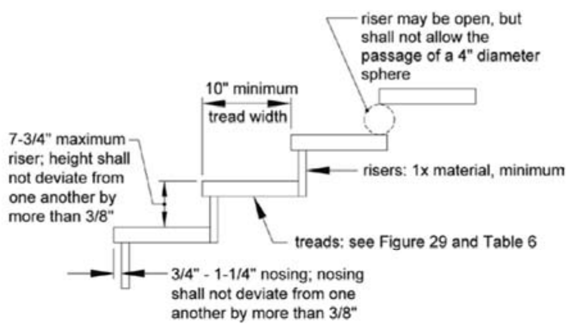
Stair Requirements

- **Treads and Risers**
  - 7-3/4″ rise & 10″ run
  - Except where amended
  - 1x risers
  - Treads per Table 6
  - Openings < 4″ diameter sphere

Figure 27. Tread and Riser Detail



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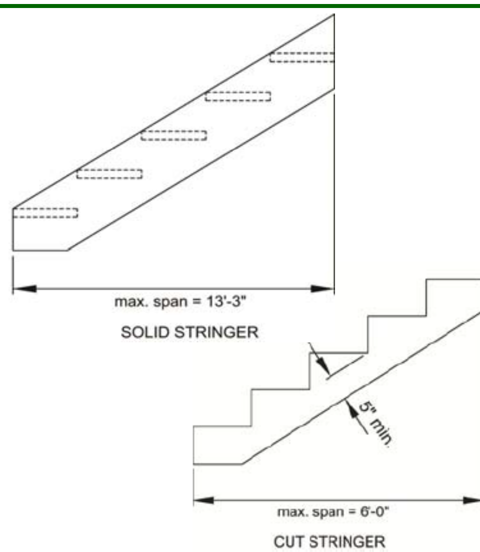
Stair Requirements

- **Stringers**
  - Minimum 2x12
  - Spans per Figure 28
  - Intermediate landings permitted



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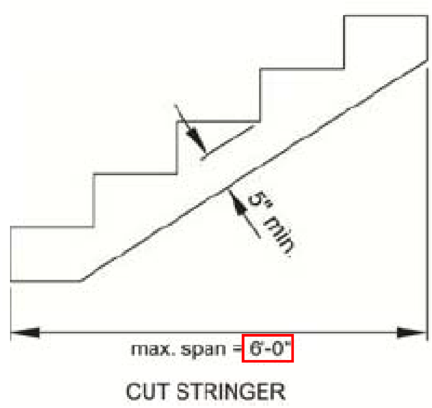
Deck Design Example 1

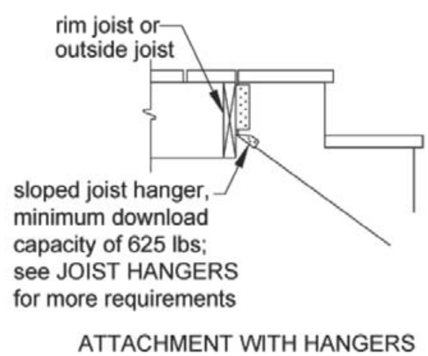
- **Stair Stringers**
  - DCA 6 Figure 28
  - 2′ deck height
  - Requires 2′-6″ cut stringer span assuming 7¾″ rise and 10″ run 6’-0” > 2’-6” ok
  - Use a Cut stringer



Stair Requirements

- **Stringer Attachment**
  - Hangers
    - Sloped joist hanger
    - Per manufacturer

Figure 31. Stair Stringer Attachment Detail



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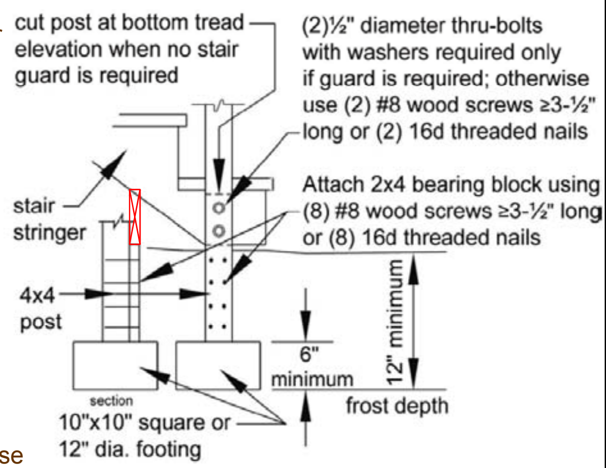
Stair Requirements

- **Stair Footings [R403]**
  - 12″ min. depth or frost line
  - 10″ square or 12″ diameter
  - 6″ thick
  - 4x4 posts centered
- **Bearing Block**
  - 2x4
  - 8 fasteners
- **Stringer**
  - ½″ bolts only if guard is required
- **Lighting**
  - Top landing
  - Illuminate all landings
  - Light switch inside the house

Figure 34. Stair Footing Detail



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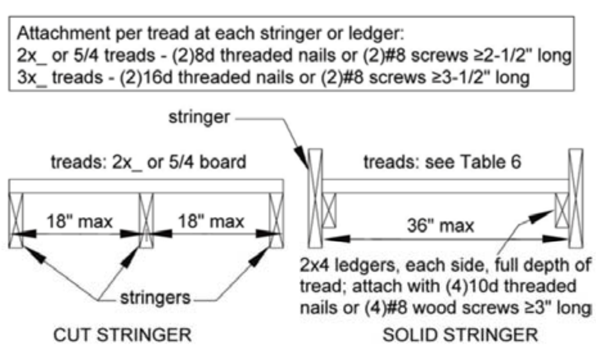
Stair Requirements

- **Stringers**
  - Cut ≤ 18″ o.c.
  - Solid ≤ 36″ o.c.
- **Treads**
  - Sizes per Table 6
  - Connections per Fig 29

Figure 29. Tread Connection Requirements



Deck Design Example 1

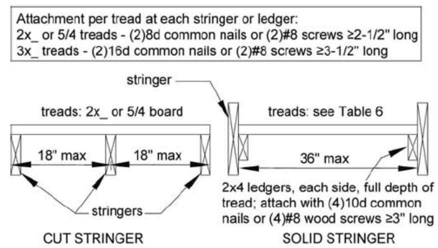
❖ **Stair Treads**

- DCA 6 Table 6
- Cut stringer
- $^5/_4$x6 southern pine treads

Table 6: Minimum Tread Size for Cut and Solid Stringers[1]

Species	Cut Stringer	Solid Stringer
Southern Pine	2x4 or 5/4	2x8
Douglas Fir Larch, Hem-Fir, SPF[2]	2x4 or 5/4	2x8 or 3x4
Redwood, Western Cedars, Ponderosa Pine[3], Red Pine[3]	2x4 or 5/4	2x10 or 3x4

Figure 29: Tread Connection Requirements

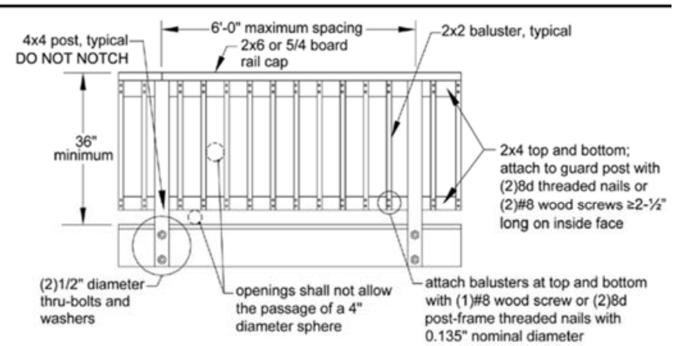


Deck Design Example 1

❖ **Guard requirements**

- Deck height < 30″
- Guard optional

Figure 24. Example Guard Detail



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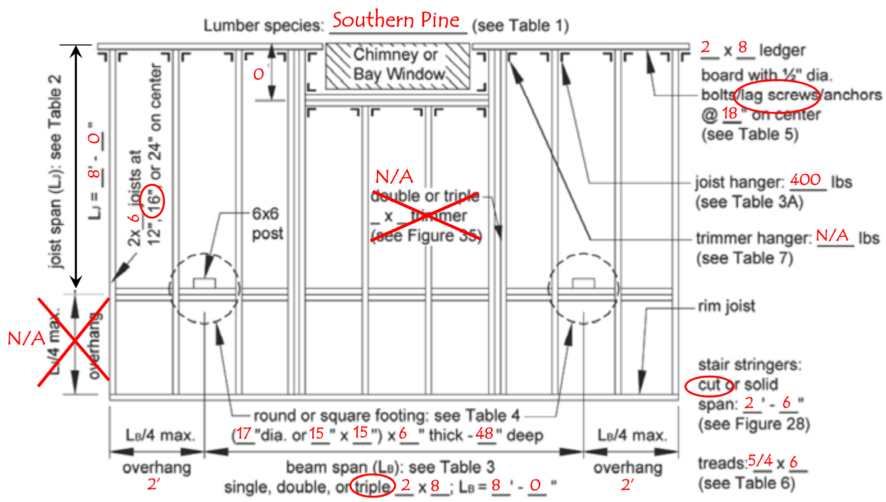
Deck Design Ex. #1 - Framing Plan

Figure 5. Typical Deck Framing Plan



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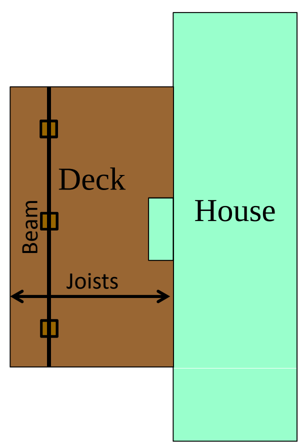
Deck Design Example 2

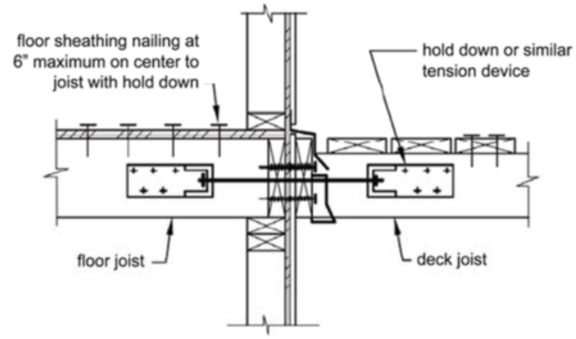
- Deck height = 8'-0"
- 16' x 20' deck surface
- Structural members: southern pine
- Decking: 5/4 radius edge southern pine decking
- Framing around a 5′ wide by 2½′ deep bay window
- Determine sizes for joists, beams, hangers, footings, stringers, and treads
- Determine fastener spacing for bolts in 1-1/8″ EWP house rim board



Deck Design Example 2

❖ Lateral attachment

Figure 23A. Example of a Lateral Load Device for a Deck Attached to a House with a Ledger



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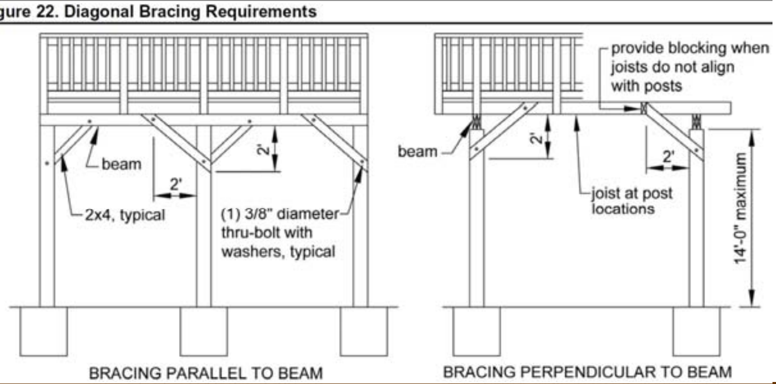
Deck Stability

- **Decks > 2′ above grade**
  - require diagonal bracing
  - Attach to exterior wall
- **Parallel to beam**
  - Lag Screw to beam and post
- **Perpendicular to beam**
  - Lag screw to post and joist or blocking

Figure 22. Diagonal Bracing Requirements



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Framing at Chimney or Bay Window

- **Trimmers**
  - Triple
    - 12"-16" joist spacing
    - Spans > 8'-6"
  - Double
    - 24" joist spacing
    - Spans ≤ 8'-6"
  - "a" ≤ 3'

Table 7: Trimmer Joist Hanger Vertical Capacity

Joist Size	Minimum Capacity, lbs
2x6	870
2x8	1155
2x10	1420
2x12	1575

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Deck Design Example 2

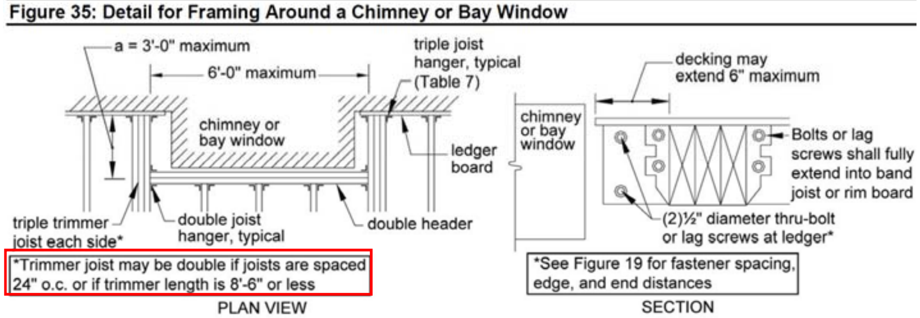
❖ Bay Window

- Header = 6′
- a = 2'-6"
- Triple trimmer joist
- Trimmer hanger = 1,420 lbs

Table 7: Trimmer Joist Hanger Vertical Capacity

Joist Size	Minimum Capacity, lbs
2x6	870
2x8	1155
2x10	1420
2x12	1575

Figure 35: Detail for Framing Around a Chimney or Bay Window



Guard Requirements

Adjacent Fixed Seating Requirement

- **36″ measurement from seat**

R312.2 Height. Required *guards* at open-sided walking surfaces, including stairs, porches, balconies or landings, shall be not less than 36 inches (914 mm) high measured vertically above the adjacent walking surface**, adjacent fixed seating** or the line connecting the leading edges of the treads.

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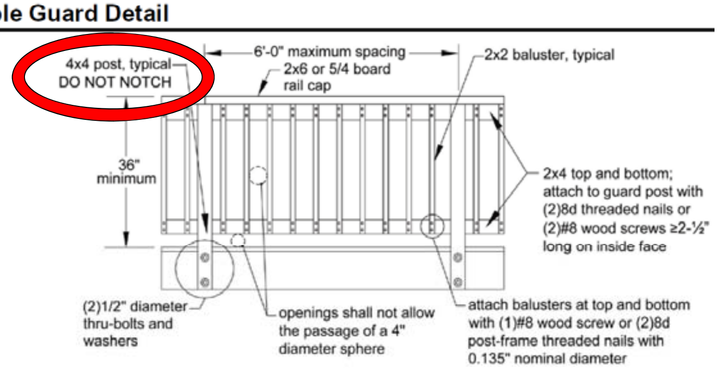
Guard Requirements

- **Decks > 30″ above grade require guard**

Figure 24. Example Guard Detail



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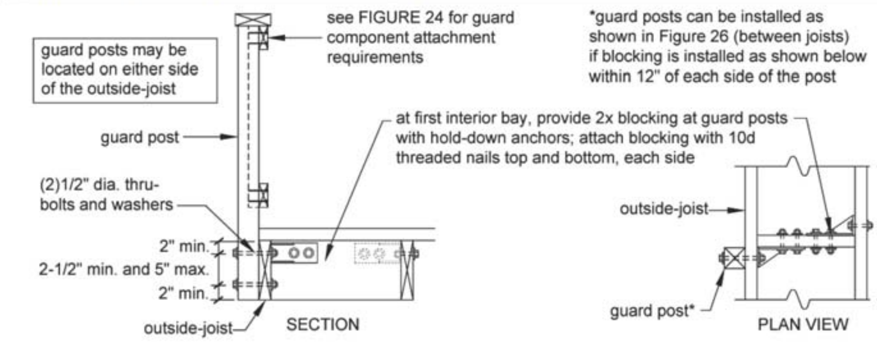
Guard Requirements

- **Minimum 4x4 post**
- **Bending design value ≥ 1,100 psi**
  - All No.2 species shown in Table 2
  - $C_M = 0.85$, $C_i = 0.80$, $C_D = 1.6$

Figure 25. Guard Post to Outside Joist Example



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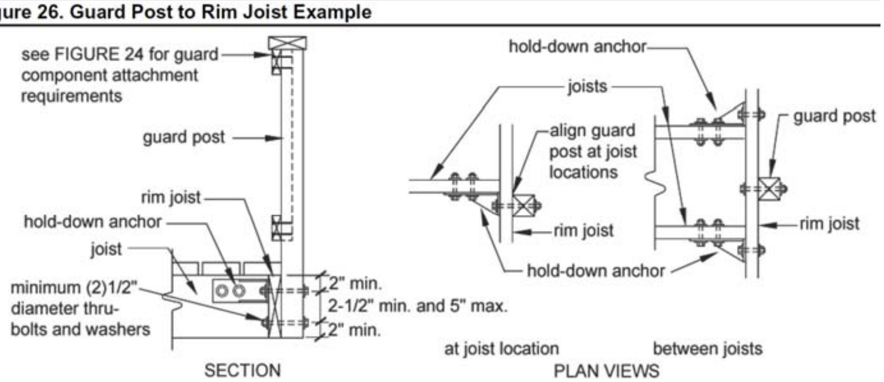
Guard Requirements

- **Guard Post to Rim Joist**
  - Hold down anchors
  - Minimum of two ½″ bolts

Figure 26. Guard Post to Rim Joist Example



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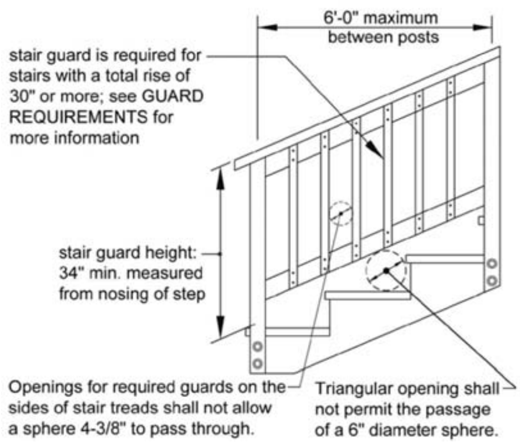
Stair Requirements

- **Guard Requirements**
  - Required if 30″ total rise
  - 6′ maximum between posts
  - 34″ height minimum
  - Opening <6″ diameter sphere
  - Openings <4$^3/_8$″ for tread guards

Figure 30. Stair Guard Requirements



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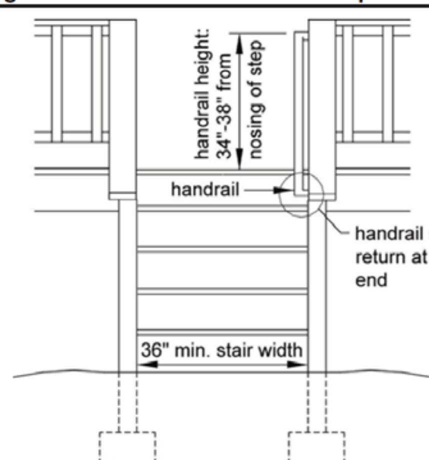
Stair Requirements

- **Handrails**
  - Continuous from lowest to highest riser
  - Return to guard at each end
  - May be interrupted by guard at turn

Figure 33. Miscellaneous Stair Requirements



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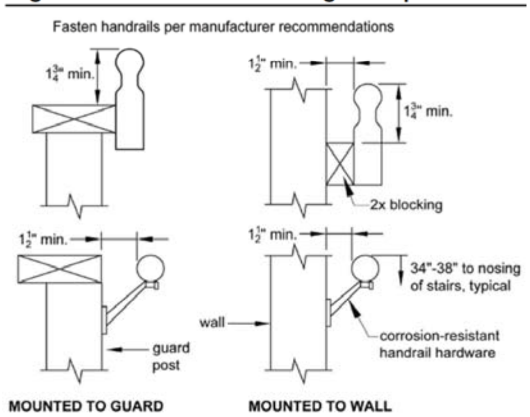
Stair Requirements

- **Handrails**
  - Required for stairs with 4 or more treads
  - Height 34″ – 38″

Figure 32A. Handrail Mounting Examples



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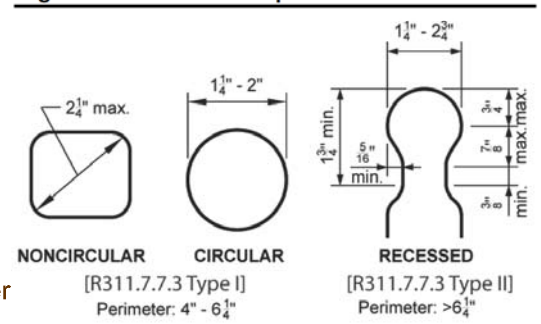
Stair Requirements

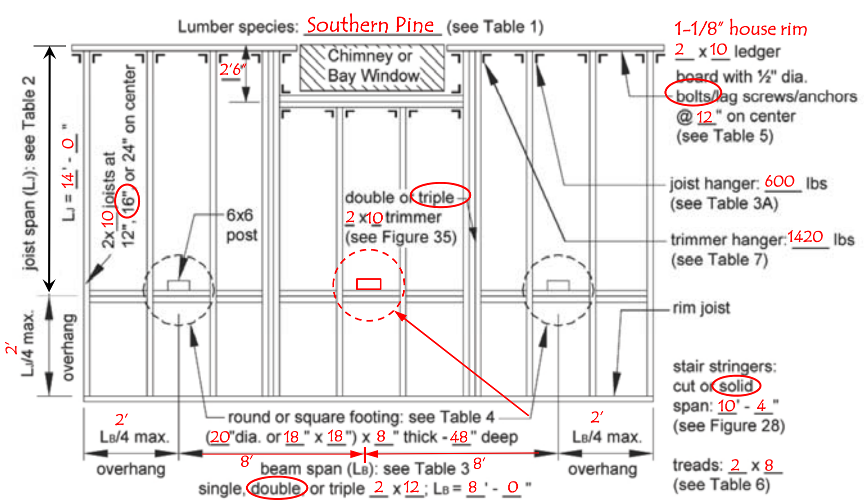
- **Handrails**
  - Type I: 4″ – 6¼″ perimeter
    - Circular
      - 1¼″ – 2″ diameter
    - Noncircular
      - Max. cross section 2¼″
  - Type II: >6¼″ perimeter
    - Graspable recess

Figure 32B. Handrail Grip Size



Deck Design Ex. #2 - Framing Plan

Figure 5. Typical Deck Framing Plan



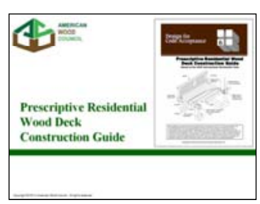
Resources

DCA6 Deck Guide

http://www.awc.org/publications/DCA/DCA6/DCA6-09.pdf

DCA6 Presentation

http://www.awc.org/pdf/DCA6-Decks-webinar-Aug2013.pdf



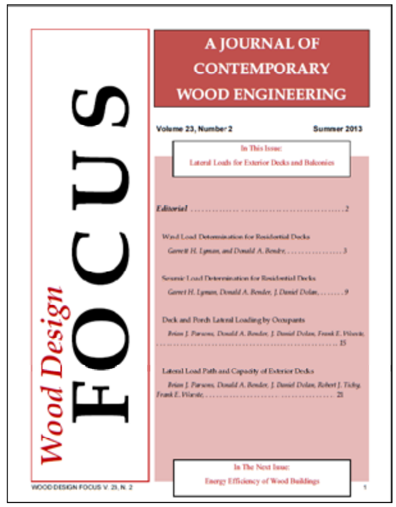
Resources

Forest Products Society

Wood Design Focus

http://www.forestprod.org/

Figure 2. Cyclic Loading Caused by Occupants Swaying Side to Side in Unison



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Volume 23, Number 2 Summer 2013

In This Issue:
Lateral Loads for Exterior Decks and Balconies

In The Next Issue:
Energy Efficiency of Wood Buildings

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Downloads

AWC DCA6 Deck Guide
http://www.awc.org/publications/DCA/DCA6/DCA6-09.pdf

AWC DCA6 Presentation
http://www.awc.org/pdf/DCA6-Decks-webinar-Aug2013.pdf

AWC DCA6 One-Pager to Post to Website
http://www.awc.org/pdf/DCA6-ResidentialDeckGuide-1009-onepager.pdf

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OPEN BUILDING: DISENTANGLMENT and FLEXIBILITY AS KEYS TO SUSTAINABLE MODULARITY

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ABSTRACT

Modular construction's success lies in the ability to complete a maximum amount of construction work off-site in quality controlled and economically advantageous conditions. Achieving high-performance building envelopes – key to meeting energy conservation goals – is also enhanced in controlled production processes. While these are clear advantages, modular building design and decision-making have till now inhibited real contributions to the goal of built-environment sustainability. The reason is the adherence to the widespread and flawed principle of deciding space plans first and then locking-in those decisions by means and methods of construction. Specifically, MEP (mechanical, electrical and plumbing) systems are conventionally buried inside walls and floors. Being buried, the possibility to defer decisions about or change the location of plumbing fixtures and electrical terminations - during construction or to upgrade later during use - is greatly inhibited. This is especially so in multi-floor, multi-tenant buildings. We know that developers like to defer decisions as long as possible. We also know that user and building owner preferences change. With buried MEP systems, the possibility to adapt buildings to new functions, new layouts, and upgraded MEP systems is greatly inhibited. Therefore, the full potential of modular construction to meet the sustainability and flexibility agendas is not being achieved, and its competitive advantage not fully exploited.

The solution to this dilemma is introduce a new "decision/product bundle" into modular building design. This can be called MODULAR FIT-OUT. The principle objectives are to disentangle the longer-lasting part of a modular building from the shorter-life-span parts by making cabling and wiring connections accessible, and by removing the piping from its usual place hidden in walls and inside the floor sandwich of modules. This is essentially a change in design decision-making. Such decoupling and disentanglement will unleash new products to provide solutions. Two such product solutions are now available: INFILL SYSTEM US's CableStud and Matrix Tile System (http://www.infillsystemsus.com). Their application in modular construction will provide a competitive advantage in the race to achieve a sustainable and adaptable building stock.

This paper offers a brief history of the evolution of this decision-making model; shows an example of a townhouse organized in an open building way; and illustrates the advantages of INFILL SYSTEM solutions.

KEY WORDS: Open Building, Modular, Sustainable, Flexible, Disentanglement

THEORY of OPEN BUILDING

Our building stock was always sustainable when it could adjust by means of "fine-grained" transformation, adjusting part-by-part to new user requirements, and changes in life-styles and cultural norms. In the late 19^{th} century, this changed. The basic unit of adjustment –the individual living "cell" (house, shop, office) – changed and large buildings became the investment unit of choice for large corporations and large governmental agencies. Large office and apartment buildings were constructed without recognition of the individual unit of occupancy as the vital living cell of the city. Individual units of occupancy were aggregated together into unified, rigid constructions. Conflict and waste of resources resulted under conditions of inevitable social dynamics and technological change.

This reduction in granularity was not only related to investment decisions by central governments and large companies. It was also attributable to the introduction of utility systems into buildings. Water pipes, drainage piping and gas lines as well as electrical cables began finding their way into buildings, hidden inside walls and floors. This was supported in no small way by the parallel introduction of steel and wood framing, construction methods that offered hollow walls and floors into which these utility systems could be routed and conveniently hidden. The problem was that, being hidden, they escaped attention by architects and also presented many problems to their maintenance and replacement when they became defective or needed to be upgraded.

Starting in the decade following the end of World War II, office building and shopping center developers began to revise their investment and decision-making strategies in response to new market forces. Base buildings (often called "core and shell" buildings) were planned and built to accommodate a variety of rapidly changing occupancies. This shift in patterns of control arose in the office and retail sectors with an explosion of small businesses supported by new transport systems accompanied by cheap energy, new logistics, innovative financing tools, the growth of the consumer market, and so on. The emergence of the base building as a new force in the real estate market forced building investors to revise their contracts with architects and engineers, who developed the skills needed to deliver new services.

The separation of base building and fit-out is now conventional practice; design practices (architects, engineers, interior designers) have methods for managing this separation; contractors specialize in these two decision levels; products aimed at these two markets are widely available internationally, and finance and regulation have adjusted accordingly.

This is OPEN BUILDING. What started in the office and retail sectors is now increasingly evident worldwide in the residential market (Holland, Finland, Switzerland, Russia, Japan, Canada and the US) and in healthcare facilities (US, Holland, Switzerland, among others).

Open Building is now poised to become part of the sustainability agenda, providing methods and processes to help investors – and users - achieve long lasting buildings - long lasting because they are flexible and recognize highly disaggregated and varied demands. As usual, demand continues to shape supply.

WHY OPEN BUILDING MATTERS TO THE MODULAR INDUSTRY

Off-site production of PARTS of buildings is already well organized in the modular industry. Software-driven supply chain management and bulk purchasing, efficient logistics and on-site construction management are already familiar. The long-heard criticism of structural redundancy (and thus higher cost) has been met and is often successfully offset by offering advantages of reduced time on-site, project speed to market and quality control.

However, unlike the streamlined separation of BASE BUILDING and FIT-OUT found in most speculative office building and shopping center building processes – and now found in leading-edge residential and health care facility projects - modular construction remains stuck in the obsolete paradigm of "whole building integration." The choice is clear: OPEN BUILDING vs. WHOLE BUILDING INTEGRATION."

The separation of BASE BUILDING and FIT-OUT suggests the following:

1). Clear separation of the BASE BUILDING from the FIT-OUT enables design and production of FIT-OUT systems independent of specific projects. Their components can be true manufactured products, like products found in building supply company catalogues.
2) Installation of separate FIT-OUT systems not only offers developers decision flexibility and users choice, it improves quality and saves time and labor on-site.
3) FIT-OUT systems can be improved over time and new ones can be installed in older buildings to give higher performance.
4) If several FIT-OUT companies are in the market, competition will drive down prices and offer greater choice to decision-makers including users.
5) Use of FIT-OUT systems means that installation of individualized floor plans is just as easy to implement as uniform floor plans.
6) Individual units of occupancy can be changed and improved over time.
7) FIT-OUT depends on good logistics and software, as well as adjustments to some building codes and building permitting processes. Unified installation teams will add to the efficiency, quality control and speed, just like in the automobile industry.
8) FIT-OUT can be financed separately from the BASE BUILDING, with different financing instruments, interest rates and pay-back periods.

In an OPEN BUILDING, we say there are LEVELS OF INTERVENTION (see figures 1-3 below).

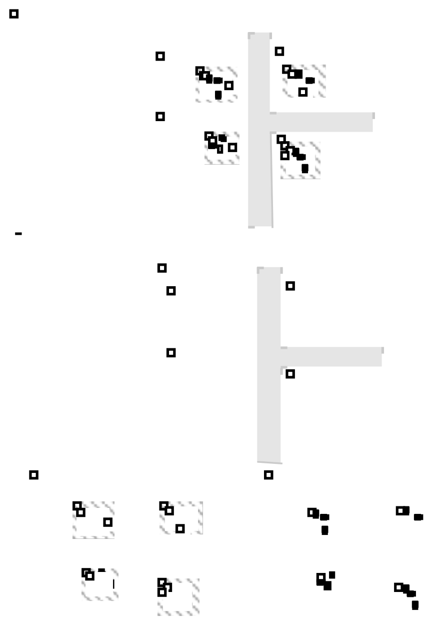


Figure 1: three levels in the built environment.
(The public street and lots; the building;
the fit-out)

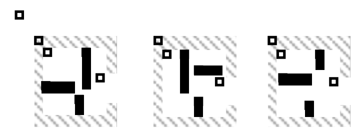


Figure 2: Two-level organization;
building with fit-out variations

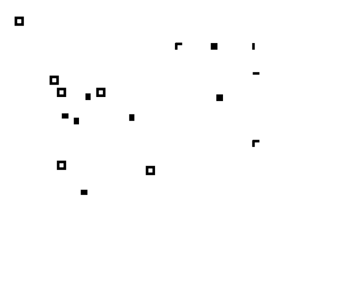


Figure 3: Two-level organization
MEP (mechanical, electrical,
plumbing) in the street and in the
building. The MEP in the building
can change independently of the
MEP in the street (with certain
“capacity” limitations).
(Figures 1-3 from Habraken)

A MODULAR OPEN BUILDING

Imagine a multi-story residential project built as a modular project using OPEN BUILDING principles.

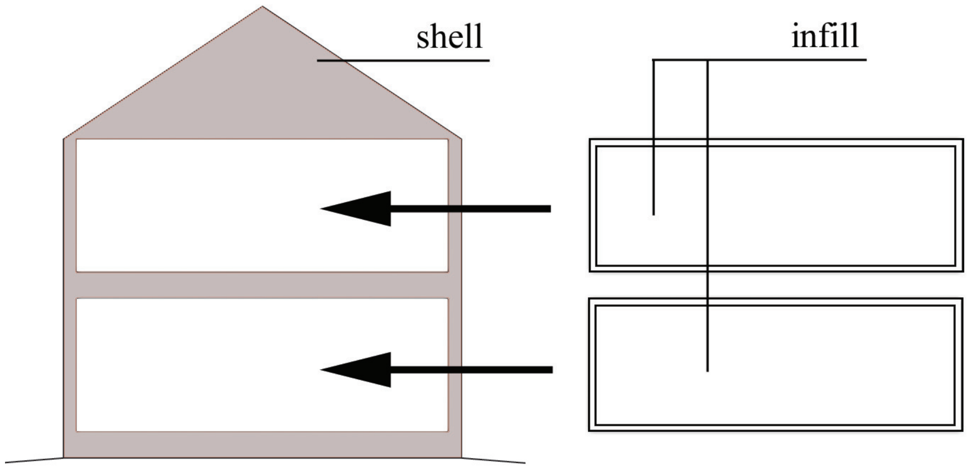


Figure 4: Separation of Shell (Base Building) and Infill (Fit-out)

This separation, applied to a townhouse constructed using MODULAR BUILDING PRINCIPLES, could look like this:

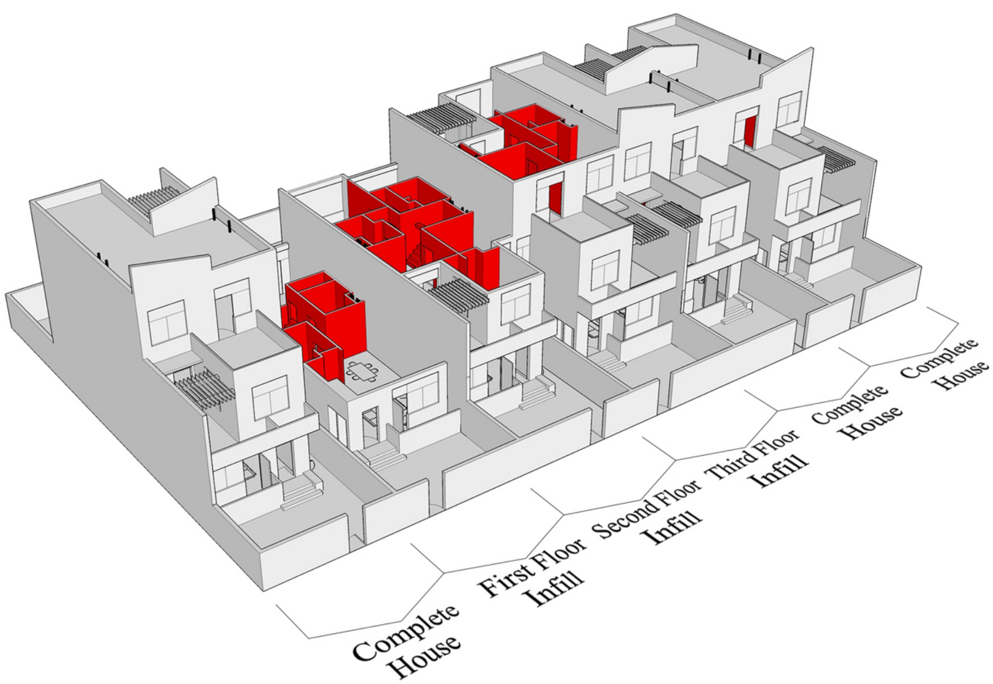


Figure 5: A townhouse solution can use MODULES and INFILL or FIT-OUT for customized interior layout and equipment.

Use of a separate FIT-OUT or INFILL system is shown in the following diagrams, indicating the range of decisions that are possible. The first floor plan of one example of a “whole house” is shown, followed by the SHELL (Base Building) with all windows and façade elements and fixed MEP system parts delivered as part of the MODULAR UNITS built in the factory. The configuration of MODULES will comply with local building codes, urban design layout and architectural themes, climatological constraints, and developer preferences.

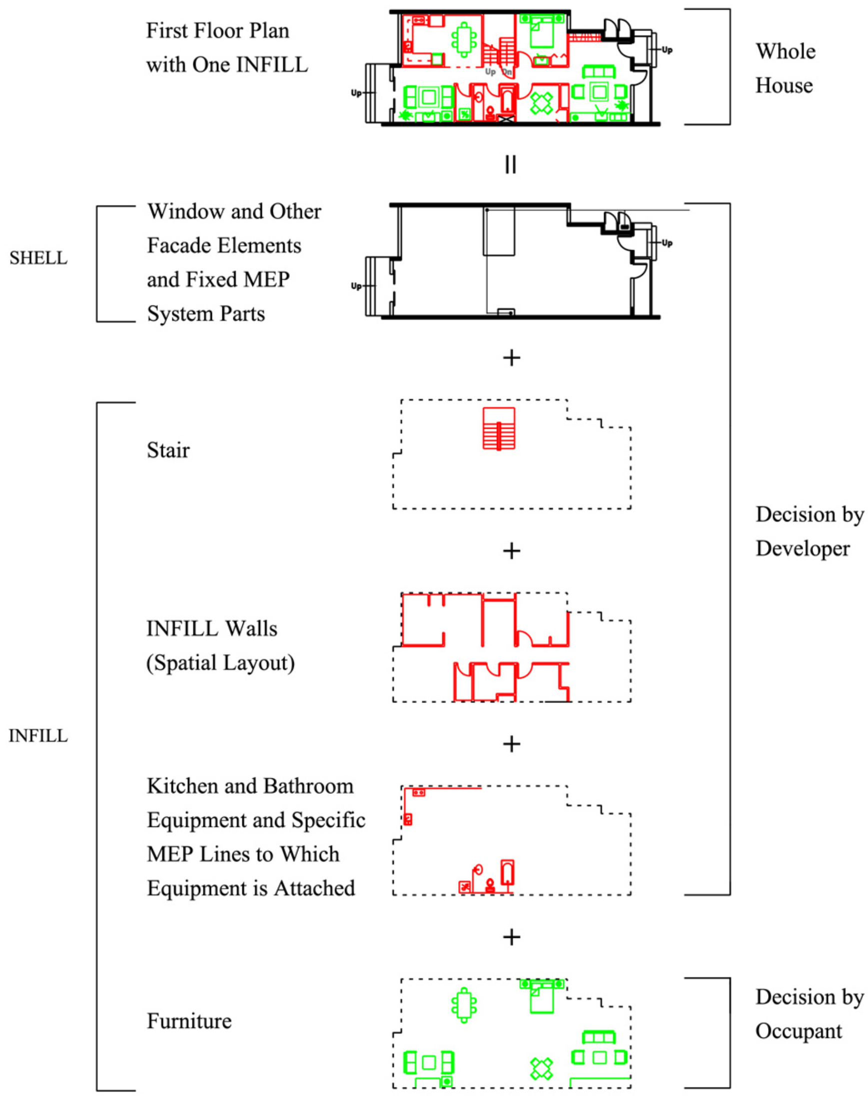


Figure 6: Scenario A – Here, the developer decides not only on the SHELL (Base Building) but also all of the INFILL (Fit-Out). The occupant decides the furnishings only. The INFILL (Fit-Out) SYSTEM conforming to the developer’s decisions can be installed either in the factory, or as a kit-of-parts prepared off-site, once the modular building has been erected at the site.

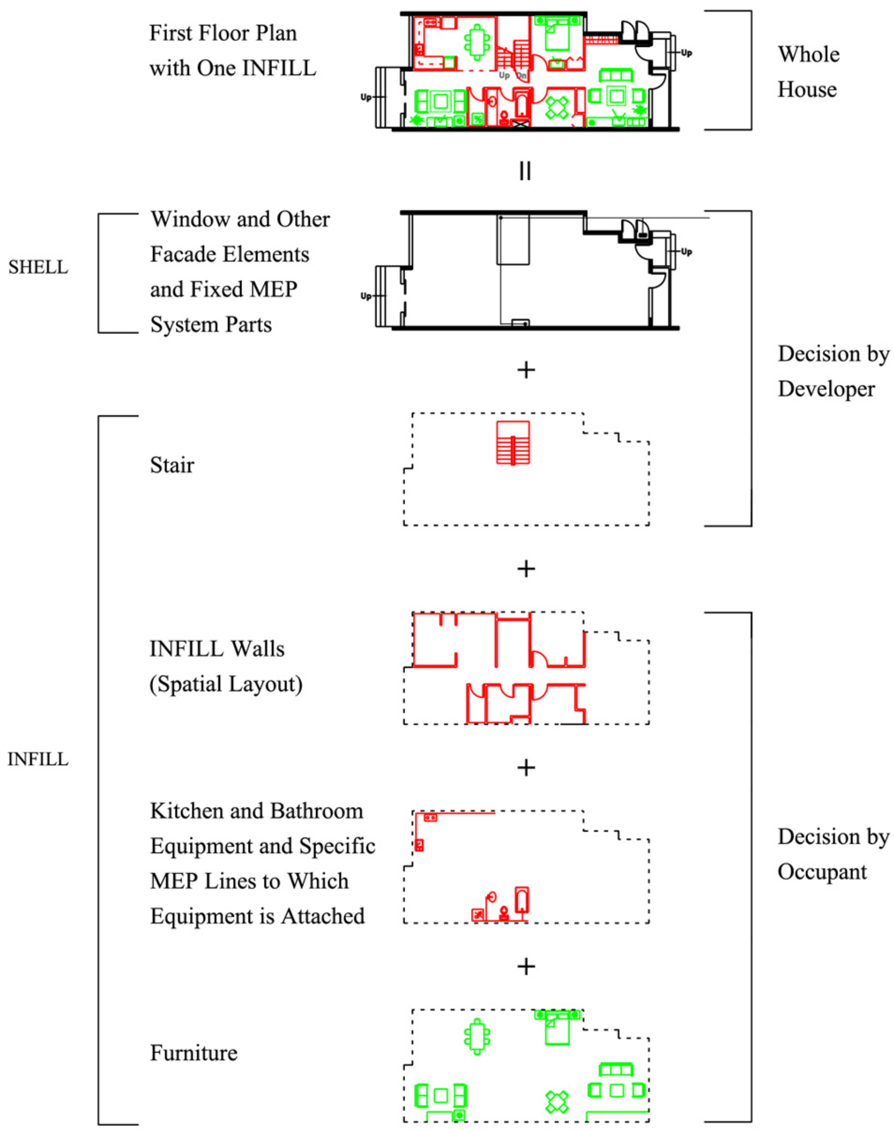


Figure 8: Scenario B – Many intermediate scenarios are possible. In this example, the developer decides not only on the SHELL (Base Building) but also the stair of the INFILL (Fit-Out). The SHELL (Base Building) is designed so that a variety of stair designs can be installed, each enabling a different floor plan on both floors. This is accomplished by sizing the "stair opening" not for one stair, but for a variety of stairs. The occupant decides the interior layout (partitions), the MEP and equipment corresponding to the layout, and the furnishings.

The stair is installed after the modules have been erected, because it connects two separate modules. An INFILL SYSTEM conforming to the occupant's decisions can be installed either in the factory or once the modular building has been erected.

INFILL SYSTEM PRODUCTS

The separation of SHELL and INFILL (Base Building and Fit-Out) can be accomplished using ordinary and familiar products. However, international experience shows that the disentanglement of piping and wiring from its standard place - buried inside walls and floors - is a prerequisite to more efficient decision making and construction, not to mention offering benefits to longer-term building management.

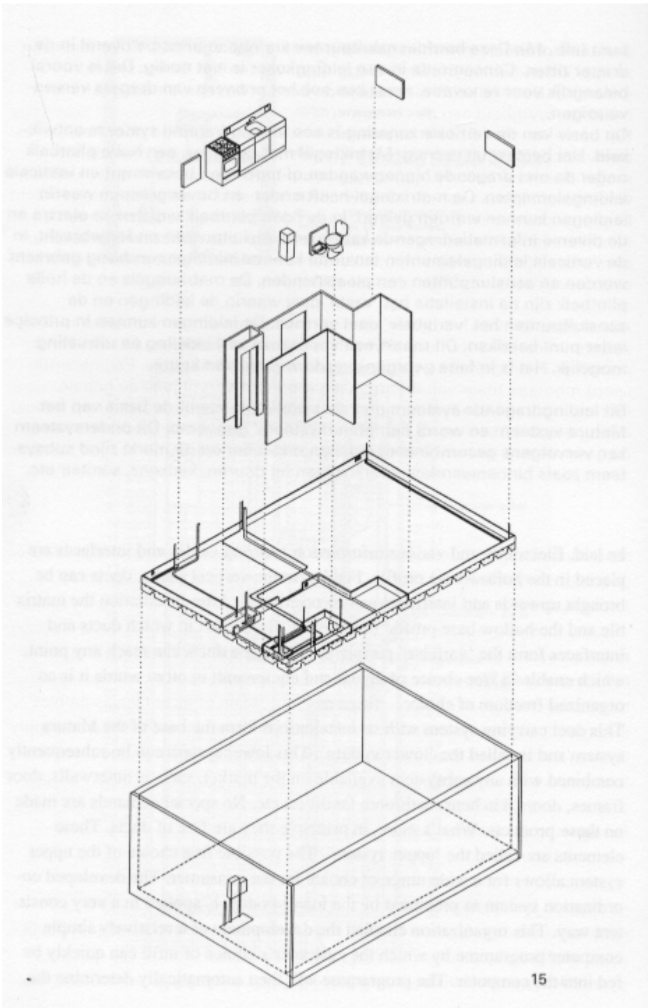
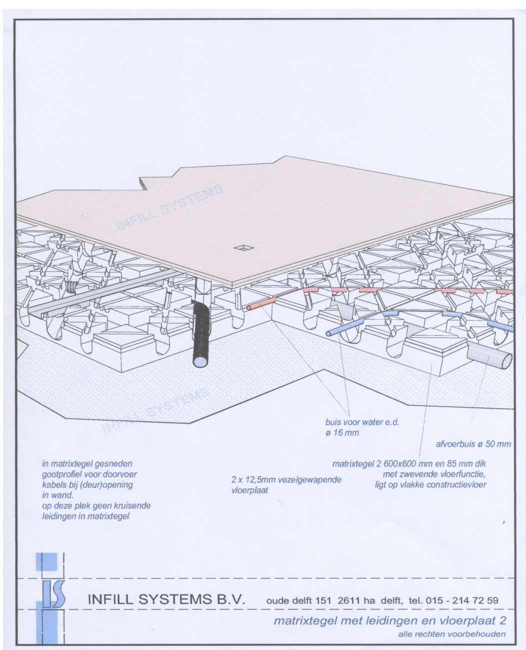


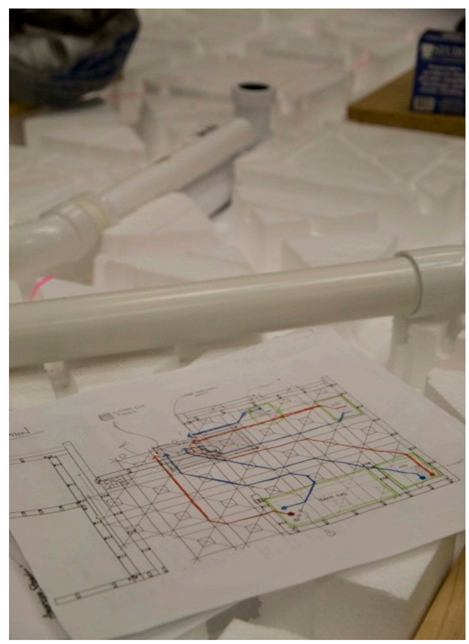
Figure 9: An empty SHELL (Base Building) space is shown with a service point from which MEP systems are connected to their respective equipment in any floor plan layout. The SHELL can be a MODULAR UNIT. Figure 9 also shows the disentangled subsystems of the INFILL (Fit-Out) System.

Several products now coming to market facilitate this OPEN BUILDING process. They are the MATRIX TILE SYSTEM and CABLESTUD. These products were developed in the Netherlands. They are invisible – like the INTEL microchip – but powerful, improving efficiency, decision flexibility and quality control in pre-construction project phases and during installation. They also offer positive ROI over short, medium and long-term cycles of churn, including adaptive reuse of old buildings. CABLESTUD is marketed in Europe by GYPROC, a company in the Saint-Gobain family of companies. They are backbone products for full, slab-to-slab fit-out systems, but are also effective as stand-alone solutions.

MATRIX TILE SYSTEM

The **MATRIX TILE SYSTEM** is a standard, injection-molded 4” thick medium density polystyrene “tile” (32” square) applied on top of a leveled base building floor. Grooves of various sizes - located in several horizontal “zones” formed in the top of the tile - allow the secure placement, without interference, of lines or conduits for various services, such as hot and cold water, gray-water drainage (0-slope), hot water piping to radiators, floor heating, flat ventilation ducts, gas pipes and so on. A 1” thick fireproof floor layer is placed after pipes and other utility services are installed. Non-loadbearing partitions are erected on this floor covering along with any finish floor covering.





Figures 10 and 11: The Matrix Tile is shown on the left with gray-water drainage lines (shown in black and gray) and domestic water pipes (shown in blue and red). The fireproof floor layer is also shown. To the right is an installation drawing showing the layout of the gray water drain lines, as well as the standard schedule 40 PVC piping and fittings. The “0-slope” gray water system is officially certified in the Netherlands and Germany by European Community-recognized testing and certification agencies, when used in the Matrix Tile. This system has been used in more than 100 dwelling units in the Netherlands and no problems have been reported after 10 years of use. Recognition of this certification is being sought in the United States as an approved alternate to standard practice of sloped gray water drain lines.

CABLESTUD

CABLESTUD is a U.S. patent-pending CLASS-A engineered-plastic construction accessory that facilitates the routing and connection of electrical and low-voltage cables at the bottom of non-loadbearing metal or wood-stud partitions, behind a removable baseboard. The installation, addition or relocation of switches, electrical outlets or data ports becomes child's play. Thanks to CABLESTUD, all wires remain inside the partition but in known locations, and connections are easily accessible.

CABLESTUD is in the market in the Netherlands, Belgium and France under the GYPROC label. GYPROC is a company in the Saint Gobain family of companies. Since metal studs are of different dimensions in different markets, the CABLESTUD products are designed to fit each markets' metal studs. Versions for several metal stud sizes and for wood-stud framing are being introduced in the United States.

Figures 12 and 13: On the left, Cablestuds are used in standard metal studs. The removable baseboard (used on one side of the partition only) is shown removed, revealing the special clips used to attach the baseboard in place. Outlets for low-voltage, power, switches and wall lighting fixtures are installed after the drywall is installed, using standard "rework" boxes. Connections are made behind the removable baseboard, in standard connection boxes or using the MOLEX self-tapping connector product as shown (approved only for use when accessible). Where NM (non-metallic) cables are not permitted, MC (metal clad) cables can be installed. On the right, the CABLESTUD for wood-frame construction is shown. Low-voltage wiring (CAT 6 or fiber optic or cable-TV) is installed in the upper portion of the CABLESTUD, and 110/220 power cables are installed in the lower portion, meeting electrical codes for separation. The current design of the CABLSTUD for the US market has capacity for 6 NM or 3 MC cables passing at each stud. Careful planning is required and where cable density is high, sub-breaker panels (e.g. in the kitchen) may be needed.

CONCLUSIONS

Modular construction is poised for active contribution to the sustainability and flexibility agendas. Long-lasting real estate assets are needed – that means they must be flexible – able to accommodate varying cycles of change and technical improvement. In our dynamic society, where change of use, upgrading of technical systems and change of preferences are normal, decision-making, building design and construction need to enable incremental and dispersed upgrading to buildings. Especially in multi-floor/multi-tenant buildings, entanglement of the MEP systems makes this difficult. Therefore, the OPEN BUILDING principle of separation of SHELL (Base Building) and INFILL (Fit-Out) is the first strategy that needs to be adopted. When this is shown to make sense, then new products such as MATRIX TILE SYSTEM and CABLESTUD will enter the market to make this more agile way of building better. Conversely, these new products offer new solutions that, when applied, will accelerate adoption of OPEN BUILDING as a general strategy.

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SECTION 4:

Sustainability, Renewable Energy, and Life-Cycle

PHRC - 2ND RESIDENTIAL BUILDING DESIGN AND CONSTRUCTION CONFERENCE 2014

LIFE CYCLE ASSESSMENT OF RESIDENTIAL STRUCTURES

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ABSTRACT

Building owners, contractors, architects, engineers, and consumers are demanding more efficient and environmentally friendly residential projects and products. However, credible and transparent information on building materials is currently very limited, hampering the ability of designers to conduct an accurate analysis. Life Cycle Assessments (LCAs) are increasingly being used to evaluate structures and building products for environmental impact and performance.

While LCA is an excellent tool for practitioners to identify environmental impacts, it is not a practical communication device for the design and consumer community. Environmental Product Declarations (EPDs) are starting to appear in the US as the common methodology to report product performance, eliminating the need to wrestle with dozens or more individual sources of a data in the LCA. An EPD is a comprehensive, internationally recognized report that compiles and standardizes technical sustainability information. The US Green Building Council's LEED v4 Rating System and Architecture 2030 Challenge for Products are starting the demand for EPD's.

This paper considers life cycle assessment methodologies for accounting residential structure's environmental impacts, the environmental product declarations that lists the relevant product impacts in a clear, consistent, and concise manner, and the international standards that are increasingly integral to production, marketing, and communication strategies across every industry. Material specifiers and design professionals can use these tools to meet today's carbon-constrained challenges and other environmental goals of residential structures.

Market Transformation

The green-building industry is in the mist of rapid change. Residential design professionals are increasingly interested in characterizing and reducing the environmental impacts of the projects they design. Recycled or bio-based content and travel distances have long been used as proxies for material sustainability. Now, we are starting to understand that these substitutes may not achieve the environmental outcomes we seek and a move towards more performance-based outcomes are starting to appear. A key aspect of moving towards this goal in sustainable design is the use of Life Cycle Assessments (LCAs) and Environmental Product Declarations (EPDs).

Over the past two decades the US Green Building Council has been transforming the marketplace with their Leadership in Energy and Environmental Design (LEED) green-building rating system. Virtually every federal agency as well as over 300 city and local governments instituting green building policies have adopted the voluntary rating system. The newest version LEEDv4, launched at their annual GreenBuild convention in 2013, will dramatically change the way designers and consumers consider building products.

LEED has always encouraged the use of environmentally-friendly products in the Material and Resources (MR) credit category, driving market innovation and rewarding design teams with points towards certification. With LEED v4, design teams that take a life-cycle approach to understanding materials and building products are rewarded. While this overhaul of the MR credits did not specifically get adopted in the LEED-Homes rating system, it sets the stage for residential projects to benefit from material reporting and disclosures that require life cycle-based information in order to get closer to the goal of building with lower total environmental impacts.

Life Cycle Assessments

Life cycle assessment (LCA) is the investigation and evaluation of the environmental impacts of a product, process or service. LCA evaluates all stages of a product's life and considers each stage interdependently, meaning that one operation leads to the next. Inputs to the process may include raw materials and energy. *Life cycle stages* (Figure 1) may include raw material acquisition, manufacturing, building use or operations and, finally, recycling or waste management. The outputs, many of which impact the environment negatively, include atmospheric emissions, waterborne wastes, solid wastes, co-products and other releases.

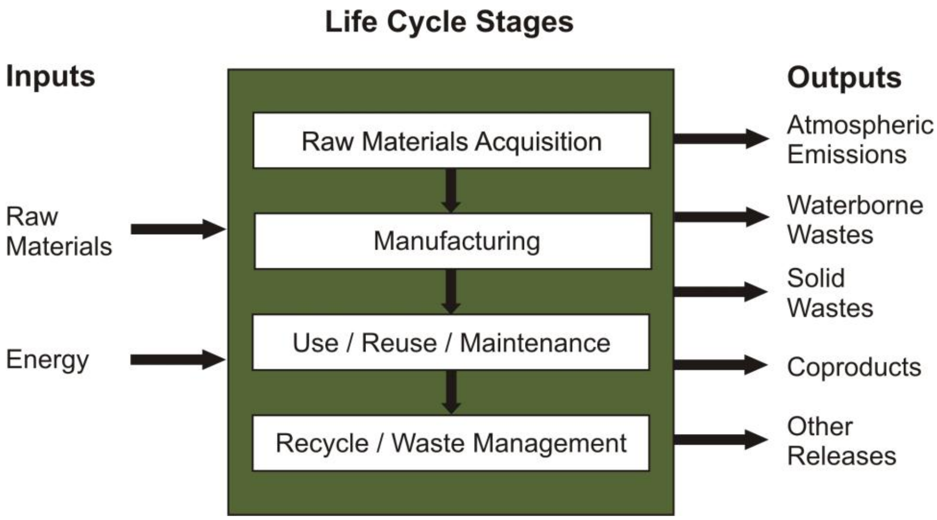

Figure 1. Life Cycle Stages per the ISO 14040 standard

Per the ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) standards, LCA is conducted in four distinct *phases*:

1. *Goal Definition and Scoping* - Define and describe the product, process or activity being analyzed. Identifies the system boundaries.
2. *Inventory Analysis* - Identify and quantify energy, water and materials use and environmental releases. Environmental releases may be solid waste, air emissions and waste water discharges.
3. *Impact Assessment* - Assess the potential human and ecological effects of energy, water and material usage, and the environmental releases identified in the inventory analysis. Environmental impact categories include: ozone depletion, global warming, acidification, eutrophication, photochemical smog, human health issues, ecotoxicity, fossil fuel use, land use, and water use.
4. *Interpretation* - Evaluate the results and select the preferred product or process.

LCA is a more comprehensive way for evaluating the environmental impacts (Figure 2) associated with the entire life cycle of a product, process or building. An LCA of a building, for instance, will tell you how much impact was caused by the building from the point where minerals were mined to the point where the building waste is landfilled. This means the LCA uncovers the whole environmental story and allows the designer to understand the trade-offs that influence design decisions. That way, if a building product has more impacts during manufacture but saves impacts during use, they can see if it is a better environmental choice.

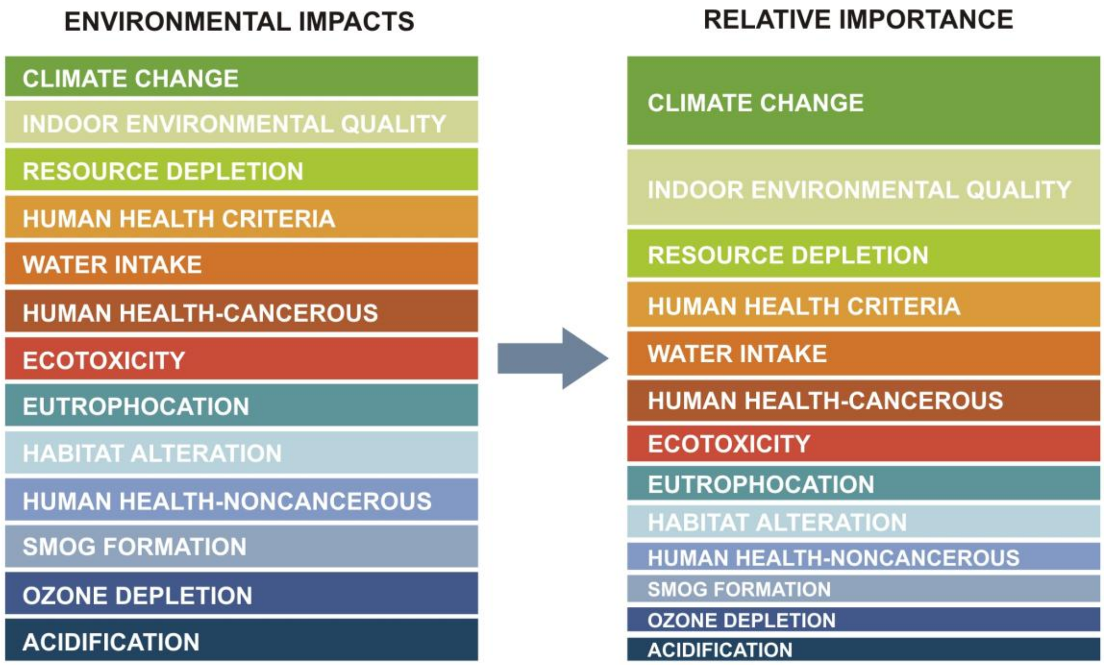

Figure 2. Example of Environmental Impacts and Weighting

For example, the more insulation is added to the house, the less energy you need to heat or cool the building. By adding insulation the designer is adding manufacturing impacts, but the environmental benefits of insulation are so large that the more insulation you add the fewer environmental impacts (specifically carbon as a result of energy use) you get overall, for a net positive environmental outcome. The point is to beware of the past tendency to focus only on single attributes. The essence of LCA is to cast the net wide and capture all of the relevant effects associated with a product or building over its full life cycle.

For residential buildings, the use or operational life cycle stage impacts are significantly greater than those in the other life cycle stages. A home usually operates for decades consuming energy and raw materials with associated environmental releases. This operational stage impacts typically dwarf the environmental impacts from material extraction, manufacturing and end-of-life stages for the building. Although it depends on the type of the residence and the impacts being measured, the operational stage impacts are typically 5 to 20 times larger than stages associated with building product manufacturing and demolition. In fact, operating buildings in the U.S. consumes 19% of the nation's energy and 37% of the nation's electricity. In total, residential buildings account for 21% of the CO_2 emissions in the U.S. (Energy Information Administration 2011) Therefore, when conducting an LCA for buildings, it is extremely important to include the operational stage.

While LCA is simple in concept, designers considering LCA for general use face challenges. Most design professionals will need to rely on LCA practitioners to conduct an assessment on their building project. This can be costly and time consuming. There are also problems with consistency, and availability of data on building products especially in North America where LCA is new to the construction market. Here, environmental product declarations (EPDs) based on the LCA will also be introduced in this latest version of LEED as a communication tool to describe the results of the assessment of products.

Environmental Product Declarations

While a whole building LCA is a preferable methodology to assist designers in understanding the impact of the project, the reality is that it may be too costly and resource-intensive an undertaking for most residential projects. Until a streamlined tool is introduced into the market, it may be best to start with individual manufacturers' information based on the product LCAs. This can be found in an *Environmental Product Declaration* (EPD) which disclose life cycle-based impact information based on data collected during an LCA of material production and use, eliminating the need to wrestle with the unwieldy, background LCA documentation. This information allows customers to compare different products and decide which product has better environmental attributes, giving customers the ability to confidently choose products with low environmental impacts.

Often compared to the nutritional label found on virtually every food product, an EPD lists the relevant environmental impacts of a product or service in a clear, consistent, and concise manner. There is no evaluation or "grading" information since no predetermined environmental performance levels are set. Instead, an EPD builds on well-structured and quantitative data certified by an independent third party. It states factual information and leaves the decision of evaluation to the decision maker. For marketing purposes, EPDs can also be used to show how the impact of production is reduced over time.

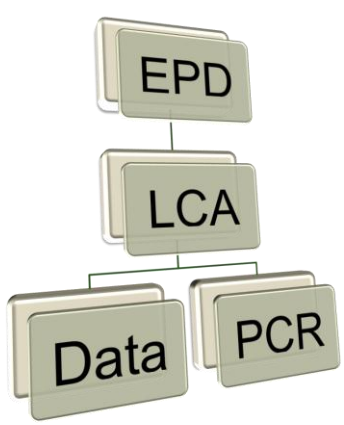

Figure 3. Environmental Product Declarations from LCA

EPDs are developed in accordance with strict international standards that include a transparent verification process for adopting Product Category Rules (PCR) by which

EPDs are developed and verified (Figure 3). EPDs are based on the ISO 14025 (ISO 2010), an international standard with principles and procedures for the development of EPDs and Product Category Rules (PCRs). While EPDs are widely available in Europe, they have only appeared in North America the past few years. For this reason many manufacturers are scrambling to get on board by developing their PCRs and conducting the LCAs to develop their first EPDs. This alphabet soup of new standards and processes will likely cause confusion initially, but as more data become available, the design community only stands to benefit from the increased awareness and disclosure.

LCA Case Studies

LCA is still a relatively new science and can be extremely time consuming and expensive to conduct. Most researchers have only conducted partial LCAs and choose to limit the scope of an LCA by ignoring certain life cycle stages because of the lack of data or scope of research. Others focus on specific impacts to simplify the LCA process. Two examples compared life cycle impacts of insulated concrete form (ICF) and wood-framed residence developed at the CTL Group and the Massachusetts Institute of Technology (MIT) Concrete Sustainability Hub (CSHub) are summarized here.

Case Study 1: Comparison of the Life Cycle Assessments of an Insulating Concrete Form House and a Wood Frame House, *M. Marceau and M. VanGeem, CTL Group, 2008* (Marceau and VanGeem 2008)

In a study conducted in 2008 by Marceau and VanGeem, the researchers compared the results of the environmental attributes of Insulated Concrete Form (ICF) construction (Figure 4) to wood-framed construction. Each house is a two-story single-family building with four bedrooms, 2.7-m (9-ft) ceilings, a two-story foyer and family room, and an attached two-car garage. Each house has 228 square meters (2,450 square feet) of living space. The house was modeled in five cities, representing a range of U.S. climates: Miami, Phoenix, Seattle, Washington (DC), and Chicago. The life of the houses is 100 years. In this study, however, additional environmental impacts were considered instead of solely examining the global warming potential.

The LCA was conducted by first assembling the relevant LCI data from published reports and commercially available databases. The LCA software tool, SimaPro, was used to perform a life cycle impact assessment. Impact assessment is not completely scientific, so three different models were used. The methods chosen are Eco-Indicator 99 (Dutch/Swiss), EDIP/UMIP 97 (Danish), and EPS 2000 (Swedish). The prior version of the report was reviewed by the Technical Research Centre of Finland (VTT, Valtion Teknillinen Tutkimuskeskus) (Häkkinen and Holt 2002).

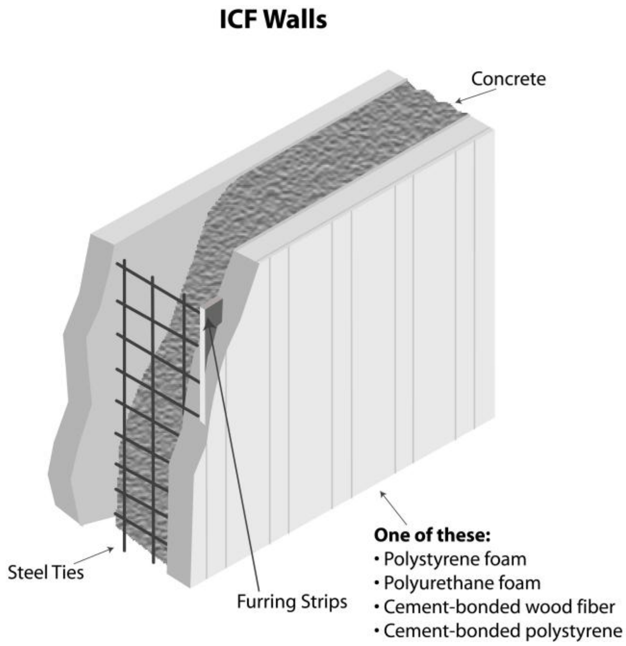

Figure 4. Cross Section of ICF Wall

The data show that in all five methods, for a given climate, the impact indicators in each category are greater for the wood house than for the ICF house. Furthermore, in each of the five methods, the ICF house has a lower single score than the wood frame house in almost all impact categories. The most significant environmental impacts are not from construction materials but from the production of electricity and natural gas and the use of electricity and natural gas in the houses by the occupants. Furthermore, the largest impacts from these uses are in the form of depletion of fossil fuel reserves and release to the air of respiratory inorganics (categorized as damage to human health).

The household use of electricity and natural gas represents 96% of the negative impacts in the ICF house, and 97% of the negative impacts in the wood frame house. The study demonstrated that the energy use is a predictor of LCA results. The ICF house performs better than the wood frame house because of the additional added R-value of the insulation and the thermal mass of the concrete.

Case Study 2: Methods, Impacts, and Opportunities in the Concrete Building Life Cycle, *J. Ochsendorf, et al., Massachusetts Institute of Technology, Concrete Sustainability Hub, Sep 2011* (Ochsendorf et al. 2011)

The general LCA methodology was applied to residential building applications again in 2011 by researchers at the Massachusetts Institute of Technology CSHub. Both Insulated Concrete Form (ICF) construction consisting of concrete walls encased in expanded polystyrene (EPS) insulation and typical light frame wood construction were studied. For all buildings, the roof, partitions and floors are designed in the same manner. Design of the exterior walls and foundations vary between the different buildings. Two types of residential buildings were considered:

1. Two-story, 2400 ft^2 (223 m^2) single-family building.
2. Four-story multi-family apartment building with a total square footage of 33,763 ft^2 (3,137 m^2).

All LCAs were carried out for two different cities in the U.S. to model regional and climatic differences: Chicago, representing a cold climate, and Phoenix, representing a hot, dry climate. The annual operating energy, determined using the EnergyPlus building energy analysis software, was conducted for a 60-year life cycle. Benchmark single-family houses are designed and modeled based on the Building America House Simulation Protocol (BAHSP).

The resulting Global Warming Potential (GWP) was then quantified using CO2 -equivalents (CO2 e) for a number of purposes, including benchmarking emissions for current practices, comparing concrete with wood and understanding the relative importance of different phases of the life cycle. In particular, their work demonstrates that there are measureable differences between various construction materials. The MIT study specifically quantified the carbon emission impact of building systems over its complete life cycle. Information on system boundaries (Figure 5) and processes allocation was clearly outlined and peer reviewed.

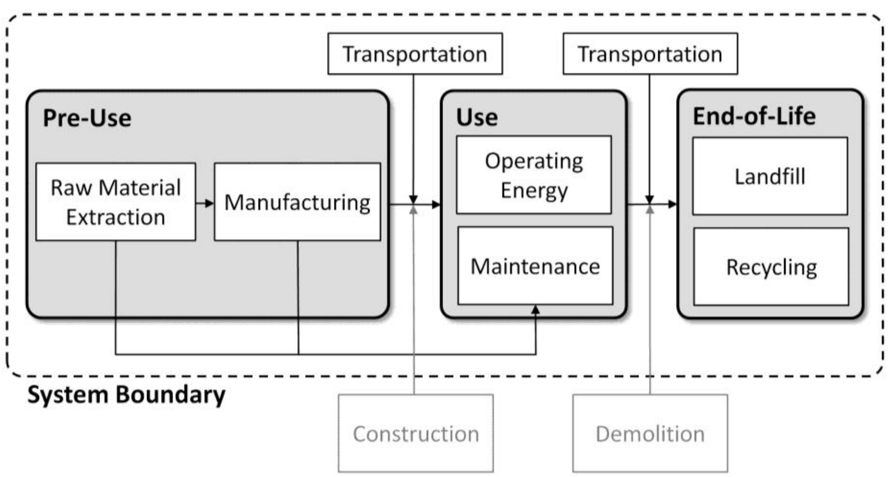

Figure 5. System Boundary Considered

Similar to the earlier study, considering the buildings' entire operational life, the MIT research uncovered concrete's ability to offer a highly resilient structure while providing thermal mass benefits resulting in energy savings. According to the report:

- Concrete homes have a higher embodied GWP in the pre-use phase— but this phase accounts for only about 2-12% of the overall GWP for the life of the home;
- For a cold climate, such as Chicago, the energy savings of an ICF house built

from average to tight levels of air infiltration saves 23% of total operating energy; and

- Over a 60-year life cycle, the lower (5%-8% for single family, 4.4%-6.2% for multifamily) operating GWP outweighs pre-use emissions.

Opportunities to Reduce Life Cycle Impacts of a Concrete Home

The research results demonstrate the benefits of concrete construction over the complete life cycle of a residential structure. There are additional opportunities to reduce the environmental impacts of design teams can take advantage of.

Figure 6. Concrete Components

1. Low Processing Energy- Water, sand, stone, gravel and other ingredients make up about 90% of a concrete mixture by weight (Figure 6). The process of mining sand and gravel, crushing stone, combining the materials in a concrete plant and transporting concrete to the construction site requires very little energy and therefore only emits a relatively small amount of CO_2 into the atmosphere. The amount of CO2 embodied in concrete is primarily a function of the cement content in the mix. Concrete uses between about 7% and 15% cement by mass depending on the performance requirements of the concrete. The average quantity of Portland cement is around 250 kg/m^3 (420 lb/yd^3). This average quantity has consistently decreased with better optimization of concrete mixtures and increased use of supplementary cementitious materials (SCMs) that can improve the strength and durability characteristics of concrete. As a result, approximately 100 to 300 kg of CO2 is embodied in every cubic meter of concrete (170 to 500 lb per yd^3) produced or approximately 5% to 13% of the weight of concrete produced, depending on the mixture proportions, which is relatively low when compared to other building materials (Marceau et al. 2007).

2. Recycled Materials- The U.S. concrete industry uses a significant amount of industrial byproducts such as fly ash, blast furnace slag and silica fume to supplement a portion of the cement used in concrete. These industrial byproducts, which would otherwise end up in landfills, are called supplementary cementitious materials or SCMs for short. The use of SCMs in concrete work in combination with Portland cement to improve strength and durability, in addition to reducing the CO2 embodied in concrete by as much as 70%, with typical values ranging between 15 and 40%. In addition to the use of SCMs in the concrete mix, concrete from demolition can be crushed and recycled as aggregate. Recycled aggregate is often used as backfill and pavement base and is sometimes used for making new concrete. Reinforcing steel in concrete (which often is made from recycled materials) can be recycled and reused (NRMCA 2013).

3. Thermal Mass- Thermal mass is the term used to describe a material that absorbs and stores heat energy. In a building system, it is the mass of the building elements that stores heat during the hottest periods of the day and releases the heat during the cooler evening hours. Concrete is one of several building materials that possess thermal mass properties. In the winter season, high thermal mass concrete walls and floors absorbs radiant heat from the sun and gradually releases it back into the occupied space during the night when the outdoor temperature drops. Concrete is an ideal building material for commercial and residential structures due to its high specific heat, high density and low thermal conductivity.

4. Urban Heat Island Reduction- On warm summer days, the air in urban areas can be 3-4 ºC (6-8 °F) hotter than its surrounding areas. This is called the urban heat island effect (Lawrence Berkeley National Laboratory 2013). The use of light colored pavements, cladding and roofing in urban areas can contribute to overall energy savings and reduced carbon emissions. Because concrete is light in color, it absorbs less heat and reflects more light than dark colored materials, therefore maintaining a relatively low surface temperature. Concrete has been demonstrated to have a positive impact on the localized ambient temperatures and therefore reduce energy required to air condition buildings.

5. Reduced Lighting Requirements- Using concrete for pavements can also help reduce energy demand for lighting. A research study analyzed the lighting required to meet specified luminance for an asphalt and a concrete parking lot. Results indicate that a 250 watt lamp used in a concrete parking lot would produce background luminance equal (or greater) to a 400 watt lamp used in an asphalt parking lot with the same geometric configurations. Therefore, by using a concrete parking surface, energy savings of up to 41% could be realized. With the assumption that an average parking lot lighting system operates up to five hours per day, in one year the asphalt parking lot would consume 60% more energy than the concrete parking lot. In addition, with the increased luminance of a concrete parking lot, the number of light poles can be reduced (Jobanputra 2005).

Conclusion

Life cycle assessment (LCA) is a valuable tool for assessing the environmental impact of buildings. LCA provides a scientific approach to evaluating the merits of design alternatives. The adoption of LCA tools into green building rating systems represents a major step forward in what will likely be an ongoing integration of LCA into the sustainable design process. It is extremely important to include the operational stage of a residential building life cycle since the operational stage impacts dwarf the impacts of material extraction, manufacturing, construction and end-of-life life cycle stages.

Environmental product declarations (EPD) are used to communicate the life cycle based data regarding the environmental profile of products and services, and can be used as a tool in environmental management. The main purpose of EPDs is to provide quantified measure of the environmental impacts of a product or service to professional purchasers, management, government and consumers. Important characteristics of EPDs are objectivity, comparability and validity.

For the few LCAs conducted that compare the environmental impacts of ICF- and wood-framed buildings, it has been demonstrated that concrete buildings can offer energy savings and significant reductions in carbon emissions. Concrete building systems combine insulation with high thermal mass and low air infiltration to make buildings more energy efficient, therefore reducing the environmental impacts of buildings over their entire life cycles. Most importantly, because of concrete’s thermal mass, concrete homes can be extremely energy efficient.

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Value-based Evaluation of the Residential Energy Assessment Process

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ABSTRACT:

Residential energy efficiency improvements represent a significant opportunity to lower national energy demand, reduce energy costs for consumers, and also to create jobs in the construction and manufacturing industry. The U.S Energy Information Administration (EIA) has stated that the residential sector has a significant impact of global energy use and carbon emissions: the residential sector consumed 22% of the total annual energy consumption, even higher than 19% consumption of commercial sector (EIA 2011). Even the use of home energy audits by energy service professionals to create market demand among homeowners to invest in energy efficiency improvements has proven to be challenging, the existing energy audits are not popular, because of the intention of hard sell, bad (and expensive) advices. (Shelton Group energy 2011). The research proposes to present an innovative approach and reclaim this misunderstanding by maximize the value of residential energy auditing processes through alternative approaches to the engagement of homeowners. The National Energy Leadership Corp (NELC) has established an experimental energy assessment program that engages both leadership training and innovative tools in regional community hubs. Through pilot programs at multiple universities, the NELC has demonstrated key value-generating transactions including pre-audit surveys, the assessment of world view and cognitive style, and the use of data collection and report-writing tools. An overview of the research and development of the NELC program, as well as experimental practices of residential energy auditing are provided. The aim of the research is to address shortcomings of traditional residential energy auditing processes while also demonstrating the value and efficiency of proposed improvements that can be experienced by homeowners, community members, and energy service/retail professionals.

Observations from Model-scale Thermal Tests on Heat Exchanger Pile

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Geothermal energy harvested through heat exchanger piles can be used to partially meet the heating and cooling energy demand for residential and commercial buildings. Despite the growing recognition of the benefits of this technology around the world, the complex heat transfer performance of these piles is not yet fully understood. This paper describes a series of thermal tests performed on a model concrete heat exchanger pile installed in a standard F50 Ottawa sand bed. A constant-temperature water bath was used to circulate heat carrier fluid (ethylene glycol and water mixture) through the pile. Thus the experiment closely captures different aspects of real-life heat circulation through geothermal piles. Temperature measurements were obtained at different locations within soil, on pile surface, on the tank boundary, and at the inlet and outlet points of the circulation tube. Recorded temperature data is used to obtain time-dependent heat exchange efficiency of the model pile. Results show the effects of operational and site-specific parameters on energy output from geothermal piles. Data gathered during this study not only provide insight into the physics of complex heat transfer process but also can be used for verifying results from numerical simulations with appropriate boundary conditions.

Review of Different Components of Solar Decathlon House Projects

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Abstract

Reducing fossil fuel consumption and adopting solar energy can mitigate pollution problems and improve living conditions. The required energy to be consumed in a house could be provided by natural resources such as solar and wind energy. Solar houses are good examples of application of solar energy. Studying different components of these houses could lead to better understanding of the performance and application of different materials and methods in construction of even conventional houses, in particular energy efficient design.

In this paper, the past Solar Decathlon Competition projects are reviewed in order to categorize major load-bearing and non-load bearing components. In order to compare and assess the effect of each component, the following criteria as outlined by the solar decathlon competition rules are used: market appeal, affordability, comfort zone performance and energy balance. The components studied in this paper include floor, roof, wall systems, windows and glazing, insulation materials, and structural framing type. Another type of information that is gathered in the study includes available statistical analyses regarding the percentage of different structural framing and insulation types used in the design.

Keywords: Solar Decathlon competition, wall, roof, floor, window, glazing, insulation, structural frame, energy consumption, affordability

1. Introduction

A comfortable living space is one of the primary functions a house should provide. Cooling, heating, and ventilation that often rely on fossil fuel influence the comfort of the residents. Considering that buildings in this country consume one-third of the total energy and two-thirds of total electrical energy [1], it is essential to understand what features can be incorporated in the construction of homes to make them more energy efficient and sustainable. In particular, the use of renewable energy in production of electricity and "cleaner energy" would also benefit urban air quality [2].

Solar Decathlon Competition has been developed by the Department of Energy (DOE) to encourage such movement toward building sustainable houses. This competition was held in 2002 for the first time. Since then, it has occurred every two years in 2005, 2007, 2009, 2011 and 2013. The next competition will be held in 2015. The reports of these competitions have all been published, but the reports of the 2013 competition were not available in open literature at the time of this writing. The goal of this competition has been described to challenge student teams "to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive" [3]. The competition judges choose a team as the winner of the competition "that best blends affordability, consumer appeal, and design excellence with optimal energy production and maximum efficiency" [3].

Over the past few years, this competition has also taken place in Europe and China. The Europe competitions have been held in 2010 and 2012 and hosted by Spain, while and the next one will be held in 2014 in France. The China competition was held for the first time in 2013.

Designing and building solar-powered houses are among the multiple goals of this competition. For instance, on-site generation of energy is one of the most important goals of this competition. Other stated goals of the competition include “Educating students and the public about the money-saving opportunities and environmental benefits of using clean energy products and design solutions”, “Demonstrating to the public the comfort and affordability of homes that combine energy-efficient construction and appliances with renewable energy systems available today”, and “Providing participating students with unique training that prepares them to enter our nation's clean-energy workforce” [3]. The competition houses are first constructed in different locations, normally where schools are. Then they are disassembled, shipped to the competition place, which has always been at the National Mall in Washington D.C., and re-assembled there. The houses have been judged and ranked based on 10 different criteria. Table 1 presents the criteria considered in different years for this competition. Because the results of these contests are being assessed in Washington D.C., most of the teams design their houses for the climate of this location.

Table 1- Different Criteria in Solar Decathlon Competition [3, 13, 14, 15, 16]

2002	2005	2007	2009	2011
Design & Livability	Architecture	Architecture	Architecture	Architecture
Presentation & Simulation	Dwelling	Engineering	Market Viability	Market Appeal
Graphics & Communication	Documentation	Market Viability	Engineering	Engineering
Comfort Zone	Communications	Communications	Lighting Design	Communications
Refrigeration	Comfort Zone	Comfort Zone	Communications	Affordability
Hot Water	Appliances	Appliances	Comfort Zone	Comfort Zone
Energy Balance	Hot Water	Hot Water	Hot Water	Hot Water
Lighting	Lighting	Lighting	Appliances	Appliances
Home Business	Energy Balance	Energy Balance	Home Entertainment	Home Entertainment
Getting Around	Getting Around	Getting Around	Net Metering	Energy Balance

Multiple reports of houses designed by various teams who participated in these competitions contain valuable information about different types of solar houses. These houses generate their energy from solar radiation. The use of photovoltaic (PV) panels or solar water heaters can significantly reduce the electricity required, and if designed appropriately, the electricity supplied by photovoltaic panels can be used to operate the HVAC system too. Apart from solar systems, the structural parts can play an important role in reducing the energy consumption of the house as well. Components such as walls, floors, roofs, windows and insulations in different locations of the house can affect the energy consumption and market appeal of the house. To evaluate different assemblies, the following competition criteria are used: affordability, comfort zone, energy balance and market appeal. These criteria are discussed in section 3 in more details.

2. Components of the solar-powered houses

In order to decrease the energy consumption for heating and cooling of an occupied space in different climate regions, the efficiency and performance of different components of the house should be considered. In particular, walls, roofs, floors and windows are components that can affect the performance of a solar-powered house and are reviewed in this paper. Moreover, the insulation and structural frame types, that can affect the energy consumption and affordability of the house, are studied separately.

2.1 Walls:

Walls can be considered as one of the most crucial components of a sustainable house that can influence the energy consumption and related costs. Different studies have evaluated the performance of new wall systems in comparison with more conventional systems. These studies point out that a substantial amount of the energy used for space heating or cooling is lost through the walls [1,2 and 4].

Generally, the walls used by different teams throughout these years of the competition consist of an insulation core and different layers over the insulation and framing. Figures 1 through 3 illustrate the wall systems used by Darmstadt and Maryland teams in 2007, 2009 and 2011 [14, 15, 16]. These teams ranked first in these years.

The wall assembly of Darmstadt team (Figure 1) in 2007 consists of plexiglas for interior surface of the wall, phase change material (PCM) smart boards and rock wool as a sound insulation. PCM and prefab productions are not among the systems used by other teams in 2007. The wall assembly of Darmstadt team (Figure 2) in 2009 consists of plywood, gypsum board (GB), PCM smart boards and cellulose as a sound insulation. Hardly any other teams in 2009 used PCM, but plywood and gypsum board are common materials in different wall assemblies among other teams in 2009 competition. The wall assembly of Maryland team (Figure 3) in 2011 consists of wood-based products, gypsum board and spray foam as insulation. All of these materials were commonly used by other 2011 competition teams.

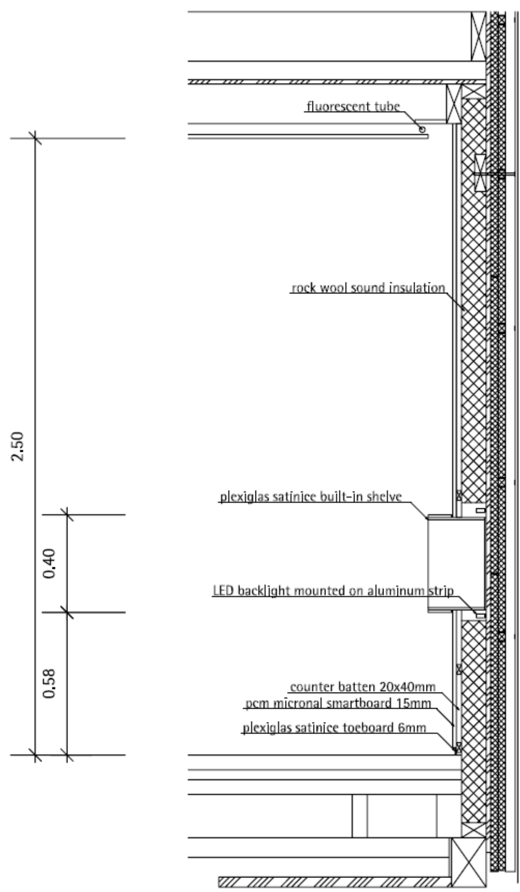


Figure 1- Typical wall section of Technische Universität Darmstadt team, ranked first in 2007 [14]

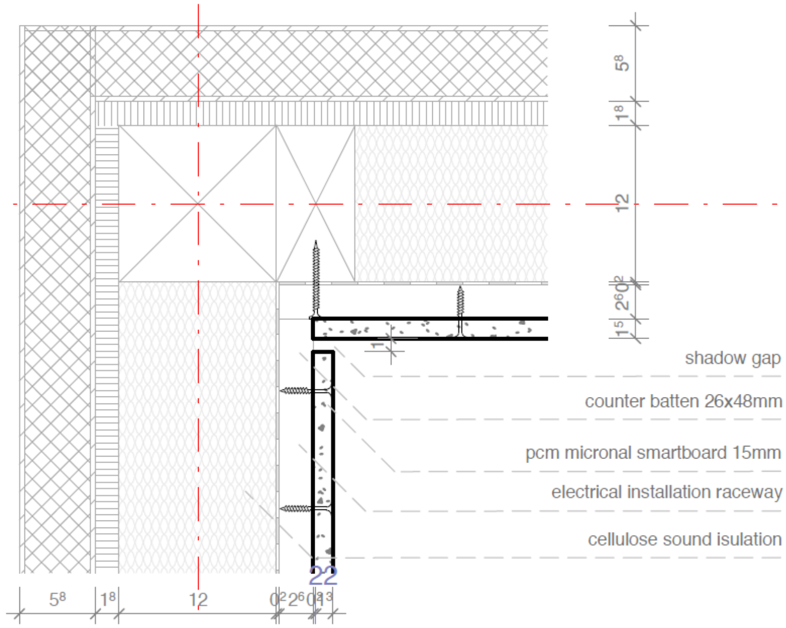


Figure 2- Typical wall section of Technische Universität Darmstadt team, ranked first in 2009 [15]

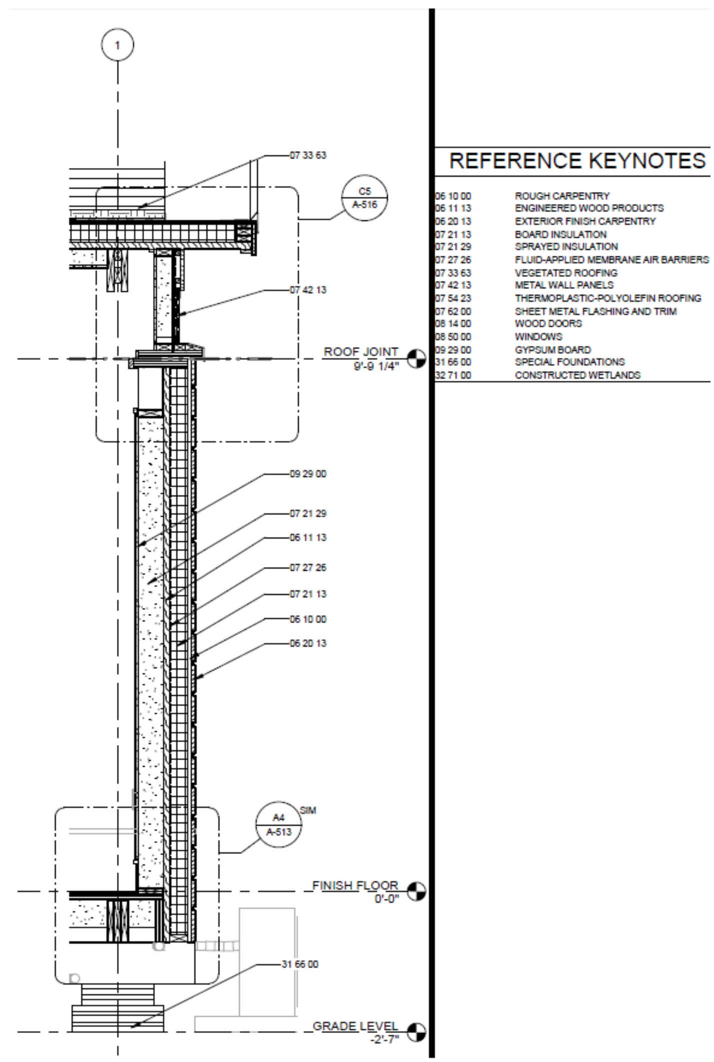


Figure 3- Typical wall section of team Maryland team, ranked first in 2011 [16]

Figures 4 and 5 illustrate different types of insulation and layers of these wall systems among different teams in 2007, 2009 and 2011 [14, 15, 16]. The wall insulation types are categorized into five different groups including: fiberglass batt, blown cellulose, spray foam, extruded polystyrene (XPS) and expanded polystyrene (EPS) as part of SIPs and Other types. Materials used as layers of the wall can be categorized into four groups including: plywood, other wood-based products (including oriented strand board (OSB) and timber board), GB and other materials (including concrete, metal board, fiber reinforced cement and prefab products).

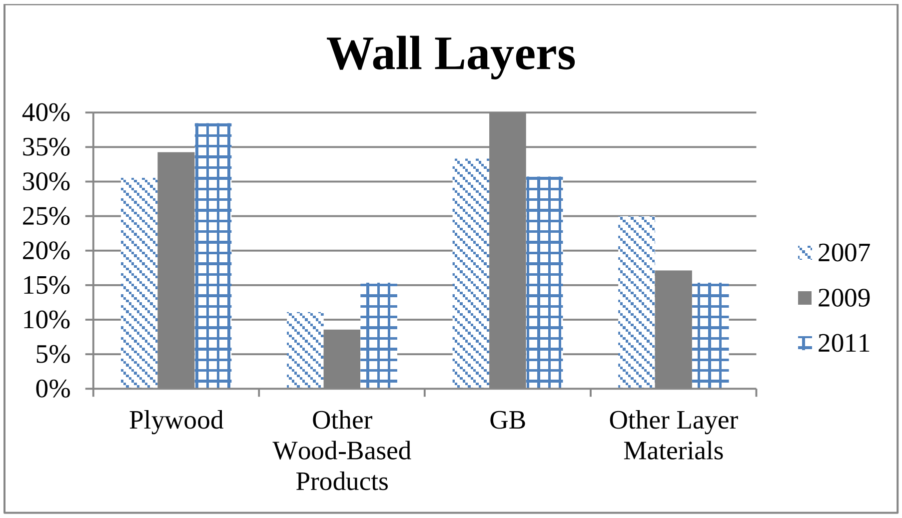


Figure 4 Percentage of different wall layer types used in Solar Decathlon competition

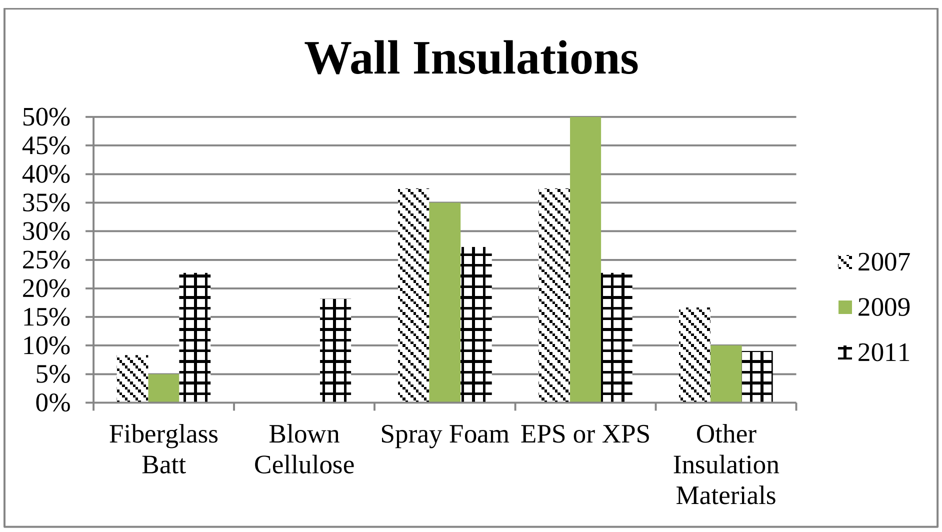


Figure 5 Percentage of different wall insulation types used in Solar Decathlon competition

As it can be observed, the plywood and GB are the most commonly used types of sheathing, respectively for exterior and interior application. Other types of wood-based products include OSB sheathing mainly used for exterior application. It is noted that the percentage of other types of wall materials used by some teams is higher than other wood-based products and that the increase in percentage of plywood has led to decrease in percentage of "other" insulation materials.

Regarding insulation types for wall assemblies, the EPS or XPS were mostly used in 2007 and 2009 as part of SIPs. The next highest used insulation material is spray foam. Other materials, including fiberglass batt, have been used the least in 2007 and 2009. Blown-in cellulose has not been used in these years. In 2011, spray foam was used slightly more than EPS products. Fiberglass and blown-in cellulose are the next highest used types, followed by other products. Generally, it seems that spray foam and rigid foam (e.g., EPS) materials have been found to be more favored by most teams, and they are thought to have better performances for a climate like that of the Washington D.C.

2.2 Roofs:

Same as the wall systems, roof assemblies are of high importance and can influence the energy consumption of the house. Different types of roof assemblies used in previous competition usually consist of an insulation core and different layers over the insulation and framing. Figures 6 through 8 illustrate the roof systems used by the Darmstadt and Maryland teams in 2007, 2009 and 2011 [14, 15, 16]. These teams ranked first in these years.

The roof assembly of Darmstadt team (Figure 6) in 2007 consists of OSB, fiber cement board and vacuum insulation. Both fiber cement board and vacuum insulation were hardly used by other teams in 2007, but OSB seems to be more common among other teams who participated in the 2007 competition. The roof assembly of Darmstadt team (Figure 7) in 2009 consists of OSB as sheathing. Two different types of the insulation used in this assembly are vacuum insulation and EPS. Again, vacuum insulation was rarely used among other teams in 2009, but the wood-based products and EPS insulation material both are common materials among other teams. The roof assembly of Maryland team (Figure 8) in 2011 consists of two different types of the insulation in the assembly: board insulation and spray foam with gypsum sheathing. Both of these materials were used by other teams as well.

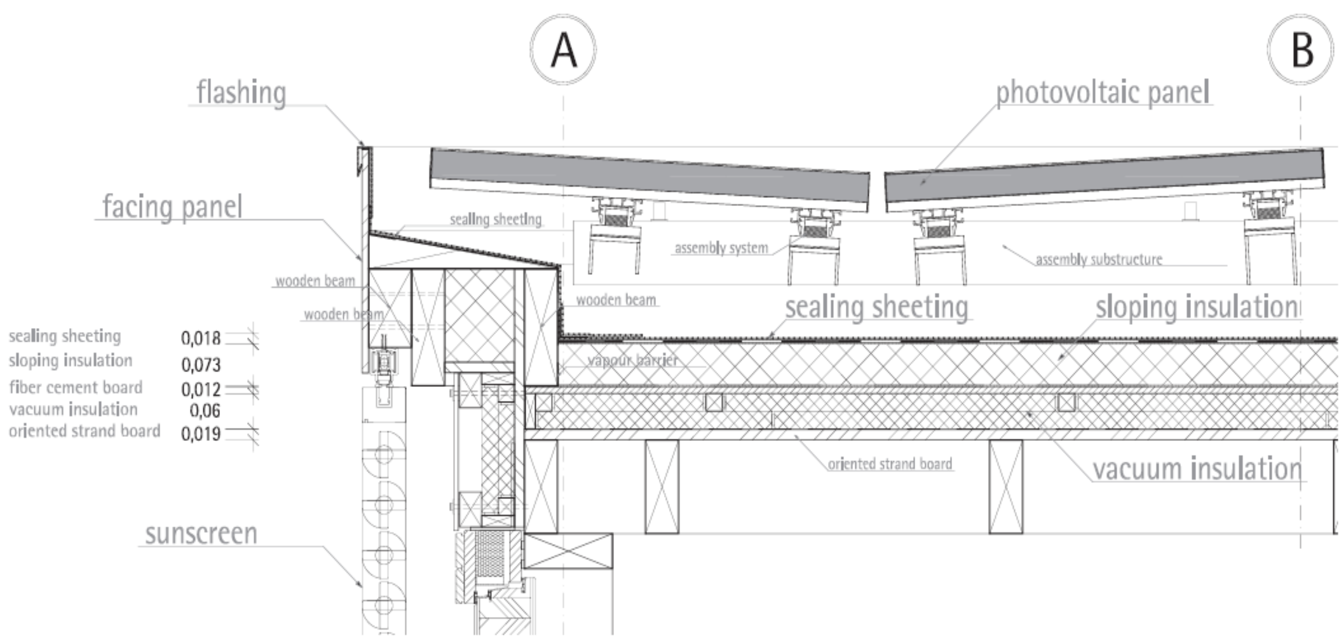


Figure 6- Typical roof section of Technische Universität Darmstadt team, ranked first in 2007 [14]

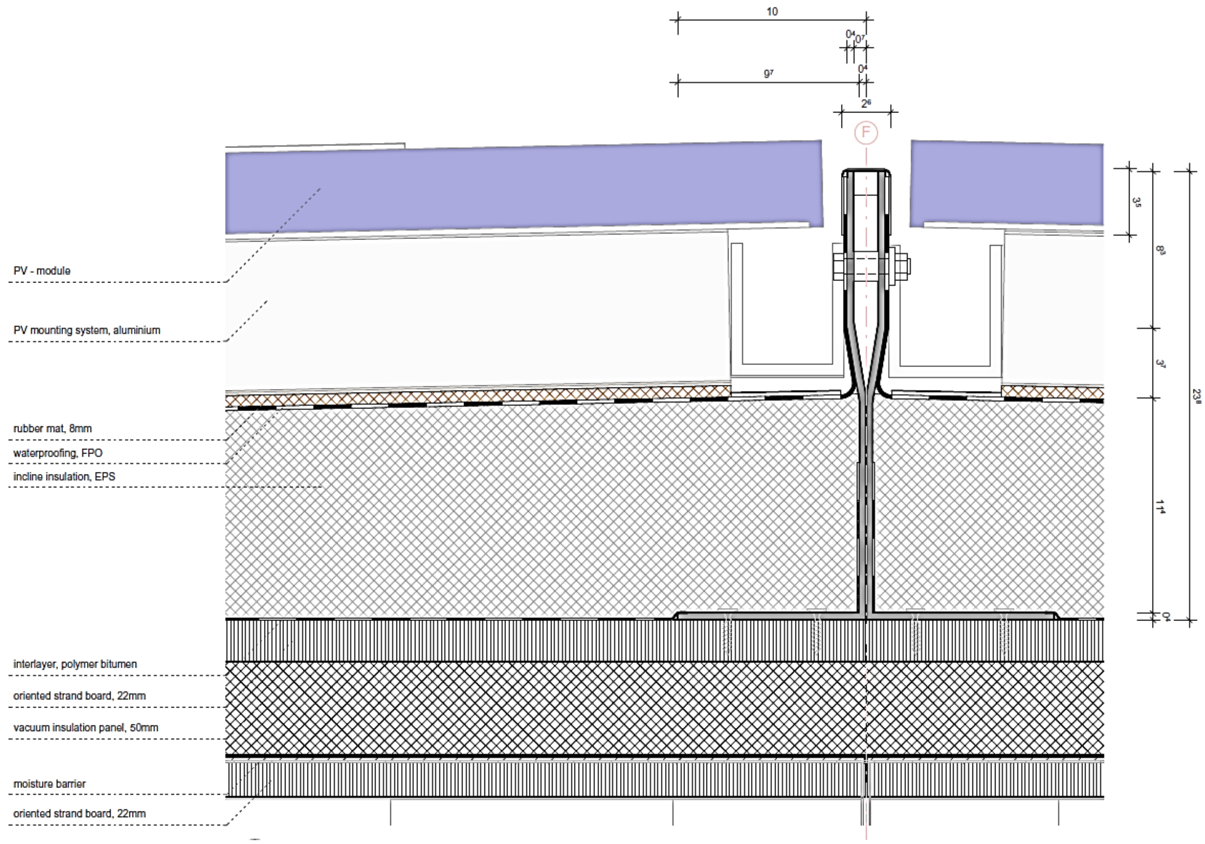


Figure 7- Typical roof section of Technische Universität Darmstadt team, ranked first in 2009 [15]

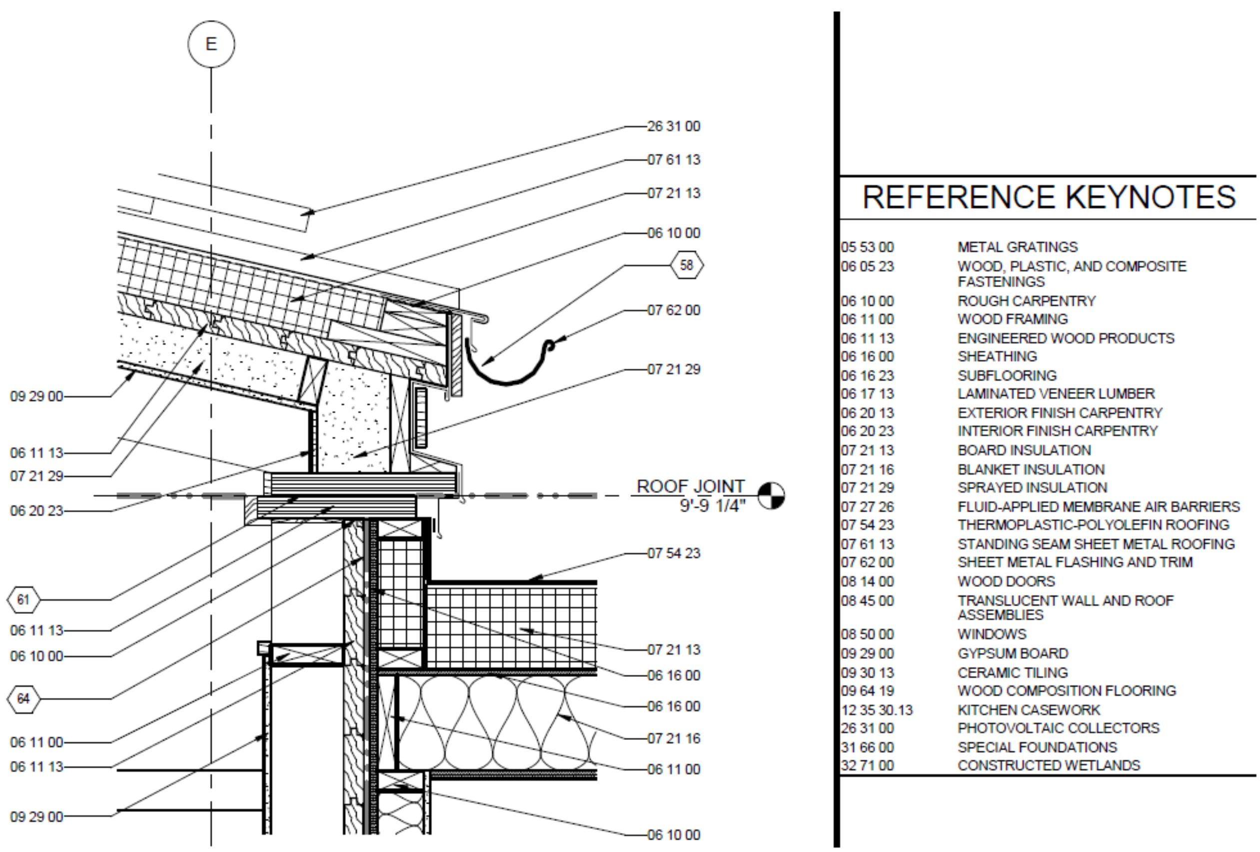


Figure 8- Typical roof section of team Maryland team, ranked first in 2011 [16]

Figures 9 and 10 illustrate different types of insulation and layers of these roof systems among different teams in 2007, 2009 and 2011 [14, 15, 16]. The roof insulation types are categorized into five different groups including: fiberglass batt, blown cellulose, spray foam and XPS or EPS as part of SIPs. Materials used as layers of the roof can be categorized into four groups including: plywood, OSB, GB and other materials (including Vegetated roof, PVC, thermo plastic materials, metal panel, aluminum deck, precast concrete and prefab productions).

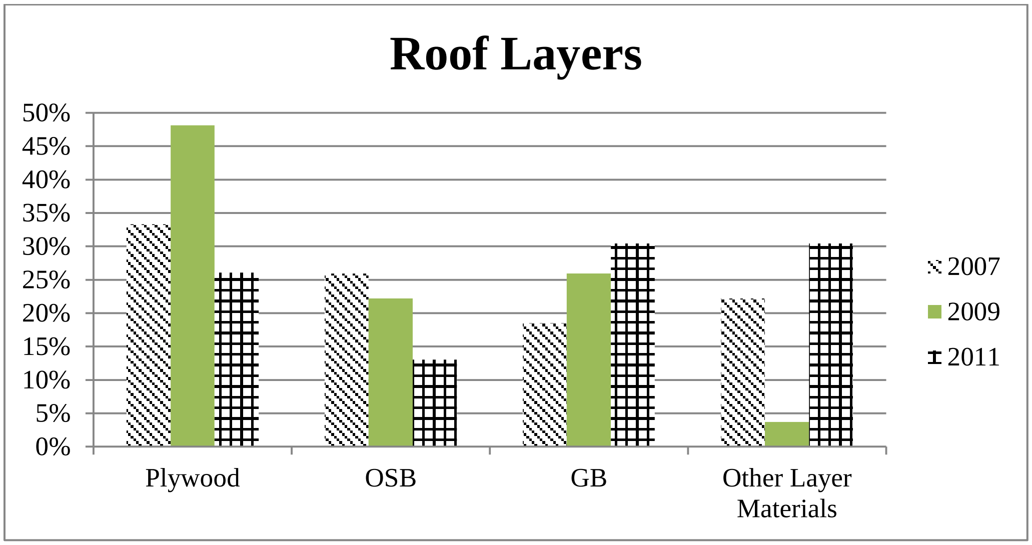


Figure 9- Percentage of different roof layer types used in Solar Decathlon competition

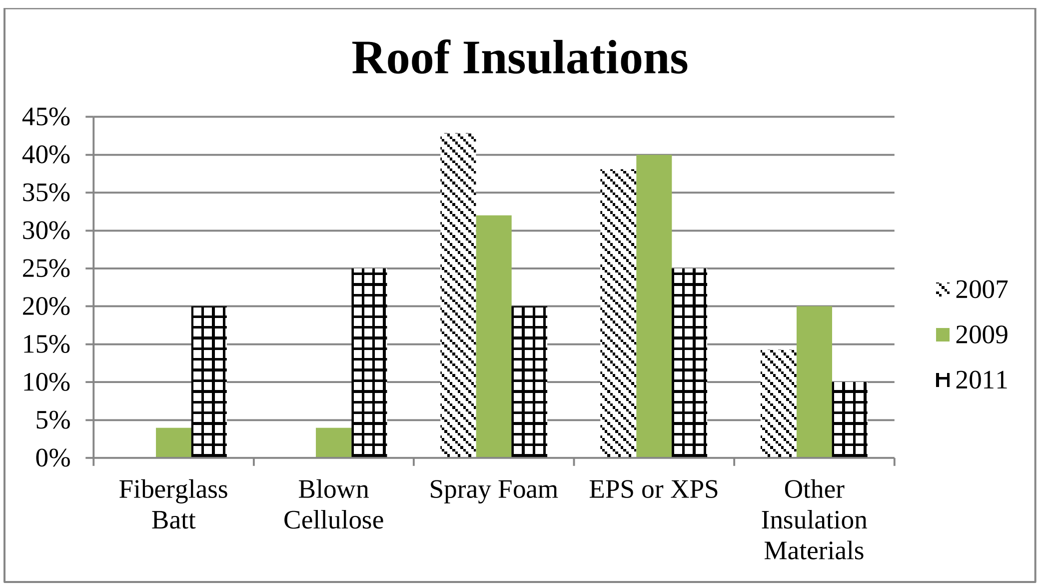


Figure 10- Different roof insulation types used in Solar Decathlon competition

Figure 4 shows that the percentage of GB has increased in these three years of the competition. In 2011, the competition teams preferred to use more innovative roof systems and it led to a decrease in percentage of plywood and an increase in other products in contrast with 2009.

Figure 10 shows that the use of spray foam and EPS products has decreased and the cheaper products like blown-in cellulose and fiberglass batt have been used more. In 2011, all insulation types are approximately used with the same percentages, while in 2007 and 2009; EPS products and spray foam are used more than other materials.

2.3 Floors:

Floor systems are mostly affected by ground temperature and moisture. Both of these factors can affect the durability and energy consumption of the house. In floor systems in contact with ground selecting proper system and materials are of high importance. The flow of heat to the ground from a building and the other way around depends on a complicated thermal process [7, 8]; therefore, learning from the experiences of such a competition can be helpful.

Beside the conventional floor systems used in buildings, in recent years, there has been a renewed interest in heated concrete slab floors to provide for space heating in both residential and commercial buildings [5]. Different types of floors used by competition teams consist of an insulation core and different layers over the insulation and framing. Figures 11 through 13 illustrate the floor systems used by the Darmstadt and Maryland team in 2007, 2009 and 2011 [14, 15, 16].

The floor assembly of Darmstadt team in 2007 (Figure 11) consists of wood-based products sheathing and sandwich panels as insulation. All the materials were commonly also used by other teams in 2007. The floor assembly of Darmstadt team in 2009 (Figure 12) consists of wood and gypsum board as sheathing and styrofoam as insulation. All the materials were also commonly used by other teams in 2009, except for Knauf boards and some insulation materials under the parquets. The floor assembly of Maryland team in 2011 (Figure 13) consists of wood-based products sheathing and spray foam as insulation. All of these materials were also used by other teams.

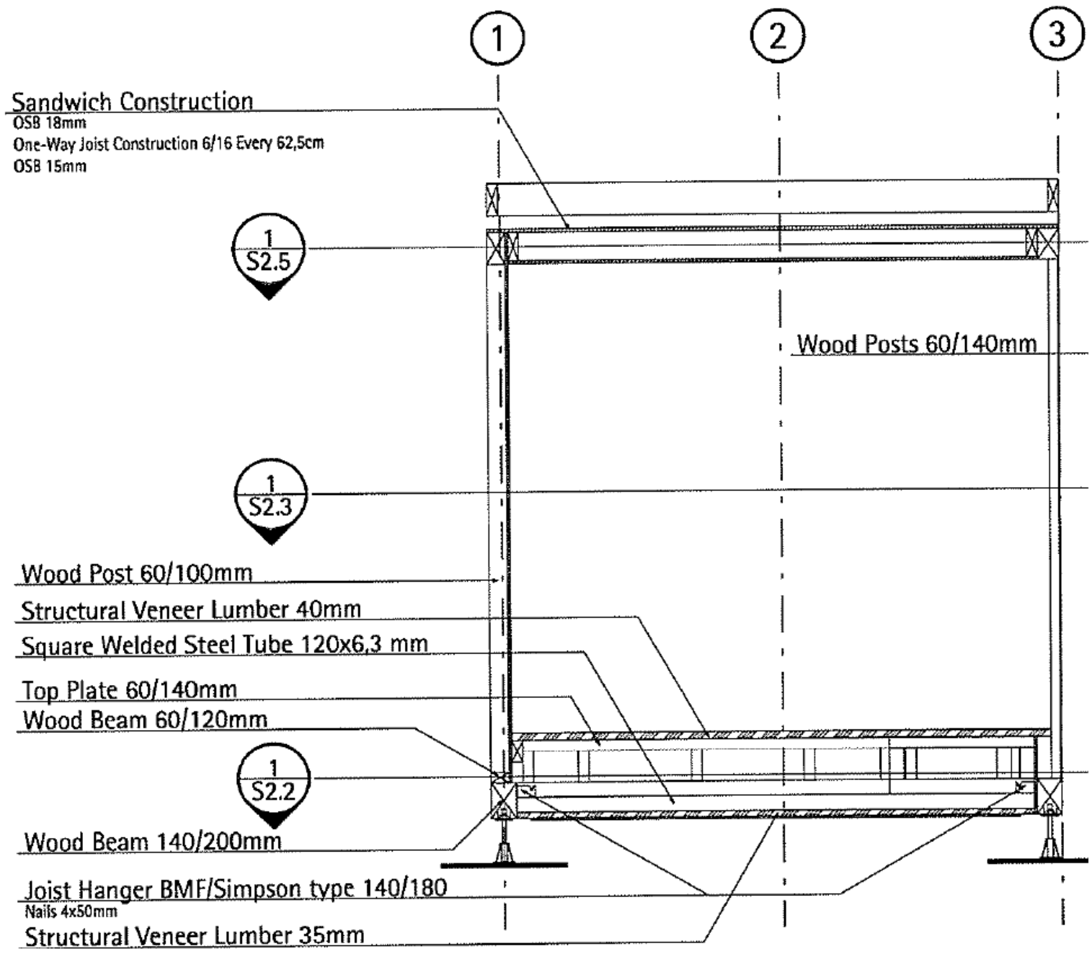


Figure 11- Typical floor section of the Technische Universität Darmstadt team, ranked first in 2007 [14]

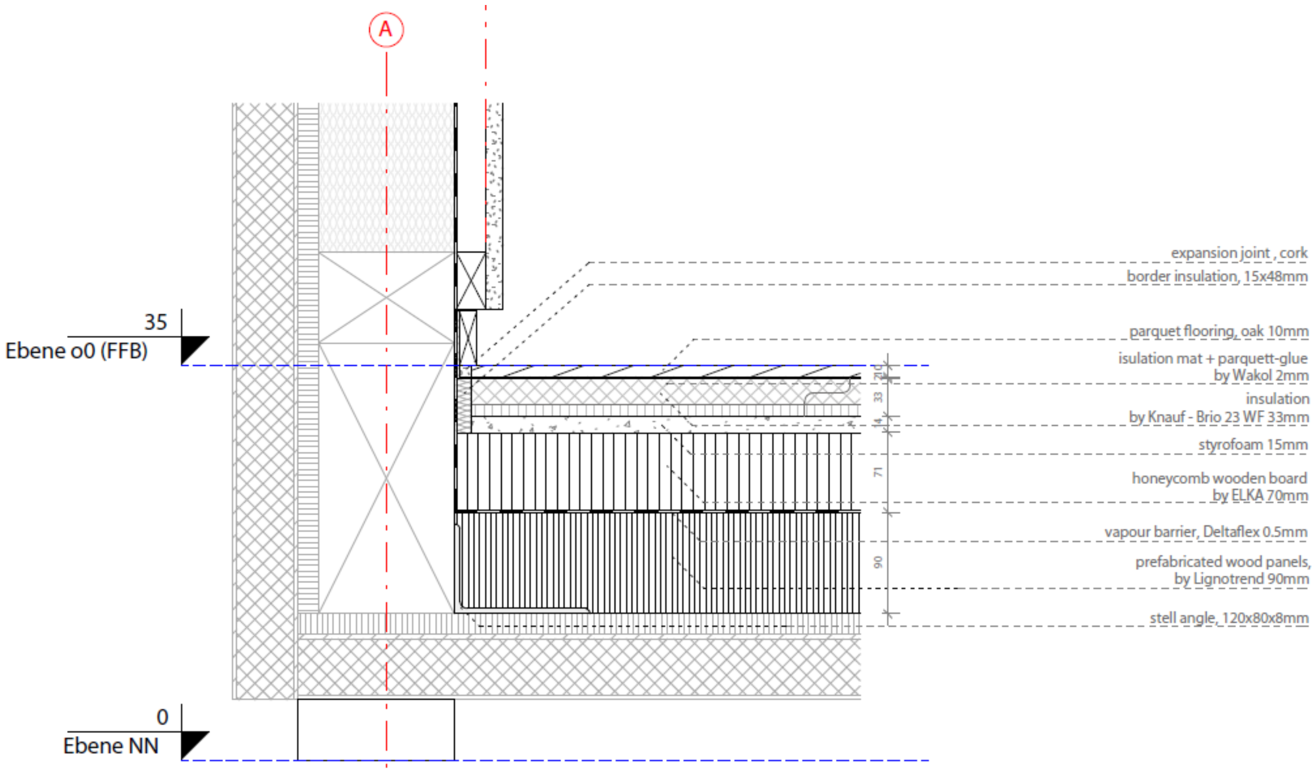


Figure 12- Typical floor section of the Technische Universität Darmstadt team, ranked first in 2009 [15]

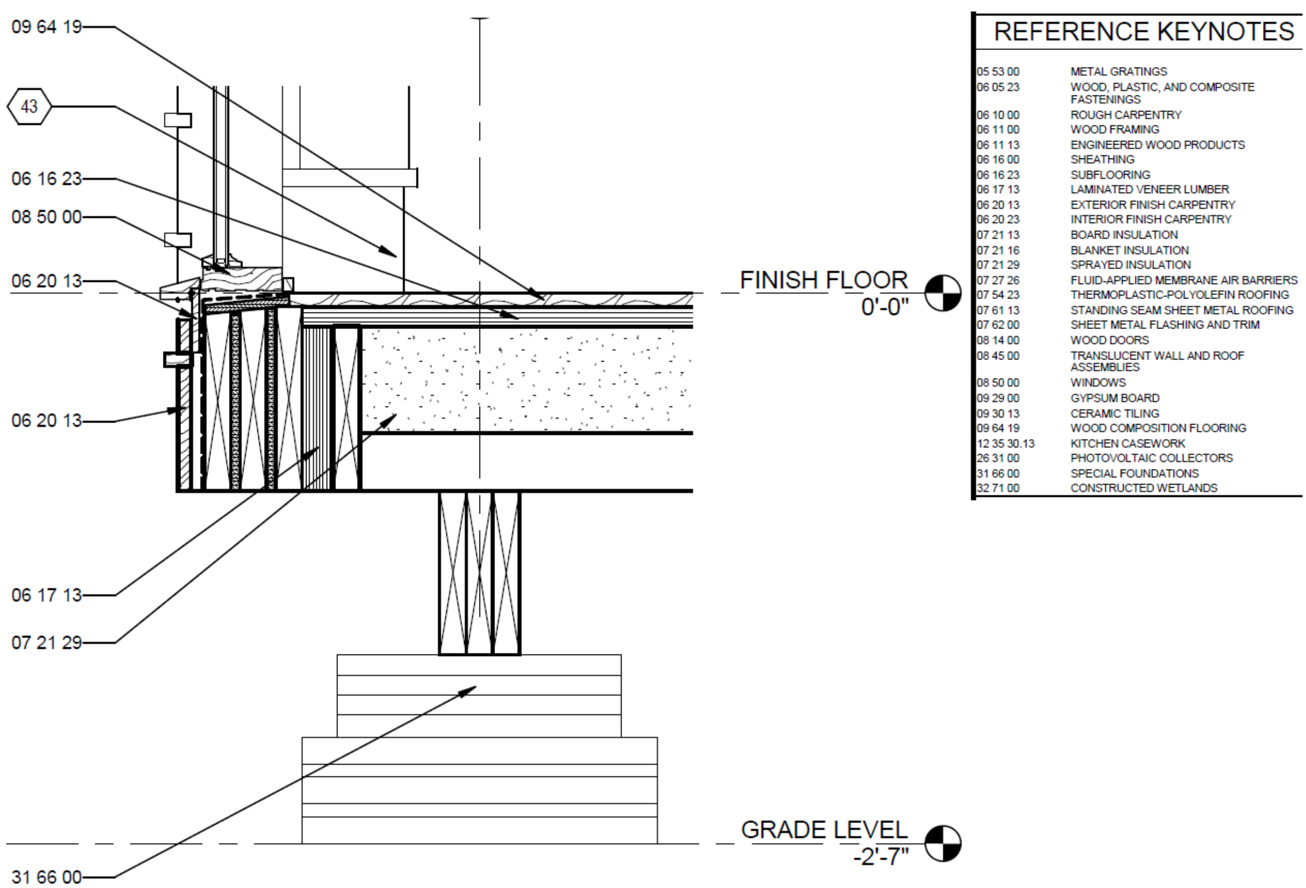


Figure 13- Typical floor section of the Maryland team, ranked first in 2011 [16]

Figures 14 and 15 illustrate different types of insulation and layers of floor systems used by different teams in 2007, 2009 and 2011 [14, 15, 16]. The floor insulation types are categorized into four different groups including: fiberglass batt, blown cellulose, spray foam and XPS or EPS as part of SIPs. Different materials used as layers of the floor can be categorized into three groups including: plywood, other wood-based products (including OSB) and timber board and wood strips) and other materials (including concrete and prefab products).

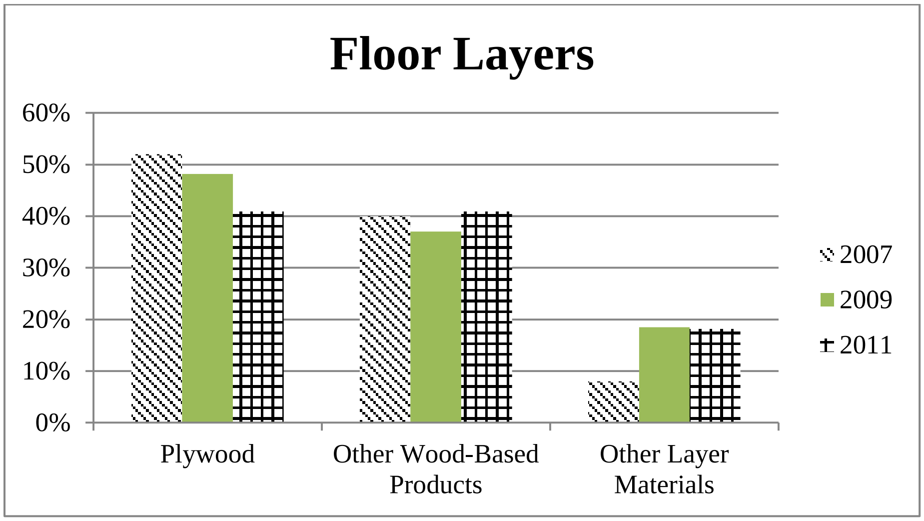


Figure 14- Percentage of different floor layer types used in Solar Decathlon competition

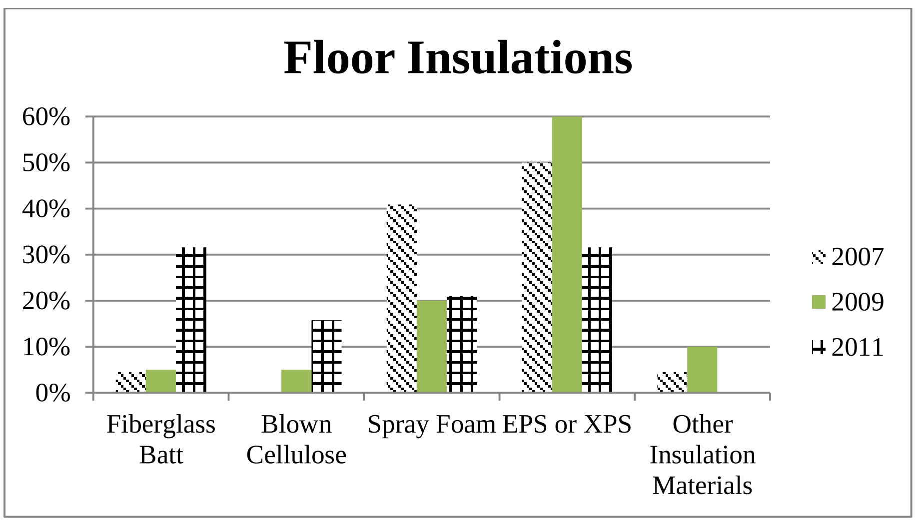


Figure 15- Different floor insulation types used in Solar Decathlon competition

There are no significant changes in the percentage of floor layer types in these three years of the competition. It can be noticed that the team's tendency toward using more innovative or prefab assemblies has increased slightly, and it has led to a decrease in plywood percentage.

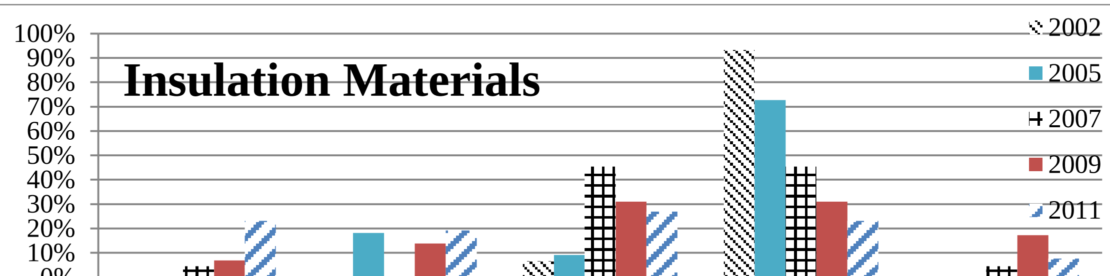
Regarding the floor insulation types, it can be observed that percentage of fiberglass and blown-in insulations has increased, and it has led to a decrease in spray foam and EPS products use. This increase could be due to both cost and energy effects of these insulations. Generally, the EPS products and spray foam are used more than other insulations.

2.4 Insulation materials:

The magnitude of energy savings as a result of using thermal insulation could vary according to the building type, the climatic, as well as the type of the insulating material used [8]. Numerous insulation materials are available in the market, including polyurethane, mineral wool, EPS, XPS and gas insulation panels. There are also new and innovative materials or technologies evolving; examples are vacuum insulation panels, nano insulation materials, aerogels and dynamic insulation materials. Currently, there exist no single insulation materials or solution capable of fulfilling all the requirements with respect to the most crucial properties [9].

There are not enough data available about the insulation types in 2005 reports of the competition. Moreover, in the 2002 competition, most teams used SIPs, which means the insulation material was likely EPS, XPS or polyurethane. Various types of insulations are used in 2007, 2009 and 2011. Figure16 demonstrates the percentage use of different types of insulation [3, 13, 14, 15, 16]. These insulations are used for both heat and sound insulation in wall, floor and roof sections. The insulations are categorized into five different groups including:

1) Fiberglass batt
2) Blown cellulose
3) Spray foam
4) EPS or XPS as part of SIPs
5) Others (including rigid sheets, innovative materials, denim fiber, rock wool and etc.)



	Fiberglass Batt	Blown Cellulose	Spray Foam	EPS or XPS	Other Insulation Materials
2002	0%	0%	7%	93%	0%
2005	0%	18%	9%	73%	0%
2007	5%	0%	45%	45%	5%
2009	7%	14%	31%	31%	17%
2011	23%	19%	27%	23%	8%

Figure 16- Percentage of different insulation material types used by the Solar Decathlon competition teams

2.5 Windows and glazing:

The characteristics of the building envelope can affect interior temperature and humidity among other parameters, which can then affect the occupant's comfort [10]. In particular, because windows have much less insulation than opaque parts of the envelope and are generally transparent, they can affect the mean radiant temperature and normally let solar radiation into the house.

The parameters that can vary and yield different window types include number of the glazing lites or panes, type of the in-fill gases (usually noble gases), and coatings. Furthermore, innovative window systems have been developed that can act like a thermal mass while allowing solar radiation to penetrate through, and also there are windows that incorporate photovoltaic. The studies on photovoltaic integrated windows indicate that solar windows can annually produce about 35% more electric energy per unit cell area compared to a vertical flat photovoltaic module [11, 12].

Teams in Solar Decathlon competition have used different window systems. The features of these glazing systems can be categorized into 7 groups including: tempered double pane, triple pane, low-e argon fill, air fill, krypton fill and insulated glasses. Figure 17 illustrates percentage of different types of features in windows used by different teams in each year [14, 15, 16].

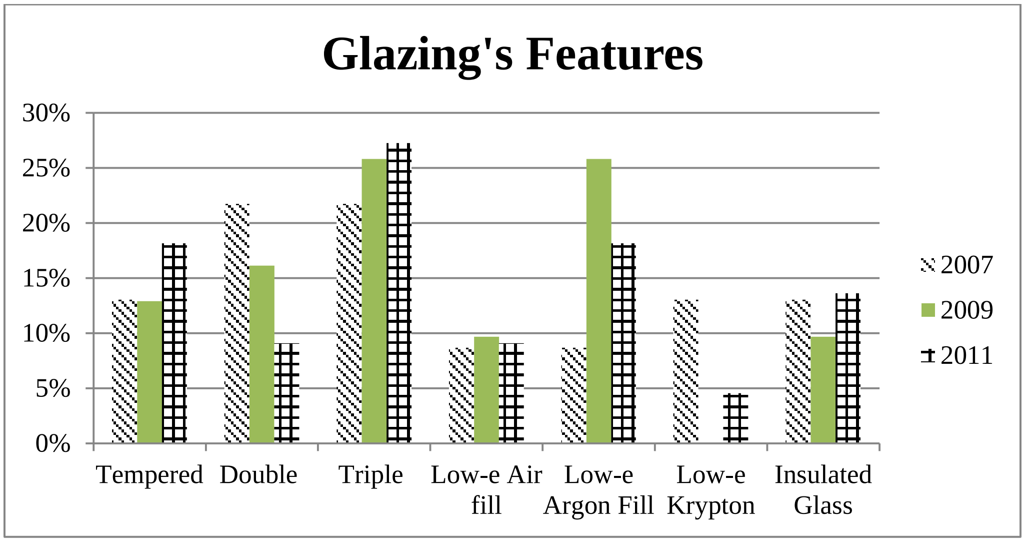


Figure 17- Percentage of different features of glazing used by different teams in 2007, 2009 and 201

Figure 17 shows that the use of percentage of using insulated glass and low-e air-filled glass did not changed significantly for the three competitions. While the use of low-e argon-filled, tempered and triple pane glasses increased. On the other hand the use of low-e krypton-filled and double pane glass decreased.

It seems that the increase in use of triple pane and low-e glass filled with argon could be due to their better performance in cold climate of the Washington D.C. Moreover, tempered glass filled with air has been another option due to its lower cost.

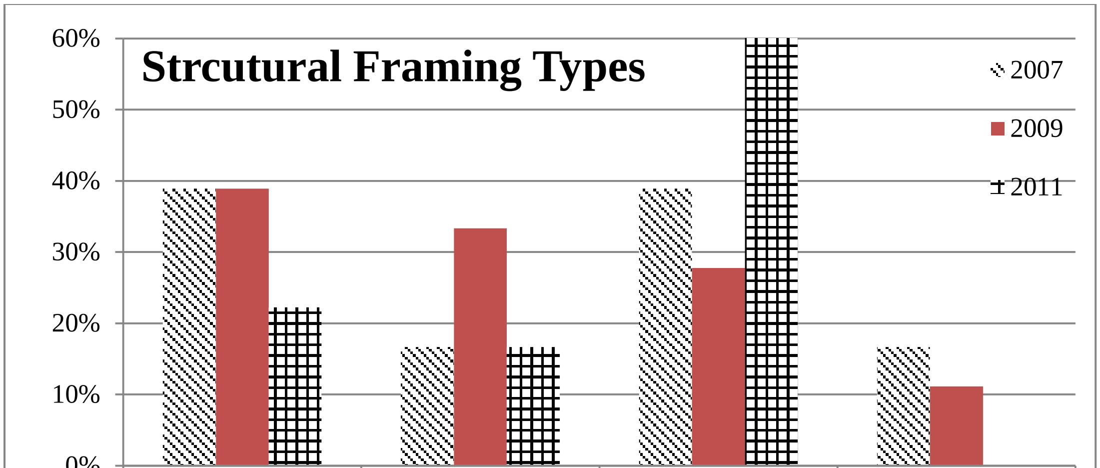
2.6 Structural framing:

Structural framing of the house can affect the properties of the house mainly in three ways. First, it can affect the choice of thermal insulation for the envelope. Second, it can affect directly the initial cost of the house. Finally, the durability properties of the envelope can be influenced directly by the materials and other characteristics of the structural frame.

In 2002 and 2005 competitions, almost all teams used Structural Insulation Panel (SIP) systems, while in 2007, 2008 and 2009 other framing systems have been used. These framing systems could be categorized into four groups including:

1) Whole steel members (including rolled and built-up sections)
2) Whole wood members
3) Combination of wood and steel members
4) Others (including aluminum and composite members)

Figure 18 illustrates the percentage of each structural framing system types used in different years of the competition [14, 15, 16].



	Steel	Wood	Steel & Wood	Other Frame Types
2007	39%	17%	39%	17%
2009	39%	33%	28%	11%
2011	22%	17%	61%	0%

Figure 18- Percentage of different structural framing system types used in Solar Decathlon competition

Generally, the tendency toward using combination of wood and steel in structural frames has increased. But, in most of these frames, the studs are made of wood and some other components made of steel. Wood and composite (wood & steel) structures altogether are found to be more favored types of frames by different teams.

3. Criteria

3.1 Affordability:

This criterion was included to the contests of the competition in 2011 for the first time. The affordability criterion encouraged teams to design and build affordable houses that combined energy-efficient construction and appliances with renewable energy systems. This way, the teams demonstrated how energy-saving features can help consumers save money right away. Professional estimators determined the construction cost of the houses. Teams earned 100 points for achieving a target construction cost of $250,000 or less. A sliding point scale was then applied to houses with estimated construction costs between $250,001 and $600,000. Houses with estimated costs more than $600,000 would receive zero points [3].

Although there are different components and appliances in these houses affecting the final price of the house, it might be useful to see how different wall, roof, floor, window and structural framing systems can affect the affordability of the house, regardless of other components, equipment and appliances.

3.2 Comfort zone:

For the 2011 competition Comfort Zone criterion, teams designed their houses to keep temperature and humidity steady, uniform, and comfortable. Full points were awarded for maintaining narrow temperature and relative humidity ranges during specified periods of time [3].

For full points, the houses had to maintain the following:

- Temperatures between 71$^{\circ F}$ (22.2$^{\circ C}$) and 76$^{\circ F}$ (24.4$^{\circ C}$).
- Relative humidity less than 60%.

3.3 Energy Balance:

For the Solar Decathlon 2011 competition, each team equipped their house 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 the contest week. This was accomplished by balancing production and consumption [3].

3.4 Market appeal:

Teams built their houses for a target market of their choosing. They were then asked to demonstrate the potential of their houses to keep costs affordable within that market. A jury of professionals from the homebuilding industry evaluated how well-suited the houses were for everyday living, determined whether the construction documents would enable a contractor to construct the houses as intended, and assessed whether the houses offered potential homebuyers within the target market a good value. The jury considered the following criteria [3]:

- Livability-Whether the house is well suited for everyday living, could accommodate the specific needs of the targeted homeowners, and offers a safe, functional, convenient, comfortable and enjoyable place to live.
- Buildability-Whether the construction documents would enable a contractor to generate an accurate construction cost estimate and then construct the building as the design team intended it to be built.
- Marketability-The house's curb appeal, interior appeal, and quality craftsmanship; how well its sustainability features and strategies contribute to its marketability; and whether the house offers potential homebuyers within the target market a good value.

4. Review of solar decathlon competition reports

4.1 General data

The format of reports in different years is not the same. Therefore, there is lack of information about some details of house components like window and glazing in reports of 2002 and 2005 competition. As a result, the data from each year is demonstrated separately in Tables 3 through 6.

As it was discussed earlier in section 3, the following four criteria have been used to evaluate the effect of different components on energy balance and affordability: affordability, comfort zone, energy balance and market appeal. These criteria have not been used in every competition. Table 2 demonstrates the year in which each of these criteria has been used. Due to lack of information in the reports of 2002 and 2005 competitions, the data from these years are not reflected in this paper.

Table 2- Use of different criteria in each year of competition [3]

Year	Affordability	Comfort Zone	Energy Balance	Market Appeal
2007		✔	✔	✔
2009		✔		✔
2011	✔	✔	✔	✔

Effects of different components on energy balance and affordability

Table 3 demonstrates top 3 teams in 2007, 2009 and 2011 based on the comfort zone criterion and lists different components use by the teams.

Table 3- Different components of top three teams in 2007, 2009 and 2011 based on comfort zone criterion [14, 15, 16]

Teams	Comfort Zone Ranking	Glass Type	Frame Type	Wall Type	Insulation Type	Roof	Floor
Illinois (2007)	1	insulated glazing	wood	GB-OSB-spray foam	spray foam	OSB-spray foam	bamboo-OSB-spray foam
NYIT (2007)	2	Low-e krypton fill	steel & wood	plywood-GB-spray foam	spray foam	SIP-plywood	SIP-plywood
Texas (2007)	3	double pane low-e	steel	GB-plywood-SIP	EPS	plywood-SIP	warmboard-plywood-SIP
Germany (2009)	1	triple pane	steel & wood	plywood-PCM-GB	vacuum insulation panel	Wood-OSB vacuum panel	OSB-Knauf-styrofoam
Illinois (2009)	2	triple pane	wood	Plywood-GB-Wood-based products	foam in-place	bamboo foam in-place	plywood-bamboo-steel tray-foam in-place
Ontario/BC (2009)	3	-	steel & wood	plywood closed cell polyurethane spray foam-veneer plywood	closed cell polyurethane spray-Mineral wool insulation	EPDM roofing membrane plywood closed cell polyurethane spray	plywood closed cell polyurethane spray-plywood
Ohio State (2011)	1	low-e, tempered triple glazed krypton fill	steel & wood	batt-GB loose fill insulation	fiberglass batt and loose-fill	OSB-GB-batt fibrous cement	batt insulation composite deck plywood
Purdue (2011)	2	-	laminate lumber-plywood	plywood-spray&batt foam-PTFE coated glass polyester	spray&batt foam	plywood-spray&batt	plywood
Maryland (2011)	1	low e argon fill	steel & wood	GB, sprayed foam wood	sprayed foam	thermoplastic polyolefin-sprayed & board foam	sprayed foam board insulation wood-based products

The top three teams in 2007 used insulated glazing, low-e filled with krypton gas and double pane low-e glass to address the comfort zone criterion. In particular, the teams identified triple pane glass and low-e glass filled with a noble gas as most efficient for their application. Most of these teams used spray foam for insulation of opaque walls. Fiber glass batt, EPS and foam-in-place are other types of insulations used.

Almost all wall assemblies used GB and plywood. Other types of wood-based products and SIPs were used too. Moreover, almost all of the roof systems were composed of plywood or other wood-based products. The same is true for the floor systems.

Table 4 demonstrates top teams in 2007 and 2011 based on the energy balance criterion and lists different components used by the teams.

Table 4- Different components of top teams in 2007 and 2011 based on energy balance criterion [14, 15, 16]

Teams	Energy Balance Ranking	Glass Type	Frame Type	Wall Type	Insulation Type	Roof	Floor
Carnegie Mellon (2007)	1	tempered-argon filled	steel	metal panel wood	metal panels	wood-GB-aluminum	wood-GB-aluminum
Cincinnati (2007)	1	krypton filled	steel & wood	plywood spray foam	spray foam	spray foam plywood mdf	spray foam plywood rubber flooring
Darmstadt (2007)	1	three glass panes	steel & wood	PCM smart board, plexiglas batten	rock wool polyurethane foam vacuum insulation	fibrous composite-OSB-vacuum insulation	plywood sandwich panel
Maryland (2007)	1	low-e tempered	steel aluminum	GB, plywood, spray foam	spray foam	spray foam rigid insulation	plywood warm board
Montréal (2007)	1	double and triple pane	steel aluminum	wood soy urethane	soy urethane	wood cladding soy urethane steel deck	wood cladding soy urethane steel deck
Santa Clara (2007)	1	smart window	wood	plywood batt&spray foam	cotton batt-polyurethane spray	plywood polyurethane spray acrylic coating	poly urethane spray
Florida International (2011)	1	-	steel & wood	plywood-metal board-spray foam- batt	sprayed foam-batt	plywood-spray foam -stretched fabric	wood floor-sprayed foam plywood
Illinois (2011)	1	tempered	steel & wood	plywood-rigid foam board GB foam in-place	foam board -foam in place	GB-foam board	prefab panel plywood foam in-place
Maryland (2011)	1	low e argon fill	steel & wood	GB sprayed foam wood	sprayed insulation	thermoplastic polyolefin-sprayed & board foam	sprayed foam board insulation wood-based products
New Zealand (2011)	1	double & triple glazed-air fill	wood steel concrete	plywood-wool batt insulation-timber board	wool batt insulation	plywood-wool batt insulation-timber board	concrete-plywood wool batt wood panel
Purdue (2011)	1	-	wood	plywood-spray & batt foam - PTFE coated glass polyester	spray foam -batt foam insulation-	plywood-spray foam -batt foam insulation-	plywood-wood floor decking
Tennessee (2011)	1	single, triple & quadruple pane-tempered-glazing	steel & wood	plywood-rigid foam-GB foam in-place	batt insulation	plywood-batt insulation-EPDM roofing-rigid	batt-plywood rigid insulation

Six teams ranked first in 2007 and 2011 based on the energy balance criterion. Most of these teams used triple pane, low-e filled with argon or krypton windows. Moreover, spray foam is the most used insulation type among these teams. In wall, roof and floor assemblies, plywood and other wood-based products are mostly used in these teams.

Table 5 demonstrates top 3 teams in 2007, 2009 and 2011 based on the market appeal criterion and lists different components used by teams.

Table 5- Different components of top three teams in 2007, 2009 and 2011 based on market appeal criterion [14, 15, 16]

Teams	Market Appeal Ranking	Glass Type	Frame Type	Wall Type	Insulation Type	Roof	Floor
Illinois (2007)	1	-	wood	GB-OSB sheathing-	honeywell polyurethane foam	reflective acrylic coating - spray foam-OSB	bamboo flooring-spray foam -OSB sheathing
Maryland (2007)	2	low e - tempered	aluminum wood	GB - corrugated metal-cypress-plywood	spray foam	spray foam insulation-rigid-polycarbonate skylight	plywood-cypress decking
Puerto Rico (2007)	3	double insulated - tempered	structural fiberglass column&wood	GB - GRC panel	SIP, rigid insulation	treated plywood sheet	SIP-plywood-radiant heating board-ash wood
Univ. of Louisiana (2009)	1	-	steel	SIP-GB-perforated aluminum - plywood	soy based spray foam	SIP	SIP
Rice (2009)	2	-	aluminum wood	corrugated metal-cdx plywood	icynene (open-cell spray)	plywood sheathing-icynene -gypsum board	plywood sheathing-icynene -gypsum board
Team California (2009)	3	-	steel & wood	plywood-thermablock-demilec spray insulation-plywood	soy based spray	plywood-bamboo -demilec spray insulation-ecorock plate	warmboard-glass mineral wool-cotton wood-soy based
Middlebury College (2011)	1	argon-filled safety glass	steel & wood	GB and wallboard-plywood-cellulose	cellulose insulation	cellulose-metal panel--zip system panel	-
Maryland (2011)	2	low e argon fill	steel & wood	GB-sprayed-wood-based products-air barrier	sprayed foam	thermoplastic polyolefin roofing-sprayed	sprayed foam-wood-based products
New Zealand (2011)	3	triple glazed-air filled, double	wood-steel-concrete	plywood-wool batt -timber board	wool batt	plywood-wool batt -timber board	concrete-plywood-wool batt -cedar

For market appeal criterion, most of top teams in 2007, 2009 and used wood in their structural framing accompanied by other materials like steel or aluminum. The same as the other houses in previous rankings, the spray foam insulation is the most used one. EPS products, cellulose and wool batt are other types used. GB and plywood are mostly used in wall assemblies in these houses. In roof systems, the plywood is mostly used as sheathing but there are some other materials like reflective acrylic coatings or thermoplastic polyolefin roofs as well. In floor assemblies, plywood is the mostly used type and in one case, concrete slab is used as well.

Table 6 demonstrates top three teams in 2011 based on the affordability criterion and lists different components used by the teams.

Table 6- Different components of top teams in 2011 based on affordability criterion [16]

Teams	Affordability Ranking	Glass Type	Frame Type	Wall	Insulation Type	Floor	Roof
Team Belgium (2011)	1	-	steel	mineral fiber cement- SIP	foam board	wood foam board	plywood foam board
Parsons NS Stevens (2011)	1	tempered –high performance-low e, argon blend filled insulating glass	wood	OSB-GB blown-in	blown-in cellulose-polyisocyanurate insulation board	-	polyvinyl chloride roofing-high density polyisocyanurate board-OSB blown-in insulation
Purdue (2011)	2	-	wood	plywood spray foam-batt	spray foam and batt	wood-plywood spray foam-batt	plywood spray foam-batt

Affordability is mainly related to the cost of the materials and systems used in the envelope. The top three teams in 2011 mostly used wood framings with the exception that the first team used steel framing. Insulation types are diverse. Spray foam, batt, blown-in cellulose and foam board are among the insulations used by these teams. In wall assemblies, again there are variety of materials like OSB, GB, fiber reinforced cement board and plywood. Wood materials are used in floor and roof systems in these top teams based on affordability criterion.

5. Summary and conclusions

In this paper, different components of the houses designed for the Solar Decathlon Competition were reviewed including insulation, structural framing, window types, and wall, roof and floor assemblies. The effect of these components on affordability, energy consumption and living comfort was assessed based on the criteria used in this competition. Four major criteria considered in this paper are affordability, comfort zone, energy balance and market appeal. Generally, based on the provided information it can be observed that:

1) Gypsum board (GB) and plywood are the most commonly used types of sheathing for wall, roof and floor.
2) Sheathing in different assemblies is not diverse enough to be able to judge their effects on each criterion, and most of the teams used approximately the same types of sheathing. Therefore, it is appropriate to also study the properties of other systems such as mechanical and electrical systems.
3) According to the considered criteria, the spray foam has been identified to have the best performance. But, based on affordability criterion, the houses that have used other types of insulation like fiberglass batt, foam board and blown-in cellulose are higher ranked because spray foam is more expensive than other insulation materials.
4) In comparison with 2002 and 2005 designs where EPS products were often used, spray foam percentage use increased significantly in more recent competitions.
5) In 2007 and 2009, the EPS products and spray foam are mostly used in wall, floor and roof assemblies. In 2011, the EPS productions and spray foam percentage use has decreased and other types of insulation like fiberglass batt and blown-in cellulose are used more than before. This might be because of team’s tendency toward decreasing the costs.

6) Triple pane, tempered, low-e argon filled and insulated glasses are used by most teams. It seems that these features lead to better performance for window systems compared with double pane glass in climate zone of Washington D.C.
7) Generally, wooden structural framings have been shown to be more favored by the teams. However, the combination of wood and steel framings is also highly favored. Other framing types like concrete and aluminum are least favored.

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SECTION 5:

Disaster, Resilience, and Health

PHRC - 2ND RESIDENTIAL BUILDING DESIGN AND CONSTRUCTION CONFERENCE 2014

POLICIES TO ENHANCE RESILIENT COMMUNITIES

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Conference Topic: Performance of Buildings under Natural Disasters

ABSTRACT

Natural disasters are physically, socially, and psychologically devastating to a community. It can be extremely difficult to rebuild and restore the lives of residents after the destructive event. Moreover, leading scientists now believe our vulnerability will increase due to climate change. Building resiliency, while reducing future greenhouse gas emissions, is a necessary and complementary strategy for dealing with the accelerated rate of adverse events.

Where do organizations and governments begin to help its constituents? FEMA, USGS, NOAA, EPA, NIBS and IBHS all offer solutions for disaster preparedness with a myriad of processes or protocols in place for dealing with the unthinkable. What is missing however is the development of specific policies to advance the security and disaster risk reduction of our infrastructure.

Resilient infrastructure policies move the community from reactive approaches to a proactive stance where stakeholders actively engage in reducing many of the broad societal and economic burdens that disasters can cause. Investing in resiliency, from strengthening building codes to restoring natural ecosystems, can be surprisingly cost-effective, greatly reducing the impact of natural hazards. Policies affecting building practices can also be instrumental in increasing economic investment in making the socio-economic dimension of our society resilient and climate proof.

This paper describes strategies that bring together the tools and activities from many different sectors in an effort to address resilience including:

1. Leveraging green-building momentum to include resilience.
2. Development of ordinances and mandatory building codes.
3. Addressing durability with lifecycle costs and ongoing maintenance.
4. Increasing and improving infrastructure investment from all stakeholders.

By spreading awareness of the resilient options available to help hazard-risk communities to prepare, policy makers can catalyze the building of efficient, livable communities that are healthier and stronger right now.

POLICIES TO ENHANCE RESILIENT COMMUNITIES

Introduction

For millions of people in the United States, the consequences of natural disasters have become increasingly real, personal and devastating. In 2012, there have been 11 natural disasters costing $1 billion or more in damage, making 2012 the second highest year with billion-dollar disasters (NOAA 2011). Early season tornadoes, the widespread and intense drought that covered at least 60 percent of the contiguous U.S. and Hurricane Sandy are expected to go down in history as the most costly weather-related disasters in U.S. history. Now, with the world's attention on the Philippines after Typhoon Haiyan, communities in the United States are rethinking the way we build to meet the challenge of the next natural or man-made disaster.

Globally, insurers lost at least $108 billion on disasters in 2011 and $77 billion in 2012 (Masters 2011). Reinsurer Swiss Re Ltd. said that 2011 was the second-worst year in the insurance industry's history. Only 2005, with Hurricane Katrina and other major storms, were more costly (Swiss Re 2013). However, most of the increased disaster losses cannot be attributed to an increased occurrence of hazards but with changes in population migration and wealth. Frequency of major US hurricane landfalls has remained constant (Figure 1) in the last 60 years (Weinkle et al. 2012), and the trend of strong to violent tornadoes (F3+) has, in fact, decreased (Figure 2) since 1954 (NOAA 2013b). So what cause is attributed to the increase in losses?

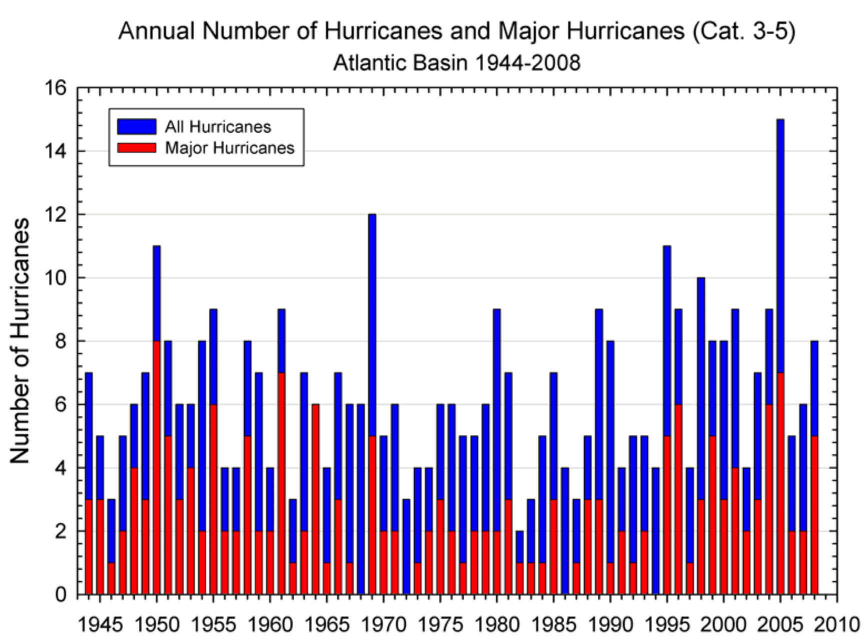

Figure 1. Frequency of Major Hurricanes (NOAA, 2013)

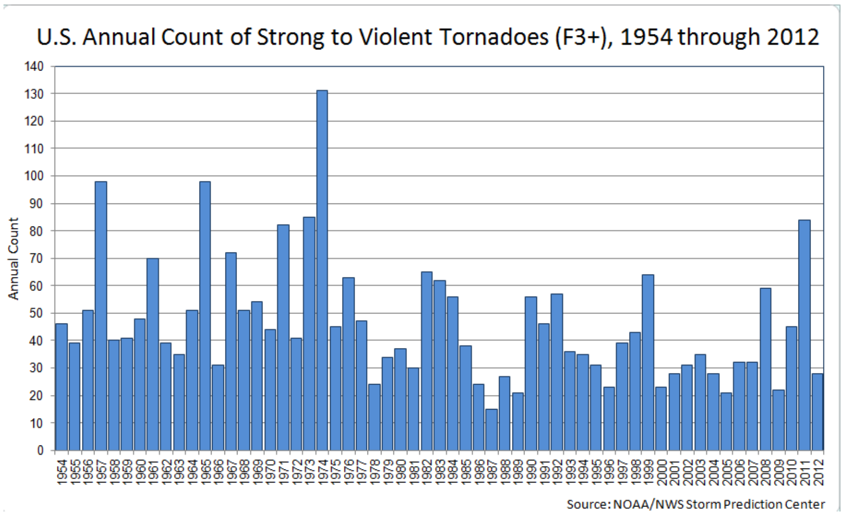

Figure 2. Frequency of US Violent Tornadoes (NOAA, 2013)

In the last several decades, population in the United States has increased and migrated toward the coasts, concentrating along the earthquake-prone Pacific coast and the hurricane-prone Atlantic and Gulf coasts. Over 60% of the U.S. population lives within 50 miles of one of its coasts (including the Great Lakes) (CRSR 1997). At the same time, wealth and the value of their possessions have increased substantially. For example, while California's Los Angeles County accounts for only 2.5% and Florida's Dale County account for only 14% of their respective states land area, yet they contain 30% of their state's property value (Guin and Saxena 2002). These changes in concentration of population and property values are significant contributors to the increased property losses from natural hazards. Moreover, many elements of our aged infrastructure are highly vulnerable to breakdowns that can be triggered by relatively minor events (Masters 2011).

Disasters result not as much from the destructive agent itself but from the way in which communities are (or are not) prepared. Disasters happen when the natural systems are encroached upon by human development. There is no such thing as a natural disaster. The extent of disruption caused by a disaster is greatly influenced by the degree to which society chooses to be fortified for the event. It's well established that the poorest people in our communities suffer disproportionately. Lives, assets, products and crops are lost; livelihoods are cut off; economic growth is curtailed or sent into reverse.

It is apparent that there needs to be significant shift in how we address natural disasters, moving away from the traditional focus on response and recovery toward emphasis on resiliency, that is, preventive actions to reduce the effects of a natural hazard.

Resilience Is The New Sustainability

Resilience can be understood as the capacity to anticipate and minimize potential destructive forces through adaptation or resistance. Basically addressing changes in the environment requires actions to mitigate their negative effects. If we identify resiliency, not solely as a state of preparedness for disaster, but as a desired characteristic of a sustainable society, one that is more in control of its energy and food production, access to water supplies, as well as being one that enables local social capital, we can begin to see the relationship to sustainability. The term 'sustainability' usually describes some aspect of maintaining our resources from the environment to the quality of life, over time. It can also refer to the ability to tolerate—and overcome—degradation of natural environmental services, diminished productivity and reduced quality of life inflicted by human's relationships to the planet and each other.

Critical infrastructures and other essential services have enabled societies to thrive and grow and become increasingly interconnected and interdependent from the local to global levels. As a society, we have placed a great deal of emphasis on recycling rates and carbon footprints. It is ironic that we are surprisingly willing to invest considerable amounts of upfront capital for a LEED (Leadership in Energy and Environmental Design) (USGBC 2013) Platinum certified building to achieve a mere 14% energy efficiency, yet we are completely satisfied if the structure meets only the code minimum requirements for seismic or wind load.

Change is coming. The California Green Building Code (California Building Standards Commission), the ASHRAE 189.1 Standard (ASHRAE), and the ICC700 (National Green Building Standard) (NAHB) all cite life-cycle assessment (LCA) as a means to promote sustainable building practices. The latest version of the LEED rating system developed by the U.S. Green Building Council (USGBC) introduces special emphasis on regionalization and LCA criteria, but does not recognize disaster resilience as one of its standard criteria. The building service life plan (BSLP) elective by the International Green Construction Code (IGCC) (ICC) gives credit to proposed projects designed to have a 100 year or 200 year life span as approved by the jurisdictions.

This is a good start as building service life is rarely considered but is critical to any analysis of long-term sustainability. Balancing long term development plans with the ability to adapt to the needs of a rapidly evolving society is vital to the ultimate success of a building life plan. But for green building standards to truly address sustainable construction, they will have to address the concept of disaster resilience.

Planners should consider the building's potential for future use and re-use as well as long service life with low maintenance costs. In addition, a sustainable building should be designed to sustain minimal damage due to natural disasters such as hurricanes, tornadoes, earthquakes, flooding and fire. Otherwise, the environmental, economic and societal burden of our built environment could be overwhelming. A building that requires frequent repair and maintenance or complete replacement after disasters would result in unnecessary cost, from both private and public sources, and environmental burdens including the energy, waste and emissions due to disposal, repair and replacement.

It doesn't make sense to design a modern building, commercial or residential, to meet LEED or other green building requirements that could be easily destroyed as a result of a hurricane, earthquake or other force of nature. That would mean that all of the green technology and strategies used in the building would go to the landfill. What is the point of installing low flush toilets in a home to conserve water if it ends up in a landfill after a tornado blows through?

Disaster Resilient Communities Workshops 2012-13

Many federal agencies – FEMA (FEMA 2012), USGS (Holmes et al. 2013), NOAA, EPA- all offer solutions for disaster preparedness with a myriad of strategies or protocols in place for dealing with the unthinkable. What is missing however is the development of specific policies at the tactical level to advance the security and disaster risk reduction of our infrastructure.

In 2012-13, motivated by the regularity of devastating events, a coalition of concerned manufacturers, trade associations and the insurance industry joined together to deliver a series of workshops to educate the public on the vital role of resilient, high-performing structures. The following presents the findings proposed by participants of the *Adopting Disaster Resilient Construction at the Local Level Workshop* (Workshop) (NRMCA 2013) and is a record of the lively discourse around disaster mitigation and preparedness that took place during the Workshops.

The Workshops covered a wide range of topics designed to formalize the process of implementing disaster resilient construction at the community level. Emphasis was given to mitigation over response or solely preparation so that it may serve local communities who intend to work in the area of planning and disaster resilience which demand interdisciplinary thinking. The Workshops attracted over 300 concerned citizen at every level, from design professionals, state agencies to local building officials and risk managers. The locations visited were as diverse as the participants representing the comprehensive list of hazard risks including: Springfield, MO, Sioux Falls, SD, Louisville, KY, Portsmouth, NH, Richmond, VA, Jackson, MS, Wilmington, NC and Orlando, FL.

The recommendations below demonstrate that disaster risk reduction can be combined with infrastructure planning to significantly boost resilience: people's ability to withstand shocks in their environment – and critical for helping us address climate change, and lessen the vulnerability of those with less means. While various parts of the nation experience different hazard risks, the Workshop saw an alignment of the responses organized around five (5) key Recommendations with a variety of Tasks a community engage at the local level:

A. Raising Awareness
B. Defining Vulnerabilities
C. Codes & Fortification Standards

D. Storm Shelters & Safe Rooms
E. Incentives

A. Recommendation: Raising Awareness

Significant knowledge gaps still remain, especially with respect to understanding the exposure and vulnerabilities within a given population. More education is needed to fully understand the risk tolerance thresholds of communities with respect to specific hazards. Addressing knowledge gaps through training and educational seminars requires multi-, inter-disciplinary teams, including emergency management professionals, design professionals, scientists, insurance agencies, governmental agencies, etc. working together.

Task A1- Developing school curricula to further educate students about storms and shelters.

Task A2- Encourage the design community toward a greater focus on resilience. This may include incorporating these concepts into formal educational programming in schools of architecture and engineering so that buildings increasingly have disaster resilience as a core consideration from the beginning, reducing the need for retrofitting buildings over time.

Task A3- Provide compelling examples to the public of how disaster mitigation works financially; do a better job aggregating the costs of responding to natural disasters and revealing their impact on government budgets, at both the federal and local levels.

Task A4- Provide educational outreach to make property owners aware of the financial benefits of upgrading their buildings.

Task A5- Require appropriate training for people managing buildings to increase both efficiency and resilience.

Task A6- Keep professional communities engaged with natural hazard mitigation through sessions at industry/trade association annual meetings, newsletters, and accreditation programs.

Task A7- Include building resilience to natural hazards as a criterion for LEED and other green standards because of the reduced environmental impact involved in saving existing buildings rather than rebuilding after a disaster.

Task A8- Launch an ongoing awareness campaign that educates local businesses, governmental agencies, non-profits and citizens about how to prepare for a natural disaster and about resources available when disasters strike.

Task A9- Organize a conference to discuss strategies to prepare for natural disasters and engage government, the private sector, and communities.

Task A10- Civic, educational, faith-based and other organizations could be enlisted to promote disaster awareness.

Task A11- Create public service messages to spread safety tips through print (with the Press), through broadcast.

Task A12- Sponsor seminars on how to apply for disaster mitigation grants, submit insurance claims and deal with contractors while after disasters.

Task A13- Utilize Facebook, Twitter, YouTube and other social media platforms to provide conduits for delivering resilience messages, answering questions interactively, and during actual emergencies, spreading warnings.

Task A14- Utilize social media to encourage ongoing, interdisciplinary discussions and exchange of best practices, policies, and strategies.

Task A15- Provide educational outreach to ensure that stakeholders have a clear understanding of their authority and responsibilities in disaster situations.

Task A16- Establish Community Emergency Response Teams (C.E.R.T.).

B. Recommendation: Defining Vulnerabilities

All planning and implementation of disaster preparedness measures should be based on an assessment and prioritization of the hazards and risks that people face, as well as their ability or inability to cope with and withstand the effects of those hazards.

Task B1- Identify the characteristics, frequency and potential severity of the hazards a community faces. Utilize tools provided in the Workshop including Insurance Institute's IBHS's disastersafety.org, Natural Resource Defense Council's (NRDC) www.nrdc.org/health/climate, FEMA's Resilient Star and/or US Department of Homeland Security's (DHS) OPRtool.org.

Task B2- Identify the main sectors of a community (population, infrastructure, housing, services, etc.) affected by a specific type of hazard and anticipate how they might be affected. Assess the ability to withstand and cope with the effects of the phenomena.

Task B3- Identify the particular geographical areas and communities that are most susceptible and vulnerable to those hazards.

Task B4- Consider the costs associated with the risk of natural hazards in developing zoning rules and enforcement standards.

Task B5- Work with FEMA to update Flood Maps.

Task B6- County EMAs and municipalities to assess their emergency needs ("gap analysis,") and then determining if there are enough resources on hand.

Task B7- Target older/historic buildings for resilient retrofits.

C. Recommendation: Codes & Fortification Standards

Whether a State mandates a statewide building code or allows its local jurisdictions to adopt building codes by themselves, regulation of building design and construction is primarily conducted through authorities of local jurisdiction. Due to various challenges at the local level, building code adoption and enforcement by the local jurisdictions can be a critical weak link.

Task C1- Participate in code formation, like the current process by the International Code Council, so that all model codes include hazard mitigation for water, energy, conservation, and land use.

Task C2- Establish local fortification standards for construction of new, rebuilt and extensively remodeled homes to save lives and property when severe weather moves through the community; provide in the code inspection procedures and enforcement rules that apply statewide.

Task C3- Reconsider existing codes and zoning rules to identify those codes that interfere with more resilient planning and design by preventing adoption of measures that go beyond the existing practices.

Task C4- Reconsider and update standards and codes along high-risk areas (i.e. coast).

Task C5- Encourage use of green infrastructure strategies and natural systems to help mitigate the impact of some disasters like flooding. Protect natural systems so that they can function as buffers in large events.

Task C6- Upgrade building codes to make structures more disaster resistant, and leverage solutions applied to other code priorities like security.

Task C7- Budget money for code compliance and change the current fee-driven structure that results in cutbacks in inspection and enforcement resources when construction activity is down.

Task C8- Require existing hospitals and clinics to meet not only building codes but also FEMA's code enhancements.

Task C9- Integrate disaster planning into larger economic planning.

D. Recommendation: Storm Shelters & Safe Rooms

More shelters — either those specifically designed to withstand fierce winds and flying debris or other fortified structures where taking refuge improves people's chances of surviving killer storms — should be designated where they already stand, built where none currently exist and publicized better.

Task D1- Increase the number of storm shelters available to the public, and publicize their locations so people know where to go when severe weather approaches.

Task D2- Factories, schools, shopping centers, "big box" stores, office and apartment complexes, municipal and public safety buildings, and mobile home parks that don't already have storm shelters should consider adding them.

Task D3- Everyone's personal disaster plan should include identifying nearby shelters beforehand and even practicing getting to them quickly.

Task D4- Work with industry representatives to require that community storm shelters be included at any new apartment complexes and mobile home communities built in tornado-prone regions, and offer incentives for adding them to existing facilities.

Task D5- Seek opportunity to use a proposed project as "demonstration" of resilient construction

E. Recommendation: Incentives

Yes, it costs money to buy and install a prefab safe room or build one from scratch or structurally reinforce an existing room. But anyone who has survived a deadly storm in a safe room or lost family members for lack of one or witnessed some of the worst destruction will agree that the investment is worthwhile. It was made clear from the 2005 Multihazard Mitigation Council (MMC) of the National Institute of Building Sciences Study (NIBS 2005) that for every dollar spent on mitigation, saved four dollars in avoided future losses. The benefits of mitigation were defined as the potential losses to society that were avoided as a result of investment in mitigation.

Task E1- Offer incentives to add safe rooms to new construction as well as existing homes and businesses.

Task E2- Utilize the existing system by which FEMA, using disaster assistance funding, offers matching grants that reimburse homeowners for 75 percent of safe room costs.

Task E3- Initiate discussion with State Insurance Commissions regarding premium incentives for building to code-plus or FORTIFIED (IBHS 2013b) standards or with robust materials.

Task E4- Propose income tax credits for building to code-plus or FORTIFIED standards modeled on other successful programs that reward, for example, the purchase of energy-efficient heating, ventilating and air conditioning systems, windows, insulation, or solar panels.

Task E5- Tax incentives should be extended to businesses offering essential services during storm events (gas stations so that fuel supplies are assured, pharmacies so that vital medicines can be dispensed, kidney dialysis, etc.).

Task E6- Advocate for code-plus, FORTIFIED (IBHS 2013b) or other programs on hazard reduction and ensure the results are widely distributed.

Task E7- Focus more resources on building science research by type of natural hazard through national entities such as National Science Foundation.

Task E8- Use life-cycle costs and savings rather than short-term expenditures to determine infrastructure spending.

Task E9- Since disaster preparedness depends on shared goals and activities across sectors, it is important that the concept be integrated into all on-going projects. For instance, all climate change planning should include assessment of potential natural hazard impacts. Partner with carbon reduction goals.

Task E10- Propose the US Green Building Council should expand its definition of environmental sustainability certification to include resiliency issues.

Task E11- Initiate discussion with banking industry regarding resilient mortgage rates (similar to energy-efficient mortgages based on Energy Star) for building to code-plus or FORTIFIED standards or with robust materials.

Mitigation Benefits Everyone

Disaster mitigation is not solely the work of experts and emergency responders from government emergency management organizations. Local volunteers, citizens, organizations and businesses have an active and important role to play before, during and after major emergencies and disasters. Therefore community-based disaster mitigation is a process that seeks to develop and implement a locally appropriate and locally "owned" strategy for disaster mitigation and risk reduction.

Based on the Recommendations and Tasks, the following describes sample Action Agendas that bring together the tools and activities from many the building sectors in an effort to address resilience including:

- Leveraging green-building momentum to include resilience.
- Development of ordinances and mandatory building codes.
- Addressing durability with lifecycle costs and ongoing maintenance.
- Increasing and improving infrastructure investment from all stakeholders.

Action Agenda A4: Understanding Cost of Resilient Construction Building to a disaster resilience standard does cost more but typically results in cost savings over the long run. The FORTIFIED for Safer Living program (IBHS 2013b) of the Insurance Institute for Business and Home Safety (IBHS) is a voluntary programs aimed at incorporating building techniques into construction to provide an optimum level of protection against a variety of natural hazards. IBHS is a not-for-profit applied research and communications organization supported by the insurance industry. One report conducted by Blue Sky Foundation of North Carolina found that the additional cost of building a home to the FORTIFIED for Safer Living standard cost an additional $3,936 or about 5% more than a home with a retail value of $80,000. Amortized at 6% simple interest over a 30-year mortgage, the additional monthly cost would be about $24 per month. According to the report, this additional cost is easily offset by likely repairs of the home after the 5-10 hurricanes anticipated over the mortgage period (BSE 2005).

Action Agenda A7: LEED Resilient Construction Pilot Credit: Resilience has become an important dimension of sustainability, and a key element of the value proposition for high performing buildings because it recognizes both the immediate risks of extreme weather and the long-term effects of climate change. The National Ready Mixed Concrete Association (NRMCA) has developed and submitted a Pilot Credit to address the “physical” dimensions of resilience. The Pilot Credit enhances the resilience of buildings and infrastructure through designed robustness, durability, longevity, disaster resistance, and safety which should be a priority for every sustainable community stakeholder.

The Pilot Credit rewards design strategies that reduces the materials required to repair and retrofit from a hazard event, enhances the robustness through the IBHS

FORTIFIED designation, or increased durability by utilizing the principles in CSA S478-95 (R2001) - Guideline on Durability in Buildings. As of this writing, the Pilot Credit is under review by the USGBC.

Action Agenda C1: Adopt a building code. Building codes are effective for reducing disaster risk. A building code sets standards that guide the construction of new buildings and, in some cases, the rehabilitation of existing structures. Currently, building codes set minimum construction standards for life safety. Maintaining the functionality of structures is important for high-risk areas, but more importantly may be critical for certain populations groups that are more vulnerable to natural hazards, those and who do not have a choice on where they live and work.

To date, among the eight States in the New Madrid Seismic Zone, five (Arkansas, Indiana, Kentucky, Missouri and Alabama) have statewide building codes for residential construction as minimum requirements, but three (Illinois, Mississippi, Tennessee) do not and they pass the responsibility to the local jurisdictions to adopt the codes themselves (IBHS 2013a). Although earthquakes are high-consequence events, seismic mitigation in Mid-America generates little public interest because earthquakes in this region are low frequency.

If we are to take people's vulnerability seriously, we must deploy—and insist on—much greater technical expertise in code adoption. Building standards and land-use codes offer important opportunities to standardize resilience and durability in buildings and infrastructure.

Action Agenda C6: Adopt High Performance Building Standards. The Portland Cement Association recently developed High Performance Building Requirements for Sustainability that go beyond the basic building code and enhance the key concepts of durability and disaster resilience. Essentially these provisions state that for a building to be considered green, it must not only conserve energy and water, use materials efficiently, and have a high-quality indoor environment, but it must also reasonably withstand natural disasters. In other words, a sustainable building must be long-lasting and durable (PCA 2012).

In addition, high performance buildings should not be a burden on their communities. They should be sufficiently resilient to disasters to ensure continuous operation and not place excessive demand on community resources such as emergency responders including fire, police and hospitals. Communities with disaster resilient buildings are more likely to be able to continuously operate hospitals, schools, and businesses after a disaster. Stronger homes and buildings mean people will have places to live and work after a disaster. Less disruption for a community means robust commerce and consistent tax revenue.

Action Agenda D5: Build with Robust Materials. A key step towards disaster resilience is to build with robust building materials. Some of the qualities of robust building materials include versatility, strength, wind and water resistance, seismic resistance, fire resistance, energy efficiency and durability. Concrete building systems are especially suited to provide resistance to natural hazards. Concrete has the necessary hardness and mass to resist the high winds and flying debris of tornadoes and hurricanes. Concrete is fire resistant and non-flammable, which means it can contain fires and will not contribute to the spreading of fire. Reinforced concrete framing systems can be designed to resist the most severe earthquakes without collapse. Concrete doesn't rot or rust even if it is subject to flooding.

The Case for Robust Materials

> Case Study 1: There are many examples of structures built with heavy building materials, such as concrete, surviving major disasters. When Hurricane Katrina slammed into the coastal counties of Mississippi with sustained winds of 125 mph and a storm surge that reached 28 feet, the only house to survive along the beachfront of Pass Christian, MS was the Sundberg home. Scott and Caroline Sundberg were 85% complete building their dream home along the Mississippi coast when the Hurricane hit. When the winds died down and the water retreated, the Sundberg home had survived the storm. All other homes on the beachfront were completely destroyed. They built their home using insulating concrete forms (ICFs) for the walls and cast-in-place concrete frame construction for the lower level, floors and roof precisely for this reason—to survive the devastating effects of a hurricane.
>
> Case Study 2: Wildfires consume an average of nearly 7,000 square miles annually since 1960. In the last decade, that number has increased to over 10,000 square miles (NIFC 2012). A 1993 wildfire in Laguna Beach, CA, consumed 17,000 acres and destroyed 366 homes in a single day. The home of To Bui and Doris Bender Los Angeles Times named the "miracle house" (Underwood 1995) shows the lone survivor which remained protected by an envelope of non-combustible stucco wall cladding and concrete roof tiles. Detailing such as stucco cladding on walls, eaves and trim, as well as Class A concrete tile roof, prevented combustion of the exterior amidst the firestorm that swept through the community.
>
> Case Study 3: The EF-4 tornado that roared through Tuscaloosa, AL, on April 27, 2011, leveled block after block in the Forest Lake neighborhood. The only thing left standing was a closet at the Blakeney residence on 16th Street East. The closet was built as a safe room using 8-inch reinforced concrete masonry to withstand high winds and flying debris caused by tornadoes (Jones 2011). Small windowless rooms such as a walk in closet are ideal locations for a safe room in a home.

Action Agenda E6: Encourage Voluntary "Code Plus" Construction. The FORTIFIED for Safer Living program of the Insurance Institute for Business and Home Safety (IBHS) (IBHS 2013c) are voluntary programs aimed at incorporating building techniques into construction to provide an optimum level of protection against a variety of natural hazards. IBHS is a not-for-profit applied research and communications organization supported by the insurance industry. Their focus is to reduce or eliminate residential and commercial property losses due to wind, water, fire, hail, earthquake, ice and snow. The programs also address other business continuity issues such as such as interior fire, burglary, lightning protection and electrical surge.

Over 250 homes have been designated as FORTIFIED since 2001. The program was battle tested by Hurricane Ike on the Bolivar Peninsula in Texas in September 2008. Ten of 13 FORTIFIED homes survived a direct hit from Hurricane Ike, including a 20 ft. storm surge. These FORITIFIED homes were the only structures left standing for miles around, precisely because they were specifically designed and built to withstand extreme wind and water damage. The three FORTIFIED homes that did not survive were collapsed when other homes in the area slammed into them.

Conclusion

Disaster mitigation works and is cost effective. Spending time and money up front to reduce the likelihood of loss during a natural disaster can bring significant benefits to building owners and communities including lower insurance costs, higher property values, security to residents, maintaining a consistent tax base, and minimizing the cost of disaster response and recovery.

The authors recognize that not everyone will agree with each recommendation or action agenda outlined in this paper. That's understandable. We were not looking for the easiest path. Instead, we wanted to create a path for disaster risk reduction with common-sense solutions. We wanted proposals that would increase preparedness without expanding the footprint of government. But this is an opportunity for the community, and we must not waste it. The policies the Workshop participants puts into place in the next six months to a year will potentially impact millions of people for decades to come. We need planning that will transcend political administrations and short-term corporate interests. Resilience promotes greater emphasis on what communities can do for themselves before a disaster hits, and how to strengthen their local capacities, rather than be dependent on our ineffectual governmental agencies and aging centralized infrastructure.

Consider the reality for 2013: As of September 2013, there have already been 7 natural disasters in the U.S. costing $1 billion or more in damage, with September 2013 as the globe's 4th warmest September since records began in 1880, according to NOAA's National Climatic Data Center (NOAA 2013a). There were both devastating tornadoes and multiple earthquakes in Oklahoma. Record rainfalls triggered historic flash flooding across in Colorado September, killing at least nine people and doing $2 billion in damage with more of the Atlantic hurricane season still to come.

Certainly, the people in the communities directly affected by these disasters, natural or man-made, have been humbled by the destruction of that day. Those of us more fortunate to have escaped a major disaster should take heed as they recover and make plans for a stronger future. We have heard their stories, we can learn from their lessons.

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Superstorm Sandy Storm Surge and Residential Damage Correlation – A case study of Long Beach, NY

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ABSTRACT

The New York City region is currently recovering from the damage caused on October 29, 2012 from Superstorm Sandy, the largest low pressure storm ever to make landfall on the US east coast north of North Carolina. This storm tested all aspects to the infrastructure of the communities living close to the Atlantic Coast. Research was performed to review and process data that were collected before, during, and after the storm. The research focused on the city of Long Beach, NY. The scope of the research included three tasks: (1) reviewing and processing hydraulic data collected from USGS tide gages before and during the storm; (2) collecting and processing structural data collected after the storm focused on extent of damage to residential buildings and type of building construction; and (3) correlating, analyzing, and mapping flood data and residential damage utilizing GIS software.

The results of this research points to a strong recovery theme– residences designed with heavier and sturdier materials (i.e. brick and stucco facades) are more likely to resist damage during a storm than those constructed with lighter materials (i.e. lightweight siding on wood frames). The damage can be resultant of hydrostatic and buoyant forces due to rising floodwaters, hydrodynamic forces due to flowing water, impact forces due to water waves, as well as hurricane force winds. The extent of damage can also be correlated to the applicable zoning laws. Homes built in accordance with stricter coastal zoning practices are better designed to resist hurricane forces.

With Long Beach acting as a snapshot of the Northeastern coast, the research conducted with this city may be applied to many other coastal communities providing invaluable guidance to rebuilding during storm recovery and preparation for future events.

INTRODUCTION

In late October of 2012, meteorologists began tracking the late season tropical storm as it approached the Atlantic coast in New Jersey and New York. On the 29th of October, the storm approached land as a Category 2 hurricane. The storm had a barometric pressure of 943 millibars, the lowest pressure storm system ever tracked that made landfall north of Cape Hatteras, North Carolina. The named storm made landfall near Atlantic City, NJ. The wind speeds at landfall placed the storm system in the "post tropical cyclone" category, but wind gusts reached 94 mph in New York, and the wind span of the storm was over 1,100 miles wide. The enormous reach and destructiveness of it prompted the storm to be renamed, "Superstorm

Sandy". The barometric pressure caused storm surges to reach 13.8 ft. at Battery Park, New York City. The highest peak wave height recorded was 39.7 ft. 500 miles south of Atlantic City. The waves at the entrance to New York Harbor were 32.5 ft. high.

The storm caused $36.8 billion of damage to the Jersey Shore, $19 billion to New York City and $41.9 billion to the entirety of New York State, including Long Island. The direct fatalities from the storm in United States reached 72, and indirect fatalities from storm cleanup efforts exceeded 87. Over 8.2 million people were left without power, including 29 hospitals, and 650,000 houses were damaged or destroyed in NY and NJ. Months of grief, safety hazards and inconvenience for the residents of those areas followed. The cities affected were anxious to rebuild and recover as quickly as possible, given the information that a storm of the same magnitude may be in the forecast in the near future. However, research into the storm and its affects needs to be compiled, and the recovery efforts, though well intentioned, may not always be the best route for long-term sustainability. This research project focuses on the structural damage caused by Superstorm Sandy. The information gathered includes what types of buildings were most affected. This information was correlated to the extent and height of the storm surge from the storm.

RESEARCH OBJECTIVES

The goal of this research project was to gather data from organizations such as FEMA (Federal Emergency Management Agency), NOAA (National Oceanic and Atmospheric Administration) and the United States Geological Survey (USGS), and use information gathered about the status of structures in areas affected by the storm, and determine if correlations exist between structural failure, building materials and hydrodynamic impacts. The project categorizes information on building materials from residential buildings that were damaged, with the overall objective being industry suggestions of the most resilient structure type, the most non-resilient structure type, or other alternatives that may prevent storm and flooding damage. There was a focus on hydraulic forces that structures experience during a flood and appropriate analyses of these forces can be considered. Ongoing work involves creating an interactive map using ArcGIS to plot on a community map the types of buildings that were damaged, where those buildings were located, the extent of storm surge inundation, and applicable wave forces measured. The information that was gathered could be used to help residents rebuild their houses or businesses to improve overall safety of the dwelling and to lower future insurance premiums. Residents may also decide to move away from the area, if risks outweigh the cost of rebuilding.

The compiling of this type of data was initially narrowed down to one coastal city – the City of Long Beach in Nassau County, Long Island, as pictured in Figure 1. Long Beach is just 18 miles southeast of Battery Park, Manhattan, New York City, and borders the communities of Atlantic Beach on the west, Lido Beach on the east, the Atlantic Ocean on the south, and the Reynolds Channel portion of the intercoastal waterway to the north. It has a 30,000 year-round population, which increases in the summer months. Figure 2 is an aerial map of Long Beach, illustrating that it is a densely populated beach community on the barrier island. Figure 2 also shows the extent of the storm surge from Superstorm Sandy. Almost all of Long Beach was flooded (shown in gray). The dark shaded areas near the bridge going over the intercoastal channel, and small spots in the south-west part of the city were the only locations that were spared water inundation.

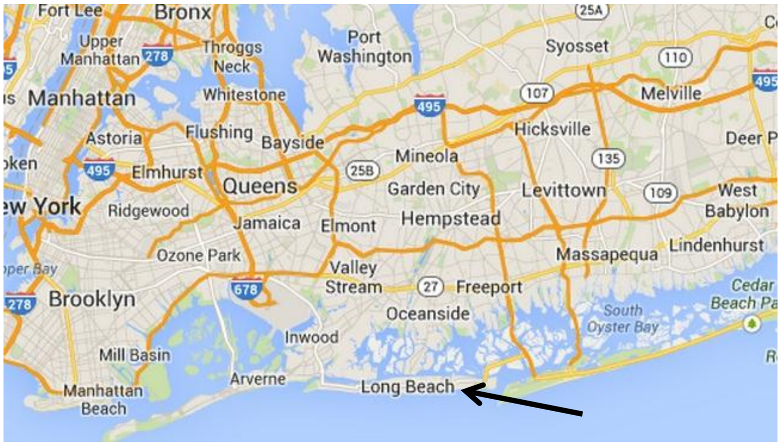


Figure 1 – Long Beach location in comparison to New York City

SUMMARY OF APPROACH

The work described here is part of a larger research program in the area of water-structure interaction as influenced by natural disasters such as hurricanes. This paper focuses specifically on the collection, correlating, and mapping of both hydraulic and structural damage data from the city of Long Beach, NY following Superstorm Sandy in 2012.

Phase 1 of the project included a field visit to Long Beach to verify and comprehend hydraulic data provided by the USGS throughout the town. The visit also provided a snapshot of the town a few months after Sandy hit. During the initial field visit, a contact was established with an organization named Sustainable Long Island. This organization focuses on economic and residential growth throughout the island. After the storm hit the group was particularly interested in the recovery of Long Beach with respect to rebuilding of both residential and commercial structures. The organization has its own division of citizens who are currently conducting research focused on economic recovery. They had already acquired a significant amount of residential data with respect to the status of homes in the town – i.e. under construction, demolished, vacant, or for sale – and shared said data with the Manhattan College research team (Sustainable Long Island, 2013).

Phase II of the work included expanding upon the previously gathered data. The damaged homes were further categorized by the type of external cladding with respect to common building materials – i.e. lightweight siding, brick, or stucco. This information was gathered by a "virtual" visual inspection of the homes.

Phase III of the work focused on the correlation and mapping of the hydraulic and structural damage data gathered in Phase I and Phase II. This information combined to make a powerful statement about structural damage due to natural disasters.

RESULTS AND DISCUSSION

Regional Flood Marks and Water Level Data

The barrier island that comprises the city of Long Beach has the potential to be flooded both from the south (via the Atlantic Ocean) or from the north (via the intercoastal channel). Table 1 lists locations near Long Beach house stations where predicted tides for the day the Storm hit,

Figure 2 – Aerial Map of Long Beach showing the Population Density and extent of Superstorm Sandy Water Inundation

October 29th, 2012. The predicted high tide water levels are calculated in advance using numerical models created by NOAA (NOAA, 2013).

Table 1 – Predicted high tide levels for October 29th, 2012 with respect to NAVD88 (North Atlantic Vertical Datum of 1988)

Station and Location	**Time of High Tide**	**Predicted Water Level in NAVD88 datum**
Long Beach Bay Side	8:19 AM	6.432 ft
Jones Inlet (Point Lookout), Atlantic Ocean East of Long Beach	7:41 AM	5.972 ft
East Rockaway Inlet, Atlantic Ocean West of Long Beach	7:54 AM	6.692 ft

The Long Beach Bay Side gage and the East Rockaway Atlantic Ocean gage were selected to be used for a data comparison to the actual water levels recorded by USGS gages temporarily deployed for the storm considering their locations are closest to the ocean and bay sides of Long Beach.

Figure 3 shows how the water heights varied throughout the city. The figure includes the predicted heights from NOAA (Table 1), and the zone's base flood elevation, or BFE. The BFE is the elevation set by the Federal Emergency Management Agency (FEMA) at which a structure must be built in order to comply with building code standards. BFE's are determined by examining water level data records. It is based off of the 100-year water levels, or the water level that has a 1% chance of occurring for a given year.

Figure 3 also compares the highest water surface elevations (high water mark, or HWM) reached at 6 different locations in Long Beach during Superstorm Sandy as recorded by temporarily deployed USGS gages, as well as the NOAA predicted water heights for that day (Table 1) and the FEMA BFE's at the same locations. Places where the HWM exceeds the BFE experienced the most damage on the island. Since structures were built using FEMA BFE levels to avoid floods, these structures were not prepared for such high flood waters. The water caused damage to electrical systems or structural supports. At every storm gage's location, the HWM exceeded the predicted water height significantly, as the predicted water height does not take into account wind forces or storm surges.

Figure 4 displays the depth of the flooding – which subtracts the water surfaces reached from the storm from the ground elevations throughout the region. The greater the depth of water, the greater the hydrostatic forces experienced by the structure, and thus potential damages to structures. The areas that experienced the greatest depth of flooding inundation were the areas that bordered the intercoastal channel, or the north side of the city. The northeast and north-central sections of the city had many blocks with over 6 ft of water. Thus, the storm surge from Superstorm Sandy flooded the city via the bay side. The southeast section of the city which is closer to the Atlantic Ocean had many blocks that had less than 2 ft of water inundation.

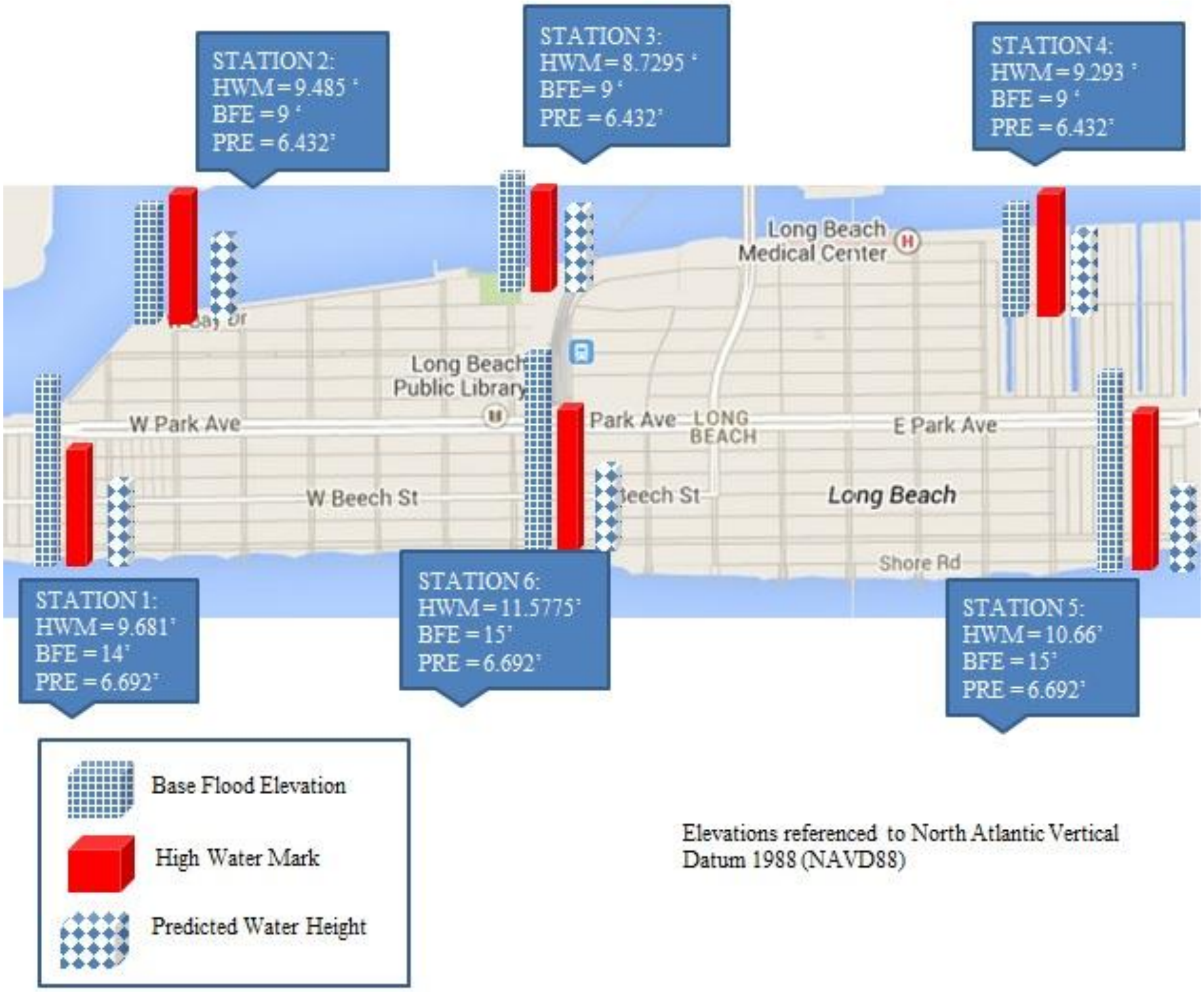


Figure 3 – Water height comparison for Long Beach during Superstorm Sandy

Survey of Structural Damage

Figure 5 shows the division of Long Beach into 3 districts (West End, Central District, and East End) and 5 zones (numbered sequentially starting in the south going north) and indicates the number of homes damaged in each of the districts. Each zone and district was analyzed by Sustainable Long Island with respect to the economic status of the homes. The Manhattan College research team analyzed homes in the same domains. They further classified the homes as damaged during Superstorm Sandy such that homes that Sustainable Long Island categorized as either affected by the storm were now considered damaged. Houses that were classified as having a refuse container ("pod") on site were assumed to be under construction to repair damages incurred during Superstorm Sandy. Houses that were originally classified as demolished were very few, and grouped together with the houses under construction for the structural assessment portion of the research. Houses that were classified as "for sale" or "vacant" were assumed to be so due to either real or perceived damage from the storm. It is recognized that the "For Sale" and "Vacant" categories may actually include some houses that were not physically damaged by the storm, but are simply for sale for other reasons, which may

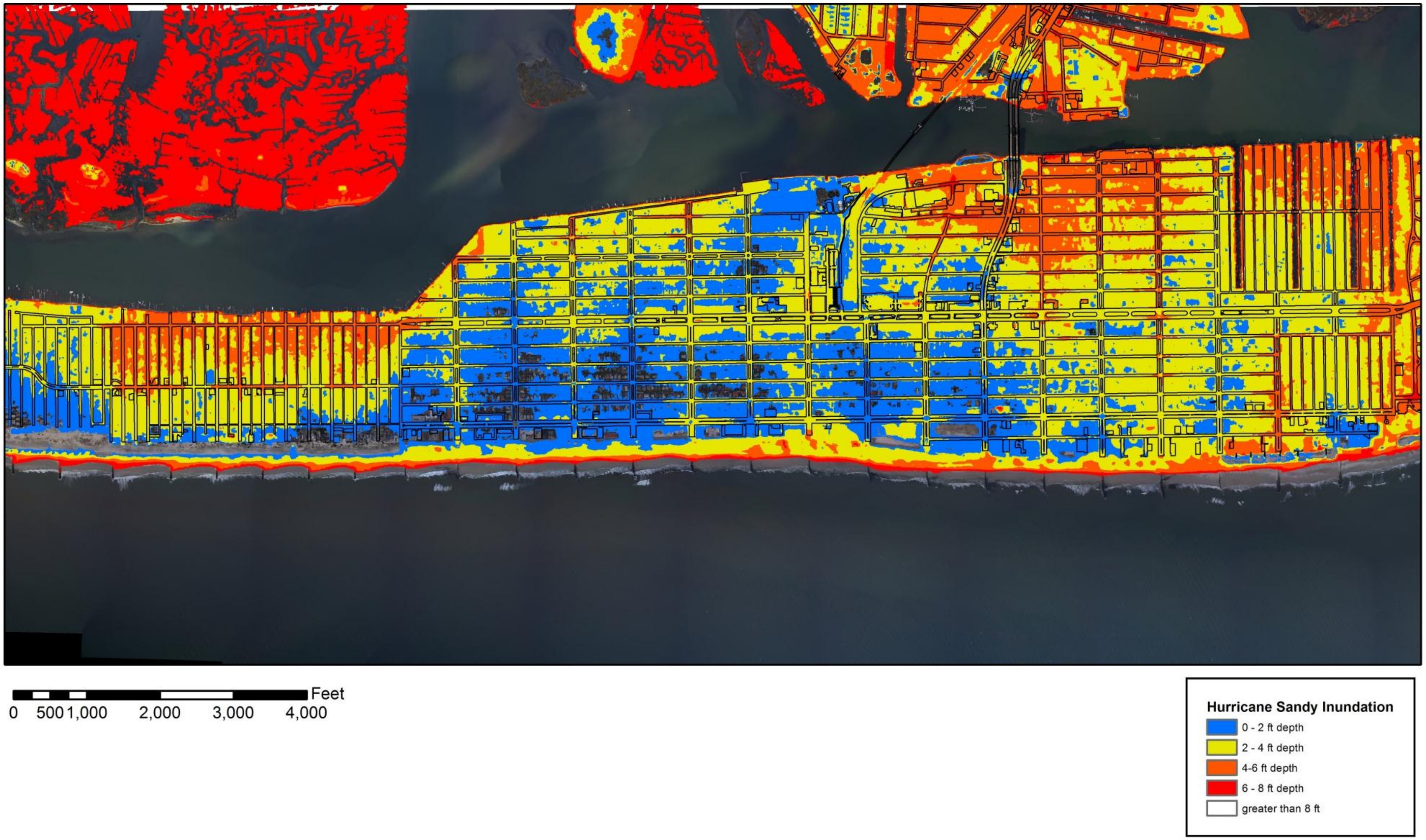


Figure 4 – Depth of Inundation during Superstorm Sandy.

or may not include fear of potential future damage. Data will be shown which distinguishes houses under construction from those for sale.

Structural assessment data focuses on the Central and East End districts of Long Beach. Similar data exists for the West End as well, but the structural assessment has as not yet been complete.

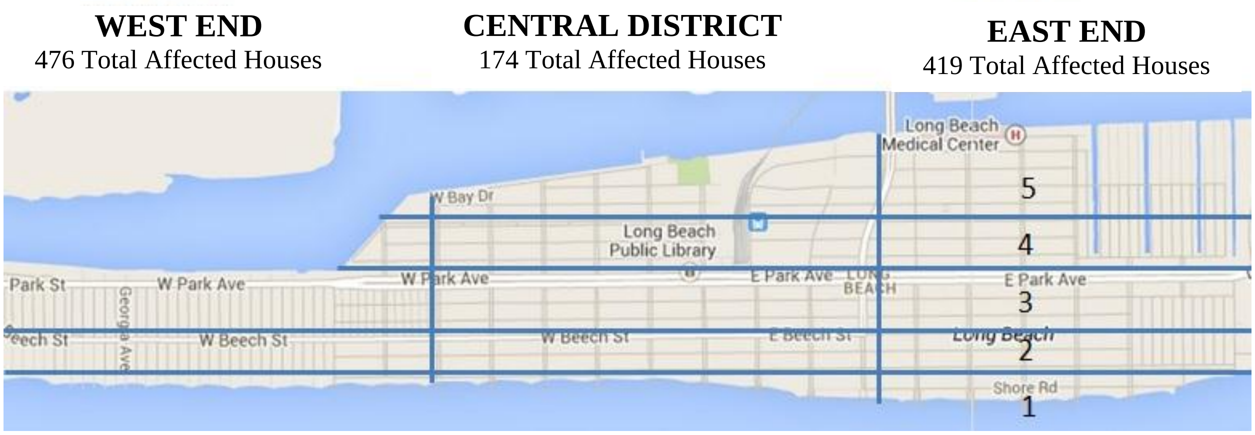
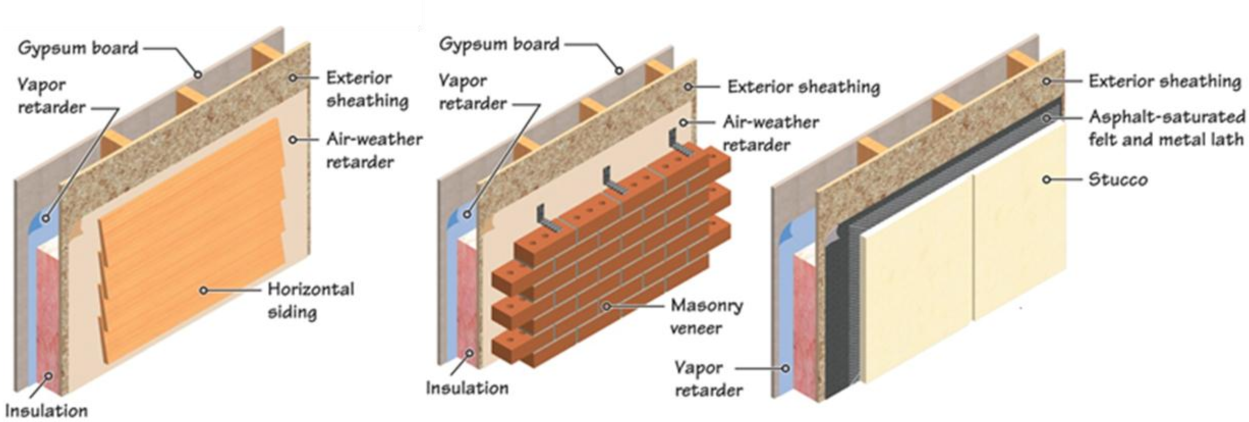


Figure 5 – Long Beach, New York when divided up into three sections (West End, Central District and East End) and zones 1-5

The Central District had less than half the number of houses affected than both the West End and East End. When again referring to Figure 4, it can be seen that inundation levels were indeed the lowest in the Central District. Lower inundation levels lead to lower hydrostatic and buoyant forces on the structures, and thus fewer total houses damaged.

The Manhattan College team virtually assessed each of the damaged homes visually to identify the building materials used for external cladding. The research team acknowledges that visual assessment does not fully define the extent of damage to a structure, but it does serve as a preliminary assessment of the houses. Homes were historically assessed through photos and images available on Google Earth.

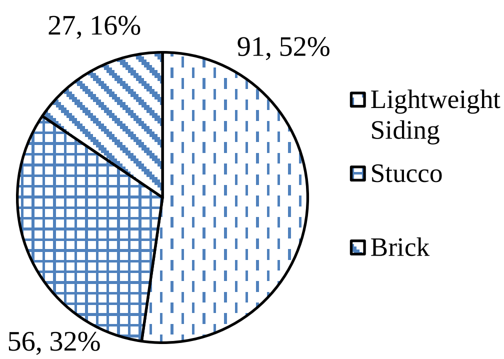
Houses were classified as lightweight siding, stucco, or brick (masonry) facades. Lightweight siding includes all houses with vinyl siding, aluminum siding, or shingles visible from the outside of the house. Stucco houses consist of those that have an adobe-type exterior, with more of a flat, textured surface acting as one slab rather than strips of siding. Brick houses have a masonry façade. Figure 6 shows examples of the external wall systems of typical houses with siding, brick, and stucco. Each of these types of houses was assumed to be internally constructed as a typical wood light frame structure.



(a) Lightweight Siding (b) Masonry Veneer (c) Stucco

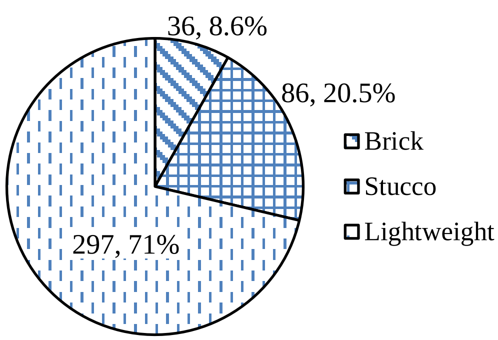
Figure 6 – Typical composition of residential buildings (Mehta et al., 2013)

A comparison of the damage to these types of houses can be seen in Figure 7 – Central District details in part (a) and East End district details in part (b). Brick, stucco and lightweight siding houses have been divided up into houses that are for sale, vacant and in construction in the central district of Long Beach. The percentages of houses with lightweight siding that were affected far surpass the percentages of both stucco and brick houses, as they are the lightest and thus least resilient type of external cladding used in house construction studied here. The conclusion can be made that houses with lightweight siding suffered the most damage from Superstorm Sandy, whereas brick houses suffered the least.



Material Type	Vacant	Under Construction	For Sale	Total Affected
Lightweight Siding	20	53	18	91
Stucco	16	31	9	56
Brick	3	21	3	27
Total	**39**	**105**	**30**	**174**

a.) Central District



Material Type	Vacant	Under Construction	For Sale	Total Affected
Lightweight Siding	76	192	29	297
Stucco	24	53	9	86
Brick	9	24	3	36
Total	**109**	**269**	**41**	**419**

b.) East District

Figure 7 – A breakdown of total affected houses in the (a) Central District and (b) the East District

Heavier building materials better resist uplift due to buoyant forces. Damage to a house can occur during storm inundation as buoyant forces cause uplift on a house, creating added stresses on the anchorage systems connecting houses to foundations. Heavier building materials also better resist overturning moment felt as hydrodynamic and hydrostatic forces push laterally on a structure. Overturning moment can also create stresses on the foundation anchorage systems. Heavier and stronger building materials (brick and stucco) will also resist damage to the external cladding systems, i.e. tearing of lightweight siding.

Houses classified as "lightweight siding" experienced the most damage in the Central and East Districts of Long Beach, NY. These houses are made with the most lightweight materials, and are more susceptible to buoyant, hydrodynamic, and hydrostatic forces. Typical lightweight siding may weigh less than 1 psf.

The classification of "stucco" denotes houses that are built with a clay or similar material as the outermost layer of the house. These materials tend to be heavier and stronger than houses that have a "lightweight siding" classification. They are more rigid and offer greater resistance to damage to the external cladding systems during storms than the thin, lightweight vinyl or aluminum siding and offer more resistance to uplift and overturning moment. A typical stucco façade of approximately 1" thickness may weigh approximately 10 psf.

"Brick" houses are more dense (30-50 lb/ft^3) and thicker (4 in nominal) than lightweight siding. A typical brick veneer may weigh approximate 10 to 17 psf. This heavier building material also provides increased resistance to uplift and overturning moment caused by the aforementioned forces.

Table 2 lists each zone and the total number of houses in the East End and Central Districts combined that were damaged categorized by external cladding material. There are 593 houses total. Recall that zone 1 is on the oceanfront and the zones are numbered sequentially to the north with zone 5 on the bay side of the Central and East End districts. It is important to note that Zone 1 falls into the FEMA designated Zone VE: Coastal flood zone with velocity hazard (i.e. wave action) and zones 2 through 5 are all in Zone AE: Special flood hazard area with BFE defined (without velocity hazard) (FEMA, 2009).

Table 2 – Total houses affected by zone and external cladding material for East and Central districts

	Total brick houses affected	Total stucco houses affected	Total lightweight siding affected	Total houses affected – all materials
Zone 1	0	0	0	0
Zone 2	4	5	6 (40% of zone 2)	15
Zone 3	14	29	35 (45% of zone 3)	78
Zone 4	13	38	76 (60% of zone 4)	127
Zone 5	32	70	271 (73% of zone 5)	373

First consider total houses damaged per zone. Zone 1 had no houses damaged in the East or Central Zones. While surprising, it is important to recall the BFEs in this zone were actually several feet higher than the HWMs were here (recall Figure 3). These houses were designed with the expectation that water levels could indeed reach and exceed that which were experienced during Superstorm Sandy. These houses are also in the FEMA defined VE zone which may experience wave impact as well as storm inundation. These houses, if properly designed to code, were designed under additional wave impact loads requiring more robust construction.

Zone 5 on the bayside had the most number of total houses damaged. Again, recalling Figure 3, the HWMs exceeded the BFEs in this zone and as such the houses experienced hydrostatic and buoyant forces during Superstorm Sandy that were greater than anticipated and provided for in the codes. From this data, it can also be seen that as each zone approached closer to the bay side, a greater number of houses were damaged.

Inundation levels should also be considered, recalling Figure 4. Inundation heights on the bayside were higher and reached further extents than the inundation on the Oceanside. Thus houses in the bayside zones were exposed to larger hydrostatic and buoyant forces than houses on the Oceanside which had lower indundation levels.

When considering number of damaged houses in each zone, the damage can be attributed to two factors: (1) HWMs exceeded expected BFEs on the bayside but HWMs were less than BFEs on the oceanside and (2) houses on the oceanside were in FEMA zone VE and designed more robustly than houses on the bayside, as houses in Zone VE are designed considering wave impact.

When considering type of external cladding material, houses with lightweight siding accounted for a greater number of damaged houses in each zone. In zones 4 and 5 there were more houses with lightweight siding damaged than houses with brick and stucco combined where in zone 5, the lightweight siding houses accounted for 72% of the total houses damaged. Again, heavier, stronger external cladding materials were able to better resist the hydrostatic, buoyant, and hydrodynamic forces felt during Superstorm Sandy.

CONCLUSIONS

This paper focuses on the preliminary studies of water-structure interaction under the influence of hurricane forces, namely hydrostatic forces and buoyant forces from water inundation and hydrodynamic forces from wave impact. Several conclusions can be made based on this work.

Results show that houses constructed using heavier building materials (i.e. brick and stucco) for external cladding were damaged to a lesser extent than houses constructed using typical lightweight siding (vinyl or aluminum) for external cladding. Heavier building materials better resist uplift due to buoyant forces. Damage to a house can occur during storm inundation as buoyant forces cause uplift on a house, creating added stresses on the anchorage systems connecting houses to foundations. Heavier building materials also better resist overturning moment felt as hydrodynamic and hydrostatic forces push laterally on a structure. Overturning moment can also create stresses on the foundation anchorage systems. Heavier and stronger building materials (brick and stucco) will also resist damage to the external cladding systems, i.e. tearing of lightweight siding.

Results also show that houses situated on the bayside of Long Beach experienced more damage than those on the Oceanside. Houses on the bayside had higher inundation levels than the

Oceanside and thus experienced larger hydrostatic and buoyant forces. High water marks also exceeded BFEs on the bayside, inferring that the hydrostatic and buoyant forces that the houses were subjected to were higher than anticipated.

Houses on the Oceanside are situated in FEMA's Coastal VE zone which assumes that the houses may experience impact from waves in addition to slowly rising waters. As such, houses in this zone were more robustly designed and better resisted the impact of Hurricane Sandy.

ACKNOWLEDGEMENTS

Funding for this research was generously made available by Dr. John Mahony, Professor of Civil and Environmental Engineering of the Civil and Environmental Engineering Department at Manhattan College. Manhattan College would also like to thank our partners at Sustainable Long Island – specifically The Director of Programs for Sustainable Long Island, Fernando Tirado – who graciously shared their data with the research team in an effort to facilitate our work.

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Resuspension and Transport of Allergen-carrier Particles in Residential HVAC Systems

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ABSTRACT

HVAC systems play an important role in transporting allergen-carrier particles that trigger asthma episodes in residential indoor environments. Unfiltered particles deposited on interior duct surfaces resuspend and transport when disturbed under mechanical vibration and varying air flow conditions in the system. Experimental data is needed to characterize the behaviors of individual allergen-carrier particles in response to HVAC system disturbances and to inform modeling work that will lead to better design and performance guidance for builders seeking to improve indoor air quality in residential settings. In this study, a combination of experimental work in residential settings and in a more controlled laboratory resuspension chamber setup is conducted to characterize the resuspension of allergen-carrier particles deposited in residential HVAC ductwork and to obtain resuspension rate data for individual allergen-carrier particles in various HVAC system environments. The results of this research investigation are important to understanding the behavior of allergen sources in residential homes.

INTRODUCTION

Asthma is a life threatening disease that is affecting one in every ten residents in Pennsylvania. In particular, high rates of asthma hospitalization were shown for children and adults over 65 who tend to spend many hours at home (PDOH, 2012).

Despite attainment of general reductions in outdoor air pollutant levels, increases in asthma prevalence has led many researchers to focus on the home environment as a potential risk factor (Custovic et al., 1998).

Factors that are known to trigger asthma episodes include exposure to house dust and allergens (e.g., dust mite, cockroach, pet dander and fur dust, pollen). Allergens adhere to dust particles found in indoor air pathways (Gomes et al., 2007). Entrainment of dust in air supplied and recirculated in residential HVAC systems is affected by several aspects of the system design. Dust particles containing allergens deposit on interior duct surfaces, then resuspend and transport when disturbed under varying air flow conditions and mechanical vibrations in the system. Currently, ASHRAE 62.2 requires that HVAC system air filters meet a minimum efficiency reporting value (MERV) of 6 for residential applications (ASHRAE, 2010). At this MERV rating, the average particle size efficiency from 3 to 10 µm, is between 35 – 50%, which allows respirable (generally defined as particles less than 10 µm in size) unfiltered particles to remain a problem. Filter bypass, which is a common problem in HVAC systems, increases the dust load further. Hence, the potential for particles distributed through HVAC system ducting to affect indoor occupant exposure is significant.

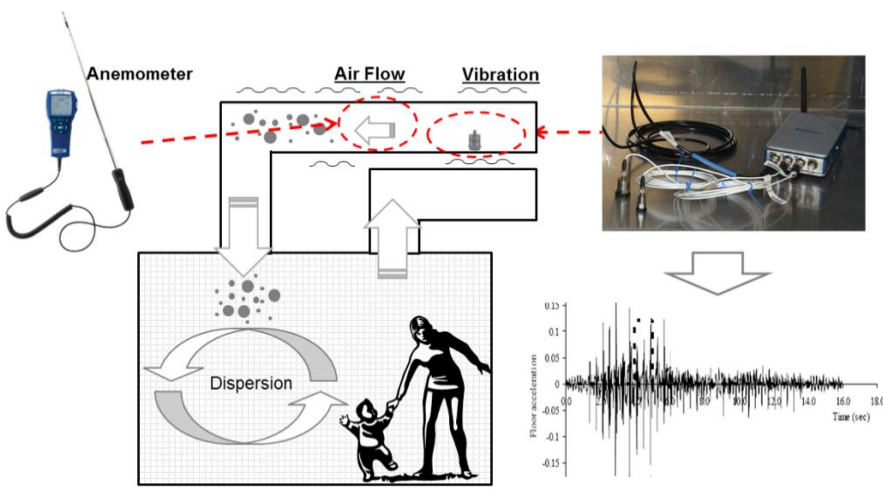
Although it is important to understand particle resuspension and transport behavior, experimental data is still limited. Previous studies (Wang et al., 2012) have attempted to analyze the lumped behavior of "average" dust particles resuspended in ducts. However, lumped behavior does not consider important aspects of individual allergen-carrier particles, whose resuspension behavior differs by particle type to various disturbances. Resuspension characteristics of individual allergen-carrier particles need to be investigated to gain insight into the impact of in-duct particles on occupant exposure and to develop best-practice mitigation approaches.

The objective of this study is to characterize resuspension and transport of allergen-carrier particles deposited in residential HVAC ductwork. Field measurements are carried out to establish the typical range of disturbances for residential HVAC duct settings. Subsequently, laboratory measurements are performed to measure resuspension rates of particles deposited on residential HVAC duct materials under the established disturbances. Measured resuspension data are used in the development of models to predict particle concentrations in the indoor environment, and to investigate the impact of in-duct particle resuspension and transport on occupant exposure, which is the broader goal of this work.

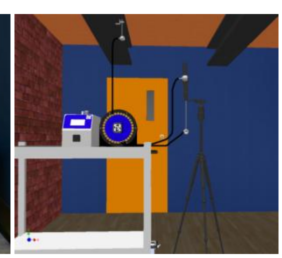
FIELD MEASUREMENT

Overview. Field measurement is designed to determine the particle disturbance factors in HVAC duct within actual residential settings. The measured disturbances are used for laboratory experiment and computational fluid dynamic simulation to quantify the particle resuspension rate and assess human exposure to indoor particle due to HVAC operation, respectively.

Measurement of mechanical vibration in the HVAC system. Mechanical vibrations in the HVAC ducting during start-up and steady-state operation of the packaged unit at various flows in the duct is measured using an array of accelerometers coupled to a wireless dynamic signal analyzer as shown in Figure 1a. Measurement locations are near the diffusers in the duct runs and at the air handler. Accelerometers are placed onto interior and /or exterior duct surfaces.



a.



b. c.

Figure 1. a. Schematic diagram of the field experiment at the MorningStar Solar Home; b. Particle sizing units that will be used to measure real time particle size distributions from 0.02 to 20 microns within the ductwork; c. Spatial profiling particle sizing set up.

Measurement of air flow, temperature and RH in the HVAC system. Air flow conditions in the HVAC duct are measured using multi-function anemometer probes and barometers at various set points for the packaged unit serving the duct runs.

Measurement of resuspended particles in the HVAC system. Resuspension of existing particles in the MorningStar Solar Home ductwork and the space served by the ductwork is measured within the ductwork and outside of the ductwork using particle counters shown in Figure 1b.

Injection of particles in the HVAC system. Minor quantities of monodisperse and natural particles are injected into the ductwork from the packaged unit inside the mechanical room as depicted schematically in Figure 2 with the diffusers covered to deposit particles on interior duct surfaces. Figure 3 shows photos of the MorningStar Home, measurement locations, and the packaged unit in the mechanical room. Subsequent measurements of particle resuspension are then made during normal operation of the mechanical system. Duct work is cleaned before and after this operation.

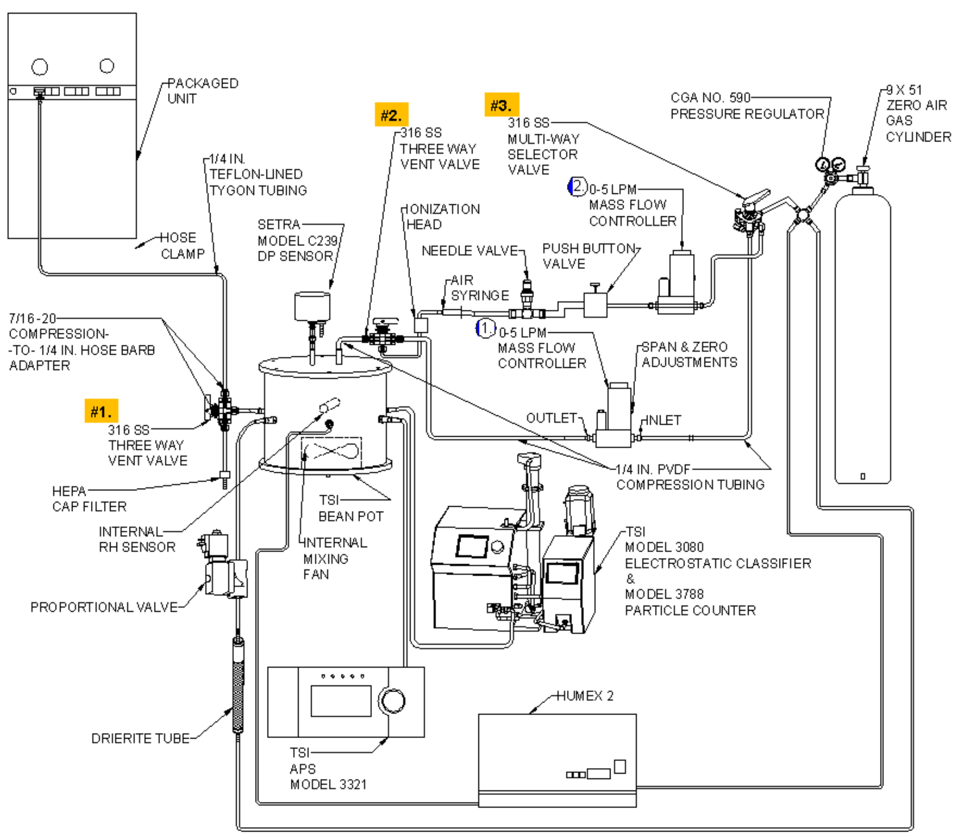


Figure 2. Schematic of apparatus layout for particulates injection into packaged unit

a.

b. c.

Figure 3. a. MorningStar Solar Home; b. Two of four measurement locations near duct diffusers; c. Packaged unit in mechanical room; red dots are approximate locations for ½ in. diameter traverse caps to be installed in the ductwork to enable velocity profiling and to fit particle injection line

LABORATORY RESUSPENSION EXPERIMENT

Overview. The laboratory resuspension experiment is designed to investigate the particle resuspension from various HVAC duct materials under the controlled HVAC disturbance forces. The measured actual HVAC disturbances such as mechanical vibration and air flow rates in the MorningStar Solar Home are replicated in the laboratory chamber experiment. The details of laboratory resuspension experiments are as follows.

Test Dusts and Flooring Samples. Quartz as a non-biological particle, and dust mite, dog fur dust and cat fur dust as biological particles are selected for this study. Quartz is one of the mineral aerosols which are commonly produced outdoors and enter through windows/cracks or are brought by occupants. Crushed Quartz #10 bt#4339 (Particle Technology Limited, UK) is used for the testing. For dust mite, Spent Mite Culture powder (Indoor Biotechnologies Inc., USA) is used. The dust mite samples are milled to produce fine mixed powder. The milled dusts are sieved to separate the particles. Dog fur dust and cat fur dust are prepared from respective pet animal fur collected from local pet grooming companies, which are then milled and separated using sieve. The grinding and sieving process is considered to prevent the dust particles from forming particle-to-particle agglomeration.

The particle size distribution of four test dusts is characterized using Wet and Dry Laser Diffraction (Mastersizer S, Malvern, UK) which has 64 bins between 0.05 and 900 μm. To confirm whether the test dusts represented typical indoor dust, the particle size distribution of test dusts is compared to that of Standard Reference Material (SRM 2583 Indoor Dust) distributed by NIST (National Institute of Standards and Technology). The NIST SRM 2583 is composed of dust collected from vacuum cleaner bags in dwelling space (US NIST 2010). For the experiment, typical metal duct and fibre-glass duct which are commonly used for residential duct systems are used as particle reservoirs. The dimension of each flooring sample is 90 mm x 90 mm.

Resuspension Chamber Experiment Setup To examine the resuspension behavior of test dusts affected by particle disturbances factors, which were measured in field tests, laboratory small-scale chamber experiments are performed in controlled temperature, relative humidity, background particle level of supply air and mechanical/aerodynamic disturbance conditions. The chamber system is originally constructed for the research of particle resuspension subjected to mechanical and aerodynamic disturbance (Gomes et al. 2007). Figure 4 shows the schematic diagram of resuspension chamber system. The system consists of a resuspension chamber, an air control system and a data acquisition (DAQ)/control system. The air control system consists of a temperature/humidity environmental chamber, a desiccant, a HEPA filter and pumps.

The resuspension chamber is made of stainless steel and has a size of 400 × 200 × 200 mm (L × W × H). The bottom center of the chamber has an area of 100 × 200 mm (L × W) where a test flooring sample is placed. As a part of the chamber, an actuator-induced mechanical shaker (F4, Wilcoxon, USA) and six aerodynamic air-jet nozzles made of copper are embedded beneath the chamber to stimulate the flooring sample with the vibration and air swirl caused by occupant walking. The controlled air supplied from the air control system is passed into the resuspension chamber. An inlet porous panel (1100S-0039-02-A, Mott Corp., USA) is installed at the longitudinal square cross section of the entrance of the chamber to ensure uniform distribution of the air. The laminar air flow sweeps the chamber carrying resuspended particles into the sampling line attached to the exhaust port. The exhaust flow is collected through an optical particle counter. The pressure inside of the chamber is measured by a pressure gauge (2020S AKPT, Orange Research, USA) to ensure the chamber was pressurized relative to the laboratory.

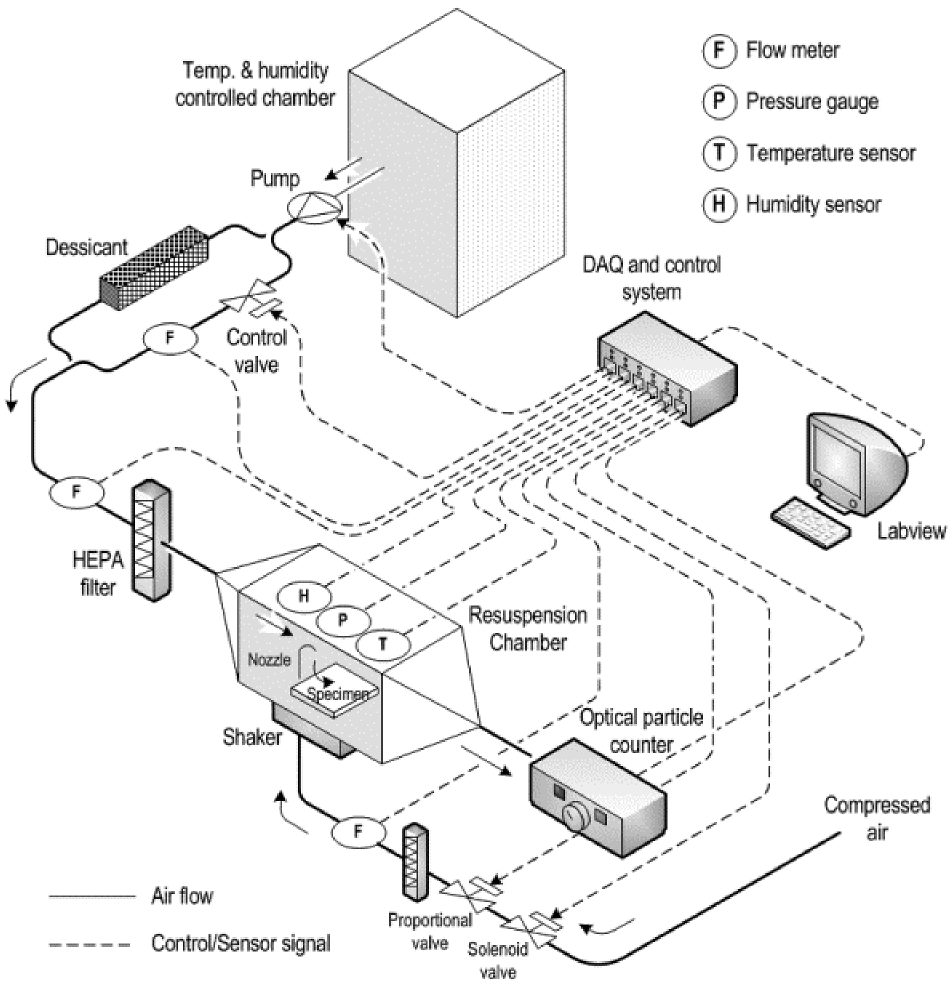


Figure 4. Schematic diagram of resuspension chamber system

The humidity and temperature of the supply air is controlled using a temperature/humidity environmental chamber (SM-8-3800, Thermotron, USA). The environmental chamber provides temperature range from -70 ℃ to 180 ℃ and humidity range from 35% to 97% at 21 ℃. The air from the environmental chamber is mixed with the air from the desiccant cartridge to meet desired humidity conditions using a proportional mixing valve. The temperature/humidity controlled supply air is filtered (HEPA CAP36, Whatman, UK) and pumped (1532-101-6288X, GAST, USA) to the resuspension chamber. The temperature and relative humidity within the resuspension chamber is monitored by a temperature/humidity sensor (HX15-W, OMEGA, USA).

The experiments are controlled and the data from sensors and optical particle counter were collected in a data acquisition (DAQ)/control system. For a high degree of automatic control and data acquisition, LabView (version 8.20, National Instrument, USA) is used communicating with a DAQ board (PCI 6259, National Instrument, USA).

Seeding and Measuring Procedures. To uniformly seed the test dusts on flooring samples for resuspension experiments, a particle disperser chamber is used. The chamber is made up of glass and stainless steel plates with dimensions of 760 × 760 × 420 mm (L × W × H), which is sealed and air tight. Total of nineteen flooring samples are laid out in five rows with five samples in each row except in the middle, where a particle injection nozzle is located. Each test dusts are injected in the amount 3 g m^{-2} by a compressed air line from a scale syringe to a cone, which is attached at the end of the particle injection nozzle. An air-jet is simultaneously injected from another nozzle hung from the top of the chamber to impact the cone. At the same time, four miniature fans placed in each of the four corners of the chamber are activated to ensure uniform dispersion of the dusts.

After the seeding process, the flooring samples are placed in a sample conditioning chamber with protective lids for at least 24 hours before each resuspension experiment to give sufficient time to reach the desired relative humidity equilibrium. The sample conditioning chamber is a plastic storage container, which enabled the samples to be controlled at desired relative humidity conditions. The conditioned flooring sample is placed in the resuspension chamber, and then the supply air is introduced at the flow rate of 0.0259 m^3 min^{-1}. Simultaneously, disturbance signal is activated and the particle concentration is measured at the exhaust port of the resuspension chamber. Sixteen-second disturbance signal ran for four minutes. Air samples from the chamber are measured using an optical particle counter (Spectro .3, Climet Instruments, USA) with a sampling rate of 7.9×10^{-3} m^3 min^{-1}. The optical particle counter has 16 bins between 0.3 to 10 μm. The particle concentration is measured every second per unit of air volume during 4-min testing period. During the resuspension experiments, the mechanical vibration and air flow patterns measured in MorningStar Solar home is replicate in the resuspension chamber by using the accelerometer and air nozzles located in the resuspension chamber.

Before each test, the particle disperser chamber and resuspension chamber are thoroughly cleaned. To check the cleanliness of the resuspension chamber, the background sample of the particle concentration is taken prior to each test. The LabView code in the DAQ system enables monitoring the real-time background data from the optical particle counter until the number reached a threshold value of 5 particles m^{-3}.

Estimation of resuspension rate. Resuspension rate (RR) is calculated as the fraction of a surface species removed in unit time as shown in Equations (1) and (2).

$$RR_d = \frac{G_d}{C_{d,surface}}, \tag{1}$$

$$G_d = \frac{\int_t Q_{sampling} \cdot C_{d,air} dt}{A_{surface} \cdot \frac{1}{60} \cdot \int_t dt}, \tag{2}$$

where RR_d is the resuspension rate for particle size d, G_d is the surface removal rate for particle size d, $C_{d,surface}$ is the surface dust concentration for particle size d, $Q_{sampling}$ is the sampling air volume flow rate, $C_{d,\,air}$ is the air dust concentration for particle size d, $A_{surface}$ is the surface area. The mean value of the 2-min data is used as a representative resuspension rate for each particle size of test dusts.

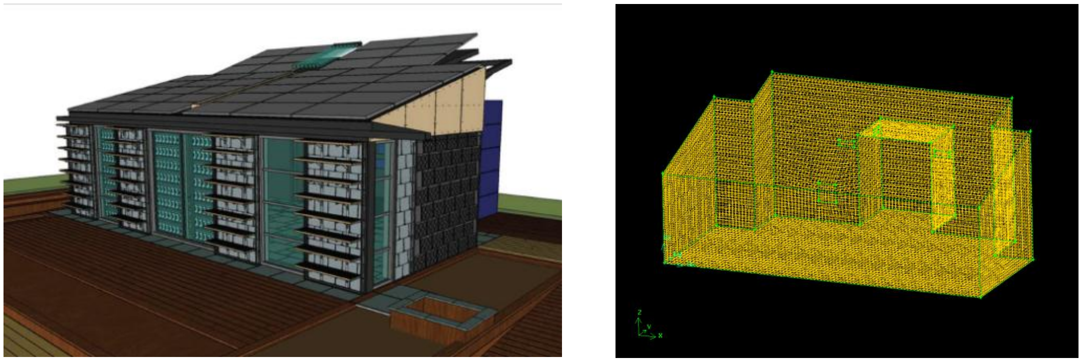
CFD (COMPUTATIONAL FLUID DYNAMICS) SIMULATION

Overview. Indoor airflow and particle dispersion in a Morning Star Solar Home is simulated by CFD modeling. Resuspension data previously measured in the laboratory resuspension experiment are used in the development of models to predict particle concentrations in the indoor environment, and to investigate the impact of in-duct particle resuspension and transport on occupant exposure.

Indoor Airflow and Particle Transport Analysis. The indoor airflow is modeled by the renormalization group (RNG) *k-ε* turbulence model. The RNG *k-ε* turbulence model is suggested to be suitable for indoor airflow simulation. The particle dispersion is modeled by a Lagrangian discrete random walk (DRW) model. The Lagrangian method solves the momentum equation based on Newton's law to calculate the trajectory of each particle. This study uses Fluent 6.0 with GAMBIT as a pre-processor for the simulation.

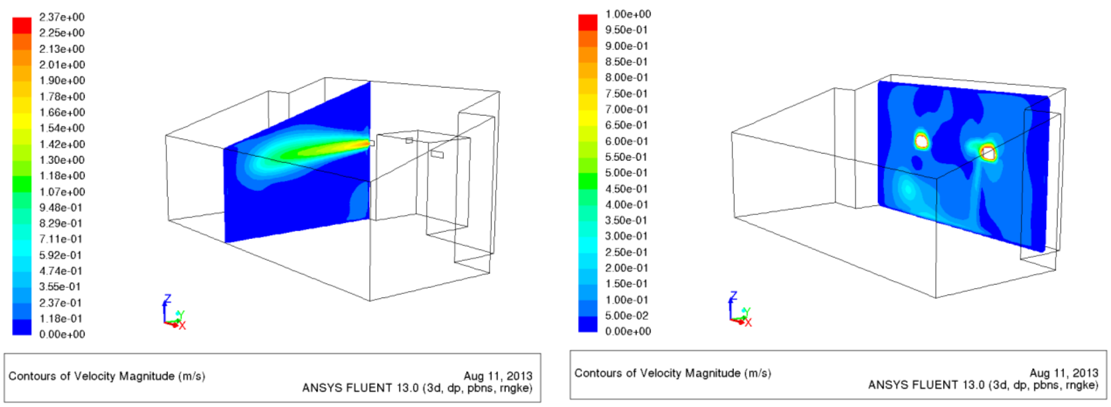
$$\frac{du_p}{dt} = F_D(\overrightarrow{u_a} - \overrightarrow{u_p}) + \frac{g(\rho_p - \rho_a)}{\rho_p} + \overrightarrow{F_a} \tag{3}$$

where u_p is velocity vector of the particle; u_a is the velocity vector of the air; $F_D(u_a - u_p)$ is the drag force per unit particle mass; ρ_p is the particle density; ρ_a are the air density; g is the gravitational acceleration vector, and F_a is the additional forces.



a. **b.**

Figure 5. a. 3-dimensional modeling of MorningStar Solar Home; b. CFD mesh generation



a. **b.**

Figure 6. a. Velocity magnitude contour plot on the YZ cross-section plane near supply register; b. Velocity magnitude contour plot on the XZ cross-section plane near supply register and return grill

Figure 5 shows the 3-dimensional modeling of MorningStar Solar Home and the result of CFD mesh generation. Figure 6 shows the velocity magnitude contour plot on the YZ cross-section plane near supply register and the velocity magnitude contour plot on the XZ cross-section plane near supply register and return grill.

Particle Concentration Analysis. PSI-C (particle source in cell) method is used to calculate the particle concentration in the modeled space [Bin paper 9].

$$C_j = \frac{\dot{M}\sum_{i=1}^{m} dt_{(i,j)}}{V_j} \qquad (4)$$

where C_j is the mean particle concentration in a cell, V_j is the volume of a computational cell for particles, dt is the particle residence time, and subscript i and j represent the ith trajectory and the jth cell, respectively. $\dot{M}$ is the flow rate of each trajectory.

Validation of CFD model. To validate the CFD model described above, the experimental data from the previous research is used. The experiment was carried out for the particle of which diameter of 10 μm in the space of 0.8 m× 0.4 m × 0.4 m (Length × Width × Height). The CFD model for validation was identically set to have the same location of openings, diffuser location and air velocity as the experimental case.

CONCLUSION

The research is currently ongoing, partially funded by PHRC (Pennsylvania Housing Research Center). The experimental setup required for the field and laboratory experiments has been completed as described in this paper. Also, CFD model to assess human exposure to indoor particle has been done. The study will measure the disturbances of particle resuspension in MorningStar Solar Home and subsequently conduct the resuspension chamber experiment to rigorously quantify the particle resuspension rates suggested in this paper. Finally, the particle resuspension rates for the various indoor particles and duct materials will be used for CFD simulation to assess human exposure to indoor particles. It is expected that the research can contribute to assessing the health risk of occupants due to exposure to indoor particulate, which may be induced by HVAC duct.

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The Effect of Building Impact Protection Schemes on Community Resilience

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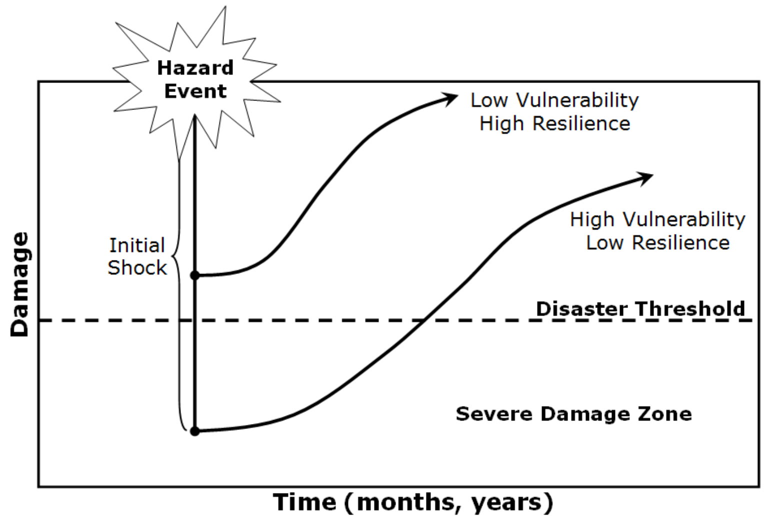
2nd Residential Building Design and Construction Conference State College, PA February 19–20, 2014

Motivation for the research

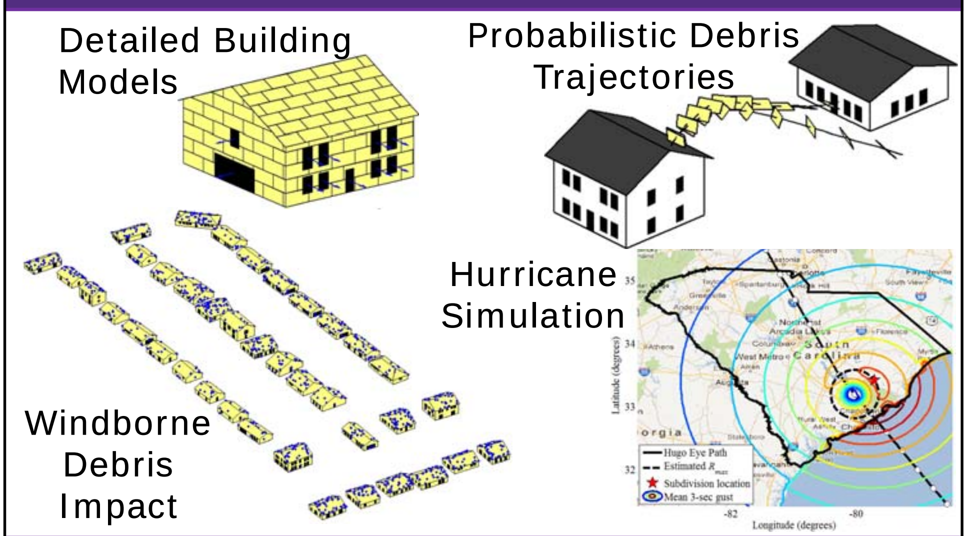
- Community resilience is a function of the socioeconomic response after the occurrence of a hazard event; however, it is also **dependent on the vulnerability** of the community to disaster
- Can increase community resilience by mitigating the **initial shock** felt by a community during a hazard event so that it does not drop below the disaster threshold

Objective is to reduce the initial shock felt by a community



* Adapted from *U.S. Indian Ocean Tsunami Warning System Program (2007)*

Overview of the Building Envelope Failure Assessment (BEFA) model



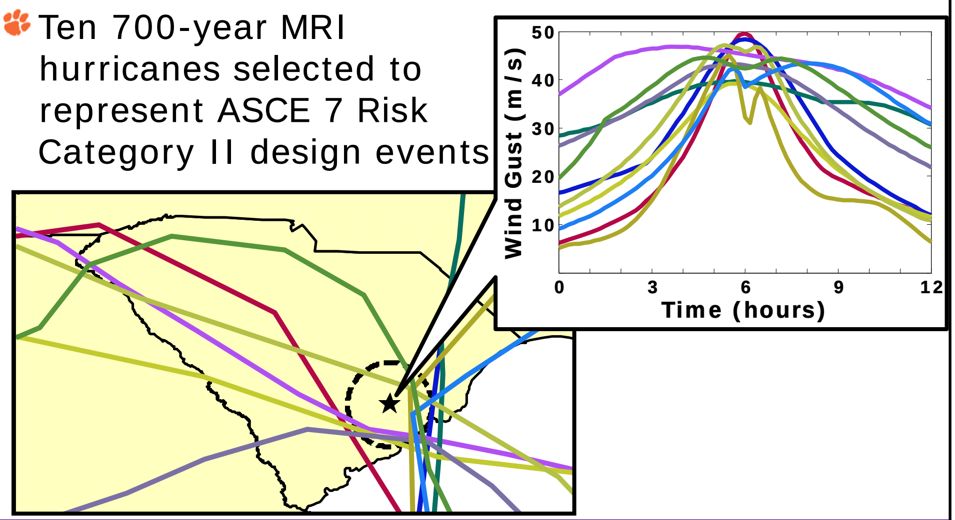
* Adapted from *Grayson et al. (2013)*

BEFA model provides …

- the time evolution of wind-borne debris release
- the time evolution of building envelope damage
- the probability of community vulnerable component failures (e.g., windows and doors)
- a platform for comparing the short-term efficacy of hurricane wind event mitigation techniques

Current study incorporates the variability of the hurricane hazard

- Ten 700-year MRI hurricanes selected to represent ASCE 7 Risk Category II design events



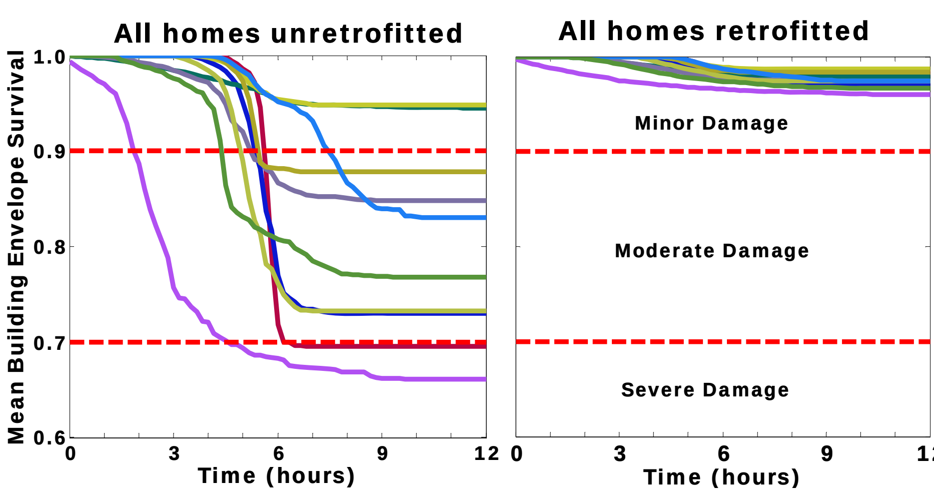
* Line colors are consistent throughout: represent hurricanes 1–10

Retrofit building components to reduce initial shock to community

Retrofit

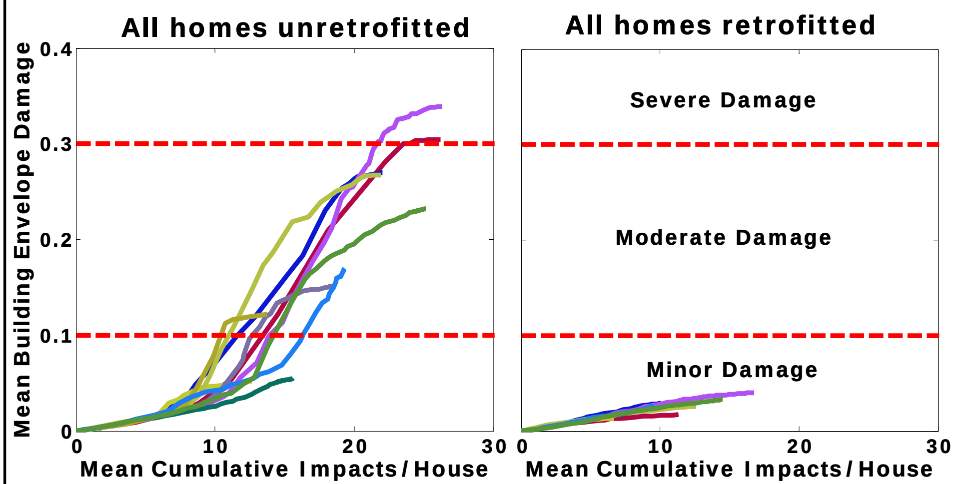
Original	Retrofitted
Roof sheathing with 6d fasteners at 6”/12”	Supplement with closed-cell spray foam
3-tab asphalt shingles	High-wind resistant shingles
Personnel/Garage Doors	Higher capacity personnel/garage doors
Annealed glass windows	Add window shutters

Survival includes pressure/impact failures of vulnerable components



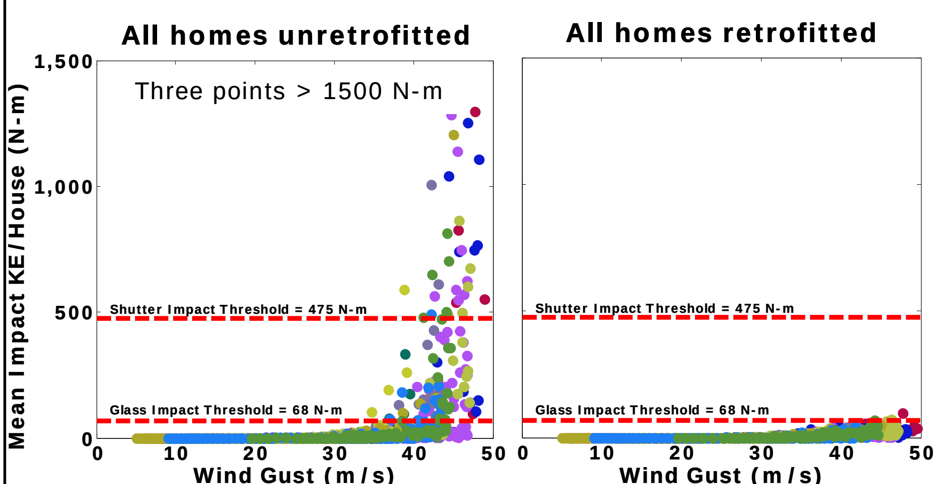
* Line colors are consistent throughout : represent hurricanes 1–10

Multiple failed component types contribute to unretrofitted damage



* Line colors are consistent throughout: represent hurricanes 1–10

Debris impact can cause damage even if impact protection is used



* Marker colors are consistent throughout: represent hurricanes 1–10

Conclusions

- Initial impacts (shallow slopes) are due to roof covering, while later impacts (steep slopes) due to the failure of multiple component types
- Impact protection schemes should consider retrofit of all building components since window protection alone does not ensure adequate protection

Future Work

- Current research will be expanded to determine the percentage of a community that must be retrofitted to receive the benefits of hurricane wind hazard mitigation techniques
- Hurricane wind hazard mitigation techniques will be compared to determine which techniques assist homeowners in providing maximum benefit to the community with a minimum of cost/effort

References

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